Cerulogy

Waste not want not

Understanding the greenhouse gas implications of diverting waste and residual materials to biofuel production

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Executive summary

Over the last ten years, it has become generally accepted that producing first generation biofuels from food commodity crops results in indirect emissions impacts. These are changes in carbon stocks or emissions rates that occur throughout the wider economy in response to growing demand for biofuel feedstocks. The most important category of indirect emissions for these land-using biofuels is indirect land use change, the emissions resulting when increased biofuel demand drives overall agricultural area expansion, or prevents carbon sequestration due to agricultural area shrinkage.

While these land use change emissions, from food crops in particular, have received a great deal of attention, analysts have also considered the possibility that increasing demand for materials usually characterised as 'wastes' or 'residues' could also have indirect emissions implications. For instance, fatty acid distillates from palm oil refining are currently utilised for applications including oleochemicals, soaps and animal feed. Using them for biofuel feedstock instead would create a gap in the market for some alternate feedstock. If this results in more palm oil being used for oleochemicals, soaps and animal feed, then the net outcome may be similar to simply using the palm oil directly for biofuel production in the first place. In such a case, it is not at all clear that using policy to incentivise the use of the residue instead of the primary product delivers on environmental goals.

In November 2016, the European Commission proposed a revision to the Renewable Energy Directive for the period 2020 to 2030, under which biofuels from materials that might be characterised as wastes and/or residues would play a major role, on the presumption that using these materials would deliver better environmental outcomes than using food crops. In this report, we assess the indirect emissions implications of producing biofuels from some of the materials listed in the proposal, and of some that may be proposed as additions to the proposal as it is discussed in the European Council and Parliament. We find that indirect emissions are likely to be significant in most cases, and that it is important for policy makers to understand potential indirect emissions when deciding which materials ought to be eligible for additional incentives.

There is no clear consensus in the existing literature on indirect emissions from waste and residue use as to how the system boundary should be drawn, and some indirect emissions that are calculated here would not be included in other studies. In order to provide maximum transparency, in this study we explicitly distinguish: indirect emissions related to increased materials production; associated land use change; changes in forest carbon stock; increased fossil fuel use; an emissions credit in cases where renewable energy resources are displaced from heat and power uses in the EU and would need to be substituted by additional renewable energy generation in order to meet EU targets (we refer to this as the 'renewable rebound').

The renewable rebound warrants some explanation, as this is an idea that has not been included in previous studies. In other renewable energy lifecycle analysis, the opportunity cost of taking a resource from an existing use (here included as increased fossil fuel use) is generally not included. Here however, these emissions are included in the analysis. It therefore seems appropriate to acknowledge that European renewables policy is set up in a way that can manage this problem of opportunity cost. As an example, if black liquor is used for biofuel production it would count towards the segment of renewable energy targets that must be met in transport, but no longer contribute to the segment of renewable energy targets expected to be met by heat and power. This would create a need to install additional renewable capacity (wind power, for instance), in order for overall targets to be met. This renewable rebound is explained in more detail in section 3.2.6.

In general, indirect emissions are significant. None of the materials considered in this report is subject to any significant rate of disposal without utilisation, and so the results reflect the expectation that in all cases increasing use of those materials for biofuel will create a supply shortfall for some other use(s), a shortfall that must be met with other materials. In many cases, the likely substitute materials are fossil fuels or vegetable oils, both of which have significant emissions implications.

Table 1 shows the results of the indirect emissions analysis. The results are split into three groups, for three different land use change assumptions – firstly ignoring indirect land use change, then using indirect land use change values from the proposed RED II, then using indirect land use change values from European Commission modelling in GLOBIOM. For each land use change case, the results are split into four system boundary cases. Firstly we show the calculated indirect emissions associated with additional materials production and land use changes, the second value adds emissions from changes in forest carbon stocks[1], the third value adds emissions from increased fossil fuel use, and the fourth column adds the renewable rebound.

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[1] Increasing demand for biomass energy from woody materials requires either increased mobilisation of forestry residues, or increased wood harvests. Removing forestry residues from the forest results in persistently reduced carbon stocks in dead wood, while increasing forest harvests may cause reduced carbon stocks in living wood. This is explained in more detail in section 3.5.

Table 1. Tabulated indirect emissions outcomes (gCO2e/MJ)

Feedstocks:	No ILUC				RED II				GLOBIOM			
	Materials only	Materials and forest carbon	Materials, forest carbon and fossil fuel	All	Materials and LUC	Materials, LUC and forest carbon	Materials, LUC, forest carbon and fossil fuel	All	Materials and LUC	Materials, LUC and forest carbon	Materials, LUC, forest carbon and fossil fuel	All
Animal fats derived FAME	8	8	66	20	18	18	76	30	42	42	100	54
Tall oil derived HVO	7	10	52	40	11	15	57	45	20	24	66	54
Tall oil pitch derived HVO	0	0	93	15	0	0	93	15	0	0	93	15
Glycerine derived methanol	19	19	28	20	28	28	37	28	41	41	50	42
Sawdust and cutter shavings derived FT diesel	15	62	93	67	15	62	93	67	15	62	93	67
Black liquor derived FT diesel	6	24	50	25	6	24	50	25	6	24	50	25
Distillers corn oil derived FAME	30	30	30	30	74	74	74	74	141	141	141	141
PFAD derived HVO	39	39	47	47	84	84	92	92	213	213	221	221

Where the sum of indirect emissions is over 50 gCO_2e/MJ, cells are shaded red. Where emissions are between 20-50 gCO_2e/MJ, the cells are shaded yellow.

Results in this table use our central scenario for carbon intensity of additional wood harvest (see section 3.5)

The table is highlighted to show cases with very high indirect emissions (pink highlighting for over 50 gCO_2e/MJ) and cases with moderate indirect emissions (yellow highlighting for 20-50 gCO_2e/MJ). As is clear from the table, the results are very sensitive to system boundary and use change assumptions.

They are also sensitive to methodological choices, and to other input assumptions. Better biofuel yields correspond directly to lower indirect emissions (as less material is needed to produce the same fuel volume), and hence the calculated indirect emissions are lower for biofuel conversion pathways with higher assumed yields.

The modelling presented in this report is causal descriptive, meaning that it is based on what we consider to be a reasonable assessment of the likely consequences of increasing demand for each potential biofuel feedstock considered. This assessment is necessarily subjective, and also necessarily imprecise – other experts may be able to present reasonable arguments to raise or lower the value of many of our input assumptions. Nevertheless, we believe that this exercise provides a useful indication of the net emissions outcomes that might be expected from supporting given biofuel pathways.

Feedstocks for which vegetable oils, and palm oil in particular, are expected to be a major substitute are associated with high land use change emissions. The results show that because distillers' corn oil and palm fatty acid distillates are more or less substitutable with virgin vegetable oils, the expected indirect land use change impacts of using these materials to produce biofuel are comparable to the expected indirect land use change impacts of using virgin vegetable oils. The indirect emissions expected from feedstocks produced by the forestry industry are highly sensitive to assumptions about the carbon stock impacts of increasing wood harvests. For sawdust and cutter shavings in particular, assumptions on the carbon stock impact of increasing wood harvest make the difference between modest, high and very high indirect emissions.

Readers of this report should take care to understand the meaning of each category of indirect emissions. The indirect emissions from materials production are based on the default feedstock production emissions calculated for first generation biofuel feedstocks in the proposed RED II, they represent the greenhouse gas implications of growing and/or manufacturing replacement material. The land use change and forest carbon stock change numbers are based on modelling of indirect land use change and forest carbon stock change, they represent the changes in terrestrial carbon stocks that are expected to result from increasing demand for replacement materials. The fossil fuel use emissions, in contrast, more directly represent an opportunity cost. This term can be thought of as the emissions savings 'lost' to the heat and power sector as resources are moved from one sector to another. Finally, the renewable rebound credit reflects the role of policy in mitigating this opportunity cost. Within the EU renewables framework, a reduction in renewable heat and power generation from a given biomass feedstock must be compensated by an increase in renewable heat and power generation elsewhere.

Including the fossil fuel use term and the renewable rebound term in calculations could lead to counter-intuitive results if taken out of context. For instance, if including the fossil fuel use change in the system boundary undertaking the same calculation for the greenhouse gas implication of continuing the existing use would also give an opportunity cost. You could easily find a case where there was a high calculated opportunity cost (large indirect emission) associated with both changing the use of the resource and with leaving it as it is. In that case, it should not be concluded that neither use was desirable. Rather, it should be concluded that a policy choice is necessary about which option to pursue, and about whether it is justified to use policy to change the use of a resource is already being used to generate renewable energy.

Similarly, when including the renewable rebound in the system boundary, it would be possible to produce results apparently showing that closing down a renewable energy facility would not result in any net change in emissions savings. In this case, it should not be concluded that renewable energy generating facilities can be shut with no negative consequence. Rather, it should be concluded that the European Union policy framework is such that reducing renewable heat and power generation from a given resource should not necessarily result in an overall reduction in renewable heat and power generation.

To date, the development of EU biofuel policy has given inadequate consideration to the potential indirect consequences of moving well-utilised residues from an existing use to a new energetic use. Hopefully, these results can help to rebalance that discussion. On the other hand, it is important to acknowledge the fact that European Union policy places an additional value on the use of renewable resources in the transport sector over other sectors. In that context, it may be considered acceptable to use policy to incentivise the use of renewables for transport instead of for heat and power, even if it provides little or no immediate net emissions advantage. In the end, these decisions are political, rather than purely analytical, and there is no simple set of analytical results that can uniquely indicate the correct choices as EU renewable energy policy develops.

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Glossary of abbreviations

CBOT	Chicago Board of Trade
CSS	Crude sulphite soap
CTO	Crude tall oil
DCO	Distillers' corn oil
(D)DGS	(Dry) distillers' grains and solubles
DME	Di-methyl ether
DTO	Distilled tall oil
EPA	U.S. Environmental Protection Agency
ERS	U.S. Department of Agriculture Economic Research Service
ETS	Emissions Trading Scheme
FAME	Fatty acid methyl ester
FAO	United Nations Food and Agriculture Organisation
FAPRI	Food and Agricultural Policy Research Institute
FOB	Free on board
FQD	Fuel Quality Directive
GHG	Greenhouse gas
HVO	Hydrotreated vegetable oil
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
(I)LUC	(Indirect) land use change
LCA	Lifecycle analysis
LCFS	Low Carbon Fuel Standard
LHV	Lower heating value
PFAD	Palm fatty acid distillate
RED	Renewable Energy Directive
RFS	Renewable Fuel Standard
TOFA	Tall oil fatty acid
TOP	Tall oil pitch
TOR	Tall oil rosin
UCO	Used cooking oil
USDA	U.S. Department of Agriculture
WTT	Well to tank

1. Introduction and context

1.1. Indirect effects of utilising wastes and residues

In the years since the publication of the first quantitative assessment of indirect land use change (ILUC) emissions associated with biofuel production (Searchinger et al., 2008), it has become generally accepted that indirect emissions represent a significant source of greenhouse gas emissions in the lifecycle of land-based biofuels. By indirect emissions, we mean emissions that do not arise directly within the system boundary of the facilities producing and processing feedstock for fuel manufacture, but that can nevertheless be reasonably expected to take place as a consequential result of increased fuel production. In the case of indirect land use change, this represents changes in carbon stocks in biomass and soils as agricultural area expands more than it otherwise would (or shrinks less than it otherwise would) due to the extra demand for feedstock for biofuel production.

While there has been great focus on these indirect land use change emissions, and a correspondingly large amount of work undertaken to refine approaches to estimate these emissions, there has generally been less focus on indirect emissions changes occurring outside of the land use sector. In particular, it has often been assumed that the use for biofuel feedstock of materials that could be characterised as wastes, residues or by-products of other processes will have a lower greenhouse gas emissions footprint than the use of purpose grown materials and low or no associated indirect emissions. However, this conventional wisdom does not necessarily hold true in the case where these materials already have existing productive uses. Depending on the nature of the current use, its efficiency, and the alternative options available to fill that niche in the market, shifting materials into use for biofuel production could result in significant net emissions changes elsewhere in the system. As with other indirect emissions from bioenergy, indirect effects of the use of wastes and residues do not only apply to the creation of new demand, but also to the continuation of existing demand (this is particularly relevant to first generation biofuels from wastes). Reducing feedstock demand for biofuels would relieve pressure on global materials supplies and land use, just as increasing demand would increase it. An indirect emissions calculation can thus be understood as an assessment of the opportunity cost of using that resource for biofuel production, rather than some other use.

While there has not been as much work or attention around this question as there has been around ILUC, there have still been several studies that have addressed the question. The earliest quantitative assessment of which we are aware was undertaken in 2008 at the behest of the UK Department for Transport (AEA Energy & Environment, 2008). This study considered the implications of diverting supplies of tallow for the purpose of biofuel production, given that the material already had existing uses in oleochemicals, soap making, boiler fuel and elsewhere in the economy. The study concluded that increasing demand for tallow for biodiesel production could potentially have significant impacts on other industrial users, and that in the case that increased use of tallow for biodiesel led to its replacement by fuel oil as boiler fuel at rendering plants, this would cause a significant indirect emissions, offset against the benefit of diesel fuel replacement by biodiesel. Further studies on these questions include follow-up work for the UK government that also considered molasses, MSW and wheat straw (Brander et al., 2009), studies commissioned by the pine chemicals industry of the implications of increased tall oil use for biofuel production (Cashman, Moran, & Gaglione, 2016; Rajendran, Breitkreuz, Kraft, Maga, & Brucart, 2016), work on Annex IX feedstocks for the UK Department for Transport (Taylor & Bauen, 2014), further work on animal fats for the European Commission (Chudziak & Haye, 2016), and assessment by the International Council on Clean Transportation of potential indirect emissions associated with feedstocks listed in Annex IX of the 2016 European Commission proposal for a revised Renewable Energy Directive (henceforth 'RED II')[2] (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

The literature on indirect emissions associated with the diversion of waste, residual and by-product materials that have existing uses towards biofuel production consistently finds that it is important to understand these potential emissions when considering differentiated incentives for the use of waste and residual feedstocks in biofuel policy. Emissions associated with producing alternative feedstocks to meet existing materials demand, from burning alternative fuels to meet energy demand, and from land use change associated with replacement materials can all be significant contributors to the biofuel lifecycle.

1.2. About this report

The RED II proposal states in its recitals that, "Feedstocks which have low indirect land use change impacts when used for biofuels, should be promoted for their contribution to the decarbonisation of the economy. Especially feedstocks for advanced biofuels, for which technology is more innovative and less mature and therefore needs a higher level of support, should be included in an annex to this Directive." This is reflected in two lists of biofuel feedstocks given in Annex IX of the proposal. Biofuels produced from materials on the first of these lists (Part A) are characterised as advanced biofuels. Part B lists other non-food biofuel feedstocks. The proposal provides substantial incentives to produce fuels from these materials – there is a target of a minimum of 3.6% of European transport energy from feedstocks listed in Part A (equivalent to a minimum of about 9 million tonnes of oil equivalent in renewable fuel). This would require a dramatic expansion of the industry. While the list of feedstock in Part A of Annex IX of the RED II proposal is intended to have a central role in future policy, there is no single analytical framework that has been presented by the European Commission that was used as the basis upon which materials have been included in, or excluded from, the list. Certainly, there is not full agreement among the Member States and the wider stakeholder community as to exactly which resources should be included in the list and which should not when the final agreed form of the RED II emerges from the decision process between the Commission, Council and Parliament. Indeed, inclusion and exclusion of materials on Annex IX is likely to be a subject of considerable discussion in the period from now to the finalisation of the RED II.

In this report, we assess the potential indirect emissions that would be expected if increasing the demand for various feedstocks that are either part of Annex IX in the proposed RED II, or that we believe might be suggested for inclusion in Annex IX during the legislative process. In particular, this report focuses on materials that have a 'rigid' supply. This means that the global production of these materials is determined by the factors other than demand for these materials – in general by the rate of production of some principle product, with the materials considered here being by-products from those processes. For instance, the supply of animal fats is dictated by the number of animals reared for meat (and to a lesser extent dairy) production. An increase in demand for animal fats would not result in more animals being raised. This contrasts to materials with elastic supply, for which a demand increase can result in a production increase. For instance, increased demand for rapeseed oil can lead farmers to plant more rapeseed.

The focus of this report is on greenhouse gas emissions changes, and our analytical results address

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[2] Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (European Commission, 2007). Please note that this report was written before any amendments had been proposed by the Parliament or Council, and thus any such amendments do not inform this report.

greenhouse gas emissions only. This focus should not be taken to imply that we believe that no other issues should be considered – we believe that it would be entirely appropriate for the European institutions to consider not net only greenhouse gas emissions changes, but also the relationship of feedstocks and technologies to longer term climate strategy and industrial strategy. In Chapter 3 we present the methodological framework that we have adopted to make assessments of indirect emissions. This is followed by discussion and indirect emissions analysis of the following biofuel feedstocks:

1. Palm fatty acid distillates (not currently inckluded in Annex IX)
2. Corn oil pressed from distillers grains ("distillers' corn oil") (not currently inckluded in Annex IX)
3. Crude tall oil (currently included in Annex IX Part A)
4. Sawdust and cutter shavings (currently included in Annex IX Part A)
5. Black liquor (currently included in Annex IX Part A)
6. Crude glycerine (currently included in Annex IX Part A)
7. Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009 of the European Parliament and of the Council (currently included in Annex IX Part B)

1.3. Wastes, residues and by-products

In the context of bioenergy policy and lifecycle analysis, terms such as 'waste', 'residue' and 'by-product' can have specific meanings that are associated with differentiated regulatory treatment. In the proposed RED II, the term waste is given the definition, 'any substance or object which the holder discards or intends or is required to discard', while the term residue is given the definition, 'a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it'. The term by-product is not given a definition in the RED II. In this report, we use the term 'waste' with regard to materials fitting the RED II definition of residues that are expected to be discarded without further use, including without energy recovery. We use the term 'by-product' to refer to a materials fitting the RED II definition of residues that are expected to be utilised to recover some amount of value, including through energy recovery. The term 'residues' is used in this report to cover materials that can by either wastes or by-products.

While terminology is important, the analysis in this report is not based primarily on the categorisation of materials, but on an assessment of what the system wide impact may be if those materials are used for biofuel feedstock. We therefore do not present a systematic labelling of materials between the three categories.

2. Methodology for estimating displacement implications of using materials for biofuel

In this report, in addition to a narrative discussion of the implications of using various materials that might be characterised as wastes or residues as feedstocks for biofuels production, we present estimates of the likely greenhouse gas emissions implications of increased utilisation for each material as a biofuel feedstock. The basic lifecycle analysis framework for generating these estimates is a consequential one based on system expansion. It is thus somewhat analogous to the framework used for assessing the greenhouse gas emissions reductions associated with indirect land use change (Laborde, 2011; Valin et al., 2015). However, while the analysis of indirect land use change associated with biofuel production has generally relied on complex economic models of the global agricultural economy, market models of that complexity and scope are not readily available for analysing potential shifts in trade and use of the materials of interest here. We therefore present an analysis within a 'causal descriptive' framework, which is to say a framework in which we identify expected market responses and make exogenous assumptions about how these will be balanced (rather than an equilibrium model in which the balance of outcomes is endogenously determined by the interaction of other parameters). We use a methodology strongly influenced by earlier work for the UK Government Department of Energy and Climate Change and Renewable Fuels Agency (Brander et al., 2009), henceforth 'the Ecometrica study'[3]. This study presented a methodology for considering the indirect GHG emissions implications of the use of materials with inelastic supply.

The causal descriptive modelling framework has the advantage that it allows us to generate emissions estimates without having access to the comprehensive market data that would be necessary to properly parameterise a full economic model. The flipside of this though is that many of the assumptions that are made in our modelling are necessarily subjective, and rely on expert judgement based on the data available. In the report, the basis for assumptions is set out to the extent possible, but often there is simply no robust analytical basis available to calculate an exact number for a given parameter, and therefore values are chosen that we consider reasonable and defensible. We fully expect some of these decisions to be subject to dispute and criticism, and that some commentators may claim that robust emissions estimates would require a more detailed equilibrium modelling framework. We do not dispute the right of commentators to make such criticisms, but we would note that even the most respected and detailed equilibrium models often do not have robust analytical bases for many of their input parameters, and a great deal of subjective expert judgement is embodied in these tools, even when this subjective input may be masked by the layers of equations constituting the model. The strength, and the weakness, of causal descriptive modelling is that these assumptions are presented relatively directly, rather than being built into the calibration of trade relationships and so on.

The alternative use scenarios developed in this report are intended to give a reasonable characterisation of the likely outcomes of increased biofuel demand for various feedstocks in the near future. The likely displacement scenarios, and material use efficiencies, may well change between now and 2030, in which case revised assessment would be appropriate. Similarly, the alternative use assumptions are

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[3] This was also the basis of the methodology adopted to consider indirect emissions associated with the use of wastes and residues in the *Wasted* project (Baral & Malins, 2014b).

based on our best understanding based on the information available to the author at the time of writing. A reassessment using different or additional data could be expected to deliver different answers.

2.1. Ecometrica methodology

The methodology proposed in the Ecometrica study is laid out as follows:

1. Define the material studied (functional unit, location of production, locations of existing uses, locations of likely bioenergy applications;
2. Estimate the quantity likely to be used for bioenergy;
3. Inventory existing uses and quantity of material in each use, and existing disposal systems and quantity of material disposed in each way;
4. Inventory substitute materials or alternative production systems, including price at which replacement might occur and constraints on substitution;
5. Propose an 'order of dispatch' – the order in which potential substitutions or changes in disposal are expected to occur. Given the quantity of material expected to be used for bioenergy, identify which substitutes would be used or disposal systems would be abandoned on the assumption that systems higher up the order of dispatch will be entirely abandoned before systems lower on the order of dispatch are affected;
6. Calculate the quantity of new demand for each substitute material, and/or the quantified change in utilisation of each disposal system;
7. Calculate the emissions implications of increased consumption of the substitute materials, and/or reduced use of each disposal system;
8. Multiply the emissions intensity of each substitute material or disposal system by the increase in usage of each substitute material, or reduction in utilisation of each disposal system;
9. Calculate the average emissions associated with each unit of use of the original material for bioenergy applications;
10. Undertake a sensitivity analysis for key parameters in steps 1 to 7.

Using this methodology, Ecometrica assessed four feedstocks in the UK context, which were UK tallow, landfilled MSW, UK wheat straw, and EU sugar beet molasses. The results of that analysis are shown in Figure 1.

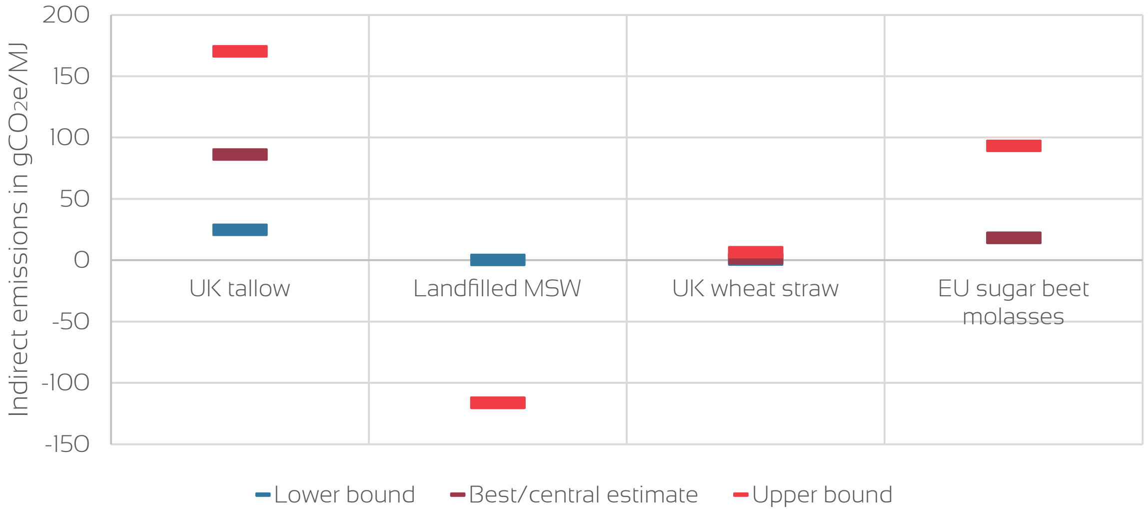

Figure 1. Indirect emissions calculated by Ecometrica

Note: Due to data limitations, for some feedstocks Ecometrica did not include a full set of lower bound, upper bound and central estimate. The numbers presented for MSW do not include a separate upper bound value, while the numbers presented for molasses have no best/central estimate.

The Ecometrica methodology is a useful starting point, but there are issues in its application. Indeed, in the Ecometrica report itself, the authors find it difficult to fully apply all steps to all feedstocks considered. In this report a modified methodology has therefore been adopted, as detailed below.

2.2. Division of results by emission category

As noted above, in this report we group indirect emissions estimates into four categories: materials production; land use change; fossil fuel use; and the 'renewable rebound'. Neither land use change emissions nor the renewable rebound credit were considered in the Ecometrica study. By explicitly dividing and documenting emissions in these categories, it is our intention to allow the reader to compare the result of setting different system boundary choices in the indirect emissions assessment. The four emissions categories are delineated as follows.

2.2.1. Energy recovery options in different sectors

In many cases, a material that can be used as biofuel feedstock may have an existing or potential alternative use as a feedstock for production of heat and power. In such cases, there may be no greater environmental benefit from using such material for biofuel production than for continuing (or starting) to combust the material for heat and power. E4tech, in their report on sustainability of using Annex IX feedstocks for biofuels (Taylor & Bauen, 2014), argue that:

> *"For … feedstocks, such as animal fats, nut shells, husks, sawdust & cutter shavings, tall oil pitch, brown & black liquor, support should only be provided if the industries involved can show replacement of the missing energy demands with low carbon, sustainable alternatives –*

> *otherwise there is a risk of increased fossil fuel use offsetting any GHG savings."*

In some previous assessment of the greenhouse gas implications of displacing materials from existing uses, the emissions associated with displacement out of existing energetic use have been counted against the biofuel pathway (Brander et al., 2009). In others, it has been assumed that material currently used for heat and power should be considered available for biofuel production and that no displacement emissions should be ascribed (Peters & van Steen, 2013).

It is important when considering indirect emissions estimates to understand that they represent a consequential consideration of the emissions implications of taking a course of action, and that this is a methodologically different type of question than that answered by the sort of attributional lifecycle analysis that is currently required for biofuels in the RED or RED II. While it has become common, following the example of the California Low Carbon Fuel Standard[4], to add an 'ILUC factor' to a direct emissions estimate to obtain an improved assessment of the overall emissions implication of expanding biofuel production, it should be understood that combining an attributional and consequential assessment in this way introduces a methodological inconsistency (Plevin, Delucchi, & Creutzig, 2014). In the case of indirect emissions from displacing materials out of other energetic uses, this inconsistency is particularly important to understand.

A noted by Ecometrica (Brander et al., 2009), if indirect emissions from displacing alternative energetic uses were counted against all bioenergy, then we might find that a biofuel pathway seemed to offer limited emissions benefits because it was no better than a heat and power pathway, but that the heat and power pathway in turn would seem to offer limited emissions benefit because it was no better than the biofuel pathway. Counting the opportunity costs against both pathways simultaneously could lead to a numerical result that seemed to imply that biomass resources should not be used for either. This would not be the correct conclusion to draw. Ecometrica suggest an approach to handling this question in which the opportunity cost is calculated both ways, and then only the difference in emissions outcomes between two alternative energy recovery pathways is counted against the less climate-efficient option. An alternative approach would be to undertake an indirect emissions assessment considering only non-energetic alternative uses.

There is no single analytically correct answer to this question of how one ought to think about indirect emissions caused by shifting energy recovery from one sector to another. On the one hand, there is not an automatic climate benefit to displacing fossil fuels from transport instead of from heat and power. The overall climate benefit of fossil fuel displacement will depend on the fuel being displaced, but Pavlenko, Takriti, Malins, & Searle (2016) showed that there is no general answer to whether biofuels will deliver more or less near term emissions savings than biomass energy in heat and power.

On the other hand European Union policy places a premium on emissions reductions in the transport sector, as evidenced by the fact that the implied carbon price under the Renewable Energy Directive has been persistently much higher than the carbon price under the ETS (Marelli et al., 2015). Policy makers must decide priorities, and decide whether it is indeed their intention to create incentives that are structured to shift resources from one type of energy recovery to another, as opposed to creating entirely new renewable energy supply chains (and entirely additional greenhouse gas emissions savings) and should interpret the results in this report in the light of those priorities.

The goal of the lifecycle analysis in this report is to provide a best estimate of the expected net indirect emissions impact of increasing demand for biofuel from each feedstock considered. Where the

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[4] https://www.arb.ca.gov/fuels/lcfs/lcfs.htm

expected outcome would be reducing the use of that material in other energy recovery applications, we seek to characterise the emissions impact of that change.

Given this methodological choice, it is vital that the reader should understand that where our analysis shows a large term associated with displaced fossil fuels, this suggests that use for biofuel may not deliver a large benefit compared to existing heat and power uses, but it does not mean that there is no value to recovering energy from the material at all. It is up to policy makers to decide whether they intend biofuel policy to support only biofuel production pathways that are fully additional (i.e. pathways that increase overall renewable energy production) or whether they are happy for policy to be used effectively to transfer resources, and the associated emissions reductions, from the heat and power sector to the transport sector.

Complicating the picture further, it must also be borne in mind that targets for renewable energy use in transport occur within a broader context of renewable energy and climate targets for the EU. The 6.8% target for the use of advanced renewable energy in transport[5] in the European Commission's RED II proposal lies within a larger 27% target for the overall use of renewable energy, a target that is expected to be stretching across the EU as a whole. Arguably, shifting renewable energy production within the EU from the heat and power sector to the transport sector would require a corresponding increase in renewable energy generation for heat and power from other sources (more windmills/solar arrays/ biomass power plants etc.). This will not generally be the case if renewable resources are displaced from heat and/or power utilisations outside the EU, as in many countries, reduced use of biomass resources for heat and power may not create a policy driver to increase use of alternate renewables.

Recognising that the overall policy framework can also play a role in determining the full outcome of shifting renewable energy resources into the transport sector, we have also calculated a 'renewable rebound' term for all fuel pathways that we expect to displace biomass resources out of heat and power generation in Europe. The calculation of this renewable rebound term is based on the assumption that when renewable energy recovery for heat and power is reduced in one location, this causes a shortfall against policy targets that must be recouped at another location, with a mix of other biomass- and non-biomass-based renewables, delivering an emissions credit. The details of the assumptions made in calculating this renewable rebound are presented in more detail in annex B.3.

As with the indirect emissions term for fossil fuel displacement, it is important that the reader should understand that this renewable rebound term is beyond the system boundary of the standard lifecycle analysis required under the RED. Not all experts would agree that it is appropriate to include the role of policy in determining outcomes in this way. We calculate and include this term though as we believe it is a reasonable representation of what would be expected to happen in response to increasing demand for biofuels from these materials.

Will all this in mind, throughout this report we have sought to be explicit in distinguishing indirect emissions that are expected to arise in different categories. We have distinguished four cases:

1. Indirect emissions from cultivation and/or production of alternative materials;
2. Indirect emissions from indirect land use change associated with alternate materials;
3. Indirect emissions from changes in forest carbon stocks;
4. Indirect emissions from increasing fossil fuel demand in other sectors;

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[5] Some forms of fossil energy from waste materials would also be eligible under the Commission's proposal, but with limited maximum contribution.

5. Indirect emissions from compensating increases in renewable energy use in other sectors to meet overall renewables targets (the 'renewable rebound').

To conclude this section, we would remind the reader that the proposed RED II includes a minimum emissions saving threshold that is intended to be applied to fuels supplied under the policy. One role of such thresholds is to mitigate the risk that indirect emissions outside the system boundary could partially or fully offset the benefits of use of a given alternative fuel. Caution should be applied if considering comparing such a threshold to emissions estimates based on summing direct emissions calculation with values drawn from one or all of the categories presented in this study.

2.2.2. Materials production

The materials production category includes the emissions associated directly with the production of materials that are expected to be required to replace material displaced for use as biofuel feedstock. These emissions are assessed based on attributional lifecycle analysis, either based on assessments undertaken with the Renewable Energy Directive LCA methodology, or else based on methodologically similar assessments. It is beyond the scope of this study to fully develop an entirely consistent new lifecycle inventory for potential replacement materials, so we have relied on values documented in the literature. For instance, for a case where using a material for biofuel production would be expected to drive additional soy oil demand, the materials production emissions would be based on the soy oil production part of the lifecycle analysis for soy oil biodiesel under the RED, as documented in Biograce (2017).

For the specific case of expectations of increased fossil fuel consumption, the production emissions from the fossil fuel pathway are *not* included in the materials production category. Instead, we have included the full lifecycle emissions for increased fossil fuel use within the separate fossil fuel use category. This means, for instance, that refining emissions for diesel production would be included in the fossil fuel use category, not in the materials production category.

2.2.3. Land use change

Some of the materials expected to replace materials diverted for biofuel production require agricultural land to produce, and are therefore expected to be associated with indirect land use change emissions (Malins, Searle, & Baral, 2014). In these cases, land use change emissions are allocated to the replacement materials based on the outcomes of equilibrium modelling studies undertaken for the European Commission. Recognising that there is uncertainty in the estimation of indirect land use change emissions, we have included results based on two different sets of outcomes. Firstly, we include land use change emissions estimates based on the mean values given in the 'ILUC Directive'[6] for different categories of food-commodity (cereals, sugars, vegetable oils). The values are modified as necessary to reflect the ILUC associated with the underlying commodity rather than a biofuel produced from that commodity. The conversion is based on information from Biggs, Oliver, Valin, Peters, & Spöttle (2016), which decomposes the indirect use change associated with the use of specific materials as biofuel feedstock. Secondly, we calculate values based on more recent analysis for the European Commission with the GLOBIOM model (Valin et al., 2015), again converting from fuel to feedstock ILUc values where appropriate.

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[6] Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.

2.2.4. Forest carbon stock change

Harvesting some of the materials expected to replace materials used for biofuel feedstock (notably forest residues or increased wood harvest for energy or materials) may impact forest carbon stocks (see e.g. Baral & Malins, 2014c). Where it is expected that this will happen, those emissions are accounted and grouped in this category (cf. section 3.5).

2.2.5. Fossil fuel use

Some of the materials considered as biofuel feedstock herein may already be combusted for recovery of heat and/or power. For each case, we assess what the likely substitute fuels are. Where it is expected that part or all of displaced energy production would be replaced by fossil fuels, the emissions associated with that increased fossil fuel demand are included in this category.

2.2.6. Renewable rebound

Within the European Union, reducing the recovery of heat and power from biomass resources (using those materials instead to produce renewable fuels for transport) would create a shortfall in renewable energy required to meet overall renewable energy production targets. The renewable rebound term represents an emission credit for that required increase in renewable energy generation elsewhere in the system. The calculation of the rebound is explained in Annex B.3.

2.3. The revised methodology

The methodology in this report for estimating the potential indirect emissions associated with biofuels from wastes, residues or by-products is strongly informed by, but different to, the Ecometrica methodology presented above. The methodological steps are as follows:

- Step 1: Material definition and biofuel yields
    - Define the material studied. Identify typical yield for the expected process(es) to produce biofuel from this material.

      Less focus is placed on the expected location of biofuel production than in the Ecometrica analysis, but all biofuel production facilities are assumed to be placed in the European Union.
- Step 2: Potential demand from RED II
    - Identify the potential level of demand for this material that might result from the Implementation of the proposed REDII.

      In the Ecometrica analysis, the estimated demand for feedstock is used to define a strict 'order of dispatch', assuming that material is displaced from existing uses one at a time. Here, we instead attempt to characterise likely fractions of material demand to be drawn from each existing use, but this is contextualised by the potential overall demand level.
- Step 3: Potential sources and existing uses

  - Identify possible sources of this material as biofuel feedstock, and if and how it is currently being utilised and/or disposed.
- Step 4: Potential substitutes for existing uses
  - Identify alternate materials or systems that could replace the feedstock material in any existing uses. The focus here shall be on materials that have elastic supply (i.e. more can be produced in response to demand), because if we assume displacement of materials with rigid supply this implies that these materials would in turn need to be replaced (ICF International, 2015).
- Step 5: Elasticity of demand
  - Estimate the potential reduction in demand for the services currently delivered using the feedstock material if supply is transferred to biofuel production.

    The Ecometrica study differed from this study in that it did not allow for any overall demand reduction in other sectors associated with increased demand for materials for biofuel feedstock.
- Step 6: Displacement assumptions
  - Document the existing uses or disposal systems that are expected to change in response to increased biofuel production, the fraction of the biofuel feedstock expected to be sourced from each existing use or disposal system, and the materials or systems expected to replace the material used for biofuel feedstock.
- Step 7: Greenhouse gas intensity of replacement systems.
  - Detail the expected greenhouse gas emissions implication of increased use of replacement materials or systems.
- Step 8: Greenhouse gas emissions per unit of material used as biofuel feedstock
  - Calculate a weighted combination of the emissions associated with increasing use of each replacement material or system, to identify the expected emissions per tonne of use of the feedstock material.
- Step 9: Greenhouse gas emissions per MJ of biofuel produced
  - Combine the results from step 8 from for emissions per unit of material with biofuel yield and co-product yield expectations to calculate greenhouse gas intensities per megajoule of biofuel produced.

2.4. Presentation of results

For each feedstock assessed, the basic displacement assumptions and analytical results are presented in two tables. Examples for the case of palm fatty acid distillate (PFAD) are shown in Table 2 and 3.

Table 2 shows the systems expected to be affected by an increased use of PFAD for biofuel, and the materials presumed to replace PFAD in those systems (the basis for these assumptions is explained below in the section on PFAD). In the left column, we see that there are three modelled market responses to increased PFAD use. These are reduced use in the feed market, reduced use in the oleochemicals market and reduced energy recovery. It is assumed that these uses are affected in the ratio 45:45:10. The percentages in the left column always add up to 100% - demand reduction is considered separately.[7] Each row then lists the potential substitute materials in that use. Again, the percentages in the rows always add up to 100%.

Table 2. Expected systems and replacement materials affected by increased PFAD demand

Displaced system	Substitute 1	Substitute 2	Substitute 3
Remove from feed market (45%)	Palm oil (80%)	Soy oil (20%)	
Remove from oleochemicals (45%)	Palm oil (80%)	Soy oil (10%)	Rapeseed oil (10%)
Reduce energy recovery (10%)	Fuel oil (RoW) (100%)		

Having established the assumptions regarding materials displacement, the indirect emissions in each emission category are tabulated in a table such as 0. In the first column, different potential biofuel pathways considered are listed. Where there is more than one pathway considered (in this case HVO and FAME), the results are distinguished by the assumed biofuel yield from each pathway, and whether any co-products are assumed[8]. In the case of HVO and FAME, similar yields are assumed. No co-product is assumed for HVO production, while 4% of the energetic output of FAME production is delivered as a glycerine co-product. The results are therefore similar but not identical.

In each row, emissions are split into the four emission categories. They are the summed into a 'total' indirect emission in the final column. For the case of PFAD, there is a significant materials production term, which derives largely from the carbon intensity of producing replacement vegetable oils. The land use emissions category shows two alternative numbers – the number based on ILUC factors given in the proposed RED II, and then in brackets a number based on GLOBIOM modelling (Valin et al., 2015). The GLOBIOM study found much larger indirect emissions for palm oil and soy than were included in the RED, and therefore the numbers in brackets are much higher than the other numbers. As seen in Table 2, fossil fuels play only a marginal role in replacing PFAD in the market, and therefore the emissions from fossil fuel use are relatively low. There is no 'renewable rebound' for the PFAD case because it is assumed that reduction of PFAD use as boiler fuel occurs in Southeast Asia, not the EU, and is therefore beyond the scope of the RED. When added together, the total indirect emissions come to about 90 gCO_2e/MJ when using the RED ILUC numbers, and about 220 gCO_2e/MJ when using the GLOBIOM results. In either case, we see that considering indirect emissions seriously undermines the environmental case for producing PFAD derived biofuels.

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[7] I.e. if there is 10% demand reduction, then the amount of PFAD removed from the animal feed sector would be 45% × (100% - 10%) = 40.5% of the amount of PFAD used as biofuel feedstock.

[8] Indirect emissions are allocated between co-products by lower heating value, in line with the allocation methodology of the RED.

Table 3. Example: summary of indirect emissions for PFAD-derived fuels (gCO2e/MJ)

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from PFAD	0.94	38	45 (171)	0	8	0	90 (217)
HVO from PFAD	0.97	39	46 (175)	0	8	0	92 (221)

Further methodological detail about the indirect emissions assessment framework is provided above, and for each feedstock additional details about the results are presented in Annex A.

2.5. Substitute biomass fuels and additional wood harvest

For some feedstocks that are displaced out of current energetic uses into transport fuel uses, biomass could form part of the replacement fuel mix. Biomass is traditionally one of the main sources of energy (Miner, 2010) in the forest industries, and in this report we assume that biomass will generally be a constituent of the replacement energy mix when forest industry by-products are displaced from existing energetic uses. The greenhouse gas emissions consequences of this change in biomass use for energy will, however, be heavily dependent on assumptions about what type of biomass might be available to meet the increased demand, and more generally to assumptions about the impact of increased biomass demand on forest carbon stocks (see e.g. Berndes et al., 2016; McKechnie, Colombo, Chen, Mabee, & MacLean, 2011).

One possible substitute fuel in the forest industries would be forest residues. Forest residues currently represent an elastically available resource, in that while total physical availability is limited the supply is determined by the amount of material that is collected and therefore enters the supply chain. The availability of forest residues in the EU is not unlimited, and therefore it is important to ask whether the scale of the available resource is consistent with playing a significant role in replacing sawdust and cutter shavings as an energy source. The 'Wasted' project of the European Climate Foundation and ICCT estimated that there are currently around 9 million tonnes of sustainably available forestry residues in the European Union (Searle & Malins, 2015). However, this resource will be potentially in demand as biofuel feedstock itself, and for other renewable heat and power applications. Further, not all of this resource will be economically collectable.

Deploying twenty commercial scale (150,000 tonne of biofuel output per year) facilities to convert woody material to biofuel would create additional demand for around 15 million tonnes of woody material (depending on type of material, conversion technologies, biofuel yields, etc.). It may well therefore not be possible to entirely replace biomass displaced into a successfully growing advanced biofuel industry with forest residues alone. In this report, there are three feedstock materials that we assume would be partly replaced by biomass when removed from energy recovery uses (crude tall oil, black liquor, and sawdust and cutter shavings). In these cases, we have assumed that where there would be demand for additional biomass energy due to material displacement, it would be met 50% by forestry residues and 50% by additional wood harvest. For a small expansion of biofuel production from woody materials, it would be possible in principle for 100% of displaced energy to come from forest residues (though not guaranteed – there are structural reasons that much residual material is still not utilised). For a larger biofuel industry, or if the economics of residue collection are simply not competitive with other biomass sources, much more of the energy might come from additional wood harvest. As with other elements in our analysis, changing input assumptions would affect the results.

The greenhouse gas intensity of increasing forest residue removals is the subject of some controversy, but it is generally agreed that with basic sustainability safeguards in place, forest residues can be considered a low carbon energy source (Baral & Malins, 2014a). In contrast, the question of how to quantify the net greenhouse gas impact of increasing wood harvest for bioenergy supply is one of the more intractable ones that is raised by the analysis in this report, and a full review or synthesis of the literature on the subject is well beyond the scope of the exercise at hand. Depending on the source taken and system considered, literature can be found to support a claim that increasing wood harvests for bioenergy will deliver large carbon savings relatively quickly (e.g. Daigneault, Sohngen, & Sedjo, 2012), or a claim that increasing wood harvests will increase climate forcing for decades to come (e.g. Holtsmark, 2012).

Clearly, for a study of indirect emissions the assessment of whether a given substitute material has a lower or higher associated greenhouse gas intensity than fossil alternatives is a crucial one. However, given the wide range of conclusions and profound lack of consensus in the literature, we find it impossible to offer only a single value for the carbon intensity of additional fuelwood harvest. For the feedstocks where forest carbon debt is potentially be a significant emissions term, we therefore present three scenarios. In the central case, we take the average carbon debt value for pulpwood, 726 $kgCO_2e$/tonne, used by the ICCT's recent indirect emissions assessment (Searle et al., 2017). For the first sensitivity case, we consider a best case scenario where we ascribe no emissions for biogenic carbon debt. This represents a system in which active management of forest carbon stocks and of harvest sustainability, along with expansion of forest area, allows additional removals for bioenergy to be entirely offset by additional growth. For the second sensitivity case, we take a more pessimistic view, using the carbon debt value for pulpwood of 2,270 $kgCO_2e$/tonne for increased boreal wood harvest from Holtsmark (2012). It is our intention that presenting this range will allow the reader to draw their own conclusions, depending on their own understanding of this issue. It should be noted that because the indirect emissions modelling framework in this study is not fully integrated, changing assumptions regarding carbon stock change from additional wood harvest does not affect potentially related parameters that are taken from other studies, notably the renewable rebound assumptions and the forest residue harvest carbon stock change assumptions. These linkages could be more fully assessed in future work.

3. Feedstock assessments

In the following sections, we discuss the potential impacts of utilising each feedstock considered. At the end of each section, we present the estimated indirect emissions for that feedstock. Additional documentation of the lifecycle assumptions for each feedstock is available in the annex, including detail of the assumptions at each methodological step (as described above).

3.1. Palm fatty acid distillates

Palm fatty acid distillates (PFADs) are a by-product of the palm oil production process, specifically of palm oil refining. They represent about 4% of the content of crude palm oil by mass (Gapor Md Top, 2010). They therefore represent a relatively minor by-product of palm oil production, and, because fatty acids have lower value than refined palm oil, production of PFADs is minimized to the extent possible. The fatty acid fraction in palm oil tends to increase as fruit bunches are damaged in handling, and as they get older. Given the size of the palm industry, overall PFAD production is still considerable. Table 4 shows the increasing production of PFADs from 1980 to 2008 by the Malaysian palm oil industry.

Table 4. Production of PFADs in Malaysia (tonnes per year), Gapor (2010)

Year	Crude palm oil production (tonnes per year)	PFAD production (tonnes per year)
1980	2,573,173	102,927
1990	6,094,622	243,785
2000	10,842,095	433,684
2005	14,961,654	598,466
2006	15,880,786	635,231
2007	15,823,745	632,950
2008	17,734,441	709,378

Table 5. Value of PFAD exports from Malaysia, Gapor (2010)

Year	PFAD		HPFAD*	
	Volume (tonnes)	Value (USD million)	Volume (tonnes)	Value (USD million)
2001	426,538	81.6	1,837	0.6
2005	574,629	198	224	0.3
2006	591,893	219.3	932	0.6
2007	514,835	265.1	2,325	1.7
2008	652,419	375.2	1,967	1.4

**Hydrogenated palm fatty acid distillate*

As shown in Table 5, PFAD export is a significant industry, with about 92% of Malaysian PFAD being exported in 2008 with an average value of 575 $/tonne (a small fraction was hydrogenated and exported at a higher value of 711 $/tonne).

Global palm oil production for 2016/17 is estimated at 63 million tonnes[9]. Given a PFAD yield during refining of about 4%, that suggests total global PFAD availability of about 2.5 million tonnes, concentrated in Indonesia and Malaysia, as shown in Figure 2.

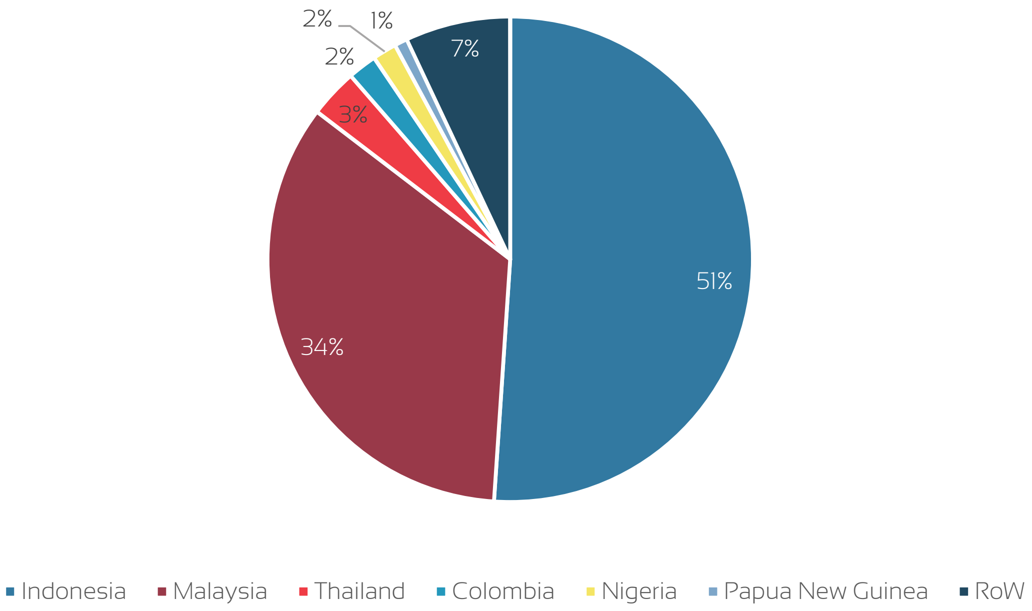

Figure 2. Estimated 2014 PFAD production locations (UN Food and Agriculture Organisation, 2017)

3.1.1. *Use as a biofuel feedstock*

PFAD can be processed to fatty acid methyl ester biodiesel, but this is more technically challenging than the conventional FAME production process due to the need for an additional preliminary esterification step. PFAD is therefore of particular interest as a feedstock for hydrotreating and HVO production.

3.1.2. *Existing uses*

PFAD is entirely utilized in the current market. Ecofys, reporting to the UK Government (Koop, 2011) identify three main uses for PFADs – oleochemicals, soap industry and livestock feed. It can also be used as fuel for industrial boilers. PFAD vendors note that, "It is used to produce food emulsifiers, foam stabilizers, water repellent, and to extract vitamin E. It is used to produce calcium soap for animal feed as a source of calcium and fat. It is also used to produce fatty alcohol and fatty acid esters used

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[9] http://www.globalpalmoilproduction.com/

in cosmetic industries. Moreover, fatty acid distillates are generally used to manufacture laundry and toilet grade soap noodles depending on oils blend and ratios in the soap industry"[10] This variety of uses is the reason that PFAD achieves an export price comparable to that for palm oil (see section 4.1.5). Additional markets for PFAD utilization including vitamin E production are currently emerging, and industry analysts expect robust demand in the near term (Gapor Md Top, 2010; ICF International, 2015).

One animal feed application is as a rumen-protected fat, a feed additive for cattle. Rumen protected unsaturated fats are particularly suitable feed additives for ruminant animals, as their higher melting point allows them to pass through the rumen in a solid state and be digested in the small intestine, complementing starchy energy feeds.[11,12] The use of 'bypass fats' can enhance ruminant animal growth and milk yield, and passing fat through the rumen prevents toxicity of unsaturated fats to rumen microbes and consequent impact on fibre digestion (Naik, 2013; Theurer, Block, Sanchez, & McGuire, 2009). PFADs are combined with calcium to produce calcium soaps, which are marketed as rumen protected fat products. Rumen protected fats can be produced by calcium addition to fatty acids, or by hydrogenation or fractionation of vegetable oils (Solorzano & Kertz, 2005; Voigt, Kuhla, Gaafar, Derno, & Hagemeister, 2006).

There is also some use reported of PFAD as boiler fuel (Cheah, Toh, & Koh, 2010; Nuansa Kimia Sejati, 2011). It seems likely that boiler fuel use has reduced as new applications in biofuel production and oleochemicals have been developed, but we have not been able to identify data on overall PFAD disposition to confirm this hypothesis, or the current split in utilization between feed, oleochemicals and energy recovery.

3.1.3. Alternatives

In the oleochemicals and soap industries, reduced supply of PFADs would result in increased demand for alternative vegetable or animal oils. In the soap industry, tallow and coconut oil have traditionally had a significant role as fatty raw materials. However, in recent decades global production of tallow and coconut oil has been relatively static, whereas production of palm oil and associated oils has risen dramatically, with the result that palm oil (for traditional tallow applications), palm kernel oil (for traditional coconut oil applications) and PFADs (for toilet soaps in particular) have taken a growing role (Thiagarajan, 2004). PFADs can also be used for extraction of tocotreniols, for which palm oil is again an alternative (Lau Lik Nang & Yuen May, 2015; Thiagarajan, 2004). Free fatty acids as by-product streams are not available from other oil production processes in comparable volumes to those produced by palm oil refining. Free fatty acid content in crude soy oil, for instance, should rarely rise above 1% unless the oil is stored for protracted periods in high temperatures and/or with high moisture content (de Alencar, Faroni, Peternelli, Silva, & Moreira, 1998), and should typically be around 0.33%, compared to 4% for palm oil (Hammond, Johnson, Su, Wang, & White, 2005). It is therefore not considered likely that a large volume of PFAD demand could be shifted to demand for any other comparable fatty acid by-product, and hence reasonable to assume that demand would shift to primary oils. In any event, the supply of other by-product oils and fats is inelastic, and therefore increased demand for such materials would be expected to result in increased demand for primary materials further down the supply chain (ICF International, 2015). Given that palm oil is cheaper than other vegetable oils (Malins, 2013), and is generally available from the same market sources as PFAD, reduced availability of PFADs for soap and

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[10] http://www.chemtradeasia.com/index.php?r=TblProduct/view&id=911

[11] http://www.tridentfeeds.co.uk/news-events/news/understanding-rumen-protected-fats/

[12] http://www.progressivedairy.com/topics/feed-nutrition/the-case-for-rumen-protected-fats

oleochemicals is considered most likely to increase demand for crude or RBD palm oil, although other vegetable oils could also be potential substitutes.

In animal feed, the likely substitutes would depend on whether livestock farmers continue to seek rumen protected feed products, or whether they would consider shifting to traditional energy feeds, a decision that would eventually be dictated by relative prices. As an alternative to PFAD, rumen protected calcium salts could be produced by hydrolysis of soy or palm oils and reaction with calcium (Solorzano & Kertz, 2005). Saturated fats are less toxic to the rumen than unsaturated fats (Naik, 2013), and longer chain saturated fatty acids are less digestible than shorter chains, such that a higher content of palmitic acids compares to stearic acids is a favourable property for rumen protected fats (Solorzano & Kertz, 2005). Palm has a much higher saturated palmitic content than other vegetable oils (43% as against 10% for soy and 4% for canola, Zambiazi, Przybylski, Zambiazi, & Mendonça, 1974), and thus in the event of a reduced supply of PFAD hydrolysed palm oil may be considered as an alternative basis for calcium soap manufacture. ICF suggest that soybean oil products may also be an alternative to PFADs (ICF International, 2015), but the choice of palm oil vs. soy oil based products may be based on C16 (palmitic acid) content (Eastridge, 2002).

As detailed below, PFADs trade at a lower price than standard vegetable oils, and so in the event of reduced PFAD supply it is possible that the market for rumen protected fats would be reduced in favour of alternative feeding strategies. A recent article in 'Farm Business'[13] discussed that a tight global palm oil market has led to 40% price rises on rumen protected fats in 2016/17, and promoted alternative strategies to increase rate of energy intake for cattle (although it should be noted that the expert quoted in the article works for a vendor of the alternative strategies in question). It is at least possible though that reduced availability of rumen protected fats from PFADs could result in increased use of starchy energy feeds (in Europe likely to be wheat, maize and/or barley), potentially associated with increased consumption of alternative additives.

In the case of energy recovery as boiler fuel, we would assume that palm mill operators would shift to the lowest cost comparable fuel available, likely to be heavy fuel oil, which should be able to be burned in any facility currently burning PFAD. There may also be potential in the longer term for any facility moving away from PFAD combustion to shift to fundamentally different materials, such as solid palm residues or natural gas. As palm mills are not located within the European Union (the majority are in Malaysia and Indonesia) energy use at palm mills would not be covered by the Renewable Energy Directive.

3.1.4. Prices

PFAD generally trades at about 80% of the value of palm oil, and is thus in a similar relative market position compared to palm as palm is relative to soy. Figure 3 compares reported market prices for soy oil, palm oil, palm kernel oil and PFAD from January to September 2013, and also shows the ratios of PFAD to palm oil price, and palm oil to soy oil price. It can be seen that even as a by-product, PFAD is a high value material (in terms of price per tonne compared, for instance, to feed grains). Ecofys (Koop, 2011) report PFAD price of 340 GBP per tonne compared to 430 GBP per tonne for palm oil. For January to March 2016, FOB prices listed by www.commodity3.com[14] ranged from about 680 to 715 USD per tonne, as compared to RBD palm oil FOB prices from about 700 to 775 USD per tonne. ICF

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[13] http://www.farmbusiness.co.uk/livestock/dairy/reduce-reliance-on-rumen-protected-fats-to-cut-price-rise-impact.html

[14] http://www.commodity3.com/instrument/PFAOMYQ1/pfad-palm-fatty-acid-distillate

(ICF International, 2015) report that in 2015 PFAD prices were about 506 USD per tonne, 86% of palm oil prices.

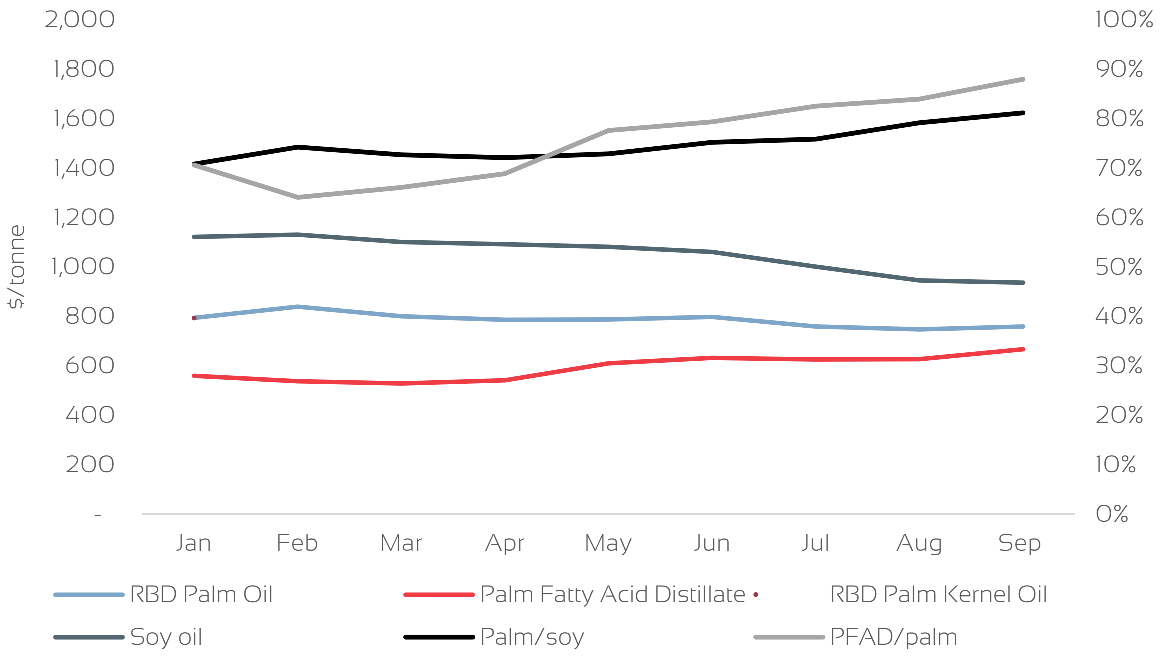

Figure 3. Prices through 2013 of palm oil, palm kernel oil, PFAD and soy oil (left axis) and price ratios of palm to soy and PFAD to palm (right axis)

3.1.5. Displacement expectations

We have been unable to identify data on global disposition of PFAD between the possible uses, and we have not been able to find any clear reason to believe that any one of the oleochemical, soap or rumen protected fat markets for PFAD are likely to be most responsive. There is likely a degree of regional difference between these markets. The oleochemicals and soap market for PFADs is concentrated in Southeast Asia[15], but rumen protected fat production may be more diffusely located, although we do not have explicit data to confirm this. Overall, we make the assumption that equal amounts of PFAD would be displaced from oleochemicals and soaps production on the one hand, and feed production on the other. We believe that use of PFAD as boiler fuel is likely limited at the present time, as most palm mills have more than adequate supplies of lower value solid residues to enable heat and power self-sufficiency (Abdullah & Sulaiman, 2013; BioGrace, 2017). It is therefore presumed that where the practice of PFAD combustion continues it is likely to reflect structural barriers to exporting PFAD into the global supply chain. We therefore assume that displacement from energy recovery is significantly less likely than displacement from oleochemical, soap and feed markets.

Based on similarity of chemical properties, palm oil seems the most likely primary oil to be used as an alternative in both the animal feed and the oleochemicals and soaps markets. We also allow for

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[15] See e.g. http://www.chemistryindustry.biz/oleochemicals.html

a marginal role of other major primary oils (soy and rapeseed) as potential substitutes in oleochemicals and soaps. We have found no reference to rumen protected fat production from rapeseed[16], and therefore in the feed market allow only for a marginal use of soy oil as well as palm oil. In energy recovery, we assume that the substitute is entirely fuel oil. Our final displacement assumptions are shown in Table 6.

Table 6. Expected systems and replacement materials affected by increased PFAD demand

Displaced system	Substitute 1	Substitute 2	Substitute 3
Remove from feed market (45%)	Palm oil (80%)	Soy oil (20%)	
Remove from oleochemicals (45%)	Palm oil (80%)	Soy oil (10%)	Rapeseed oil (10%)
Reduce energy recovery (10%)	Fuel oil (RoW) (100%)		

3.1.6. *Carbon intensity of displacement*

Table 7. Summary of indirect emissions for PFAD-derived fuels (gCO2e/MJ)

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from PFAD	0.94	38	45 (171)	0	8	0	90 (217)
HVO from PFAD	0.97	39	46 (175)	0	8	0	92 (221)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

We find that PFAD derived biofuels have significant indirect emissions implications through requirement for additional material production (mainly additional palm oil) and from land use change associated with that additional palm oil production (Table 7). Based on ILUC factors included in the proposed RED II, PFAD based biofuels are likely to have a higher net climate impact than the fossil diesel they would replace. Taking ILUC numbers from GLOBIOM (Valin et al., 2015), the indirect emissions implications of using PFAD or biofuel could be very large indeed (over 200 gCO_2e/MJ).

3.2. Corn oil pressed from distillers grains (“distillers’ corn oil”)

Distillers’ grains and solubles (DGS) is a residual material resulting from fermentation of grains, such as maize and wheat, for production of ethanol. When the starches are fermented, proteins, oils and fibres from the grain are left over, along with some residual carbohydrate content. DGS is therefore higher in

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[16] Although we did find a study comparing milk production impact of direct addition of rapeseed and palm oil to ruminant diets (Lindman, 2014).

both fat and protein than the input grain, and DGS is sold as a high protein animal feed. It is used as an alternative to other protein meals and, for the case of ruminants, can be an alternative to addition of urea to diets to support protein synthesis (Hazzledine et al., 2011; Klasing, 2012). The use of DGS for animal feed has a long history in relation to both the potable alcohol and fuel-alcohol businesses, and more recently the practice of extracting fatty content from DGS has been widely adopted, in the U.S. maize ethanol industry in particular (Z. Wang, Dunn, Han, & Wang, 2015). Much of this extracted corn oil, often referred to as 'technical' or 'industrial' corn oil to distinguish it from edible corn oil pressed from maize germ, is used for biodiesel production. About 70% of US corn ethanol production is now accompanied by corn oil extraction from distillers' grains (Flugge et al., 2017), and it is also practiced by some European ethanol refineries[17]. We are not aware of any publicly available data on the rate of adoption of corn oil extraction at European corn and wheat ethanol facilities.

3.2.1. Use as a biofuel feedstock

Distillers' corn oil (DCO) can be transesterified to fatty acid methyl ester biodiesel like other vegetable oils. This practice is already widespread in the U.S., where it is the largest use of the material. It can also be hydrotreated to produce HVO.

3.2.2. Existing uses

Prior to the development of extraction technology to remove corn oil from DGS, the oil would have remained in the grains and been supplied to the animal feed market as a constituent of DGS. Extracting oil from DGS reduces the net weight of DGS leaving the facility, and alters the nutritional profile of the DGS (reduced fat content). The change in the nutritional profile of the distillers' grains affects their value and role in the livestock feed complex.[18]

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[17] See e.g. http://www.pannoniaethanol.com/en/products#corn-oil

[18] See e.g. http://www.world-grain.com/news/news%20home/features/2012/9/corn%20oil%20extraction%20conundrum.aspx?cck=1

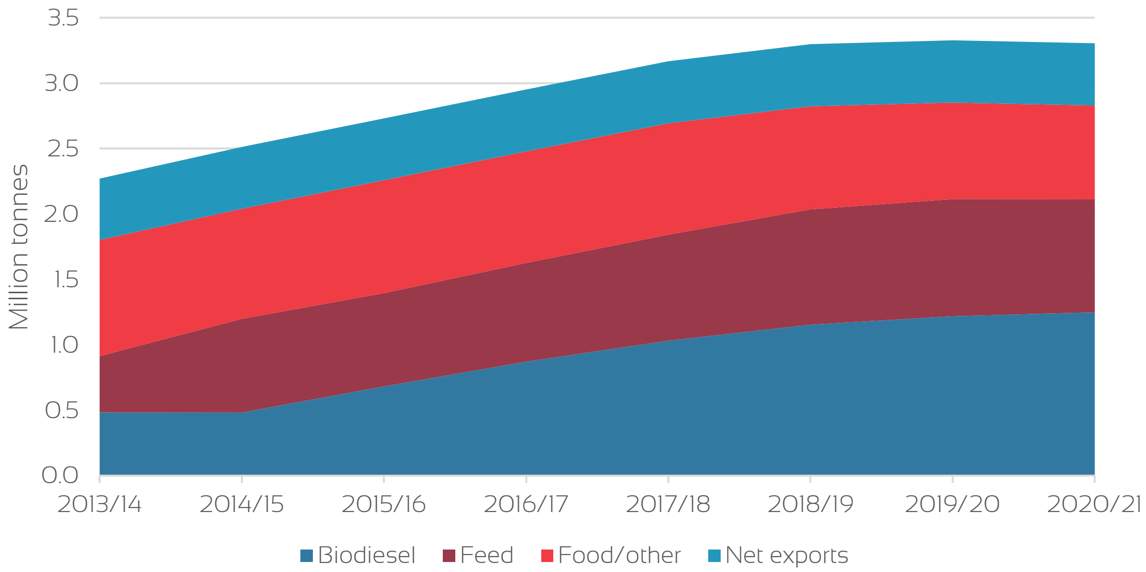

Figure 4. Current and projected disposition of U.S. corn oil (Integrated Policy Group, 2014)

Figure 4 shows historical and projected rates of US corn oil production and disposition as estimated by the Food and Agricultural Policy Research Institute (FAPRI). These statistics include both edible corn oil (extracted before fermentation) and inedible corn oil extracted from DGS. The main uses for the inedible DCO are biodiesel production and livestock feed (California Air Resources Board, 2014). FAPRI anticipates a slow shift of corn oil resources towards biodiesel uses over time, but forecasts for all three use categories (and exports) are essentially quite stable. This suggests that increased demand for distillers' corn oil for biodiesel in Europe could in principle result in displacement from any of these existing markets.

In Europe, we are not aware of DCO being used as biodiesel feedstock. Neste Oil have reported the use of US sourced DCO[19], but the resulting product may be being supplied in the US as an advanced biofuel under the Renewable Fuel Standard. This is likely contextualised by the fact that distillers' corn oil is not currently listed as eligible for double counting incentives under the RED. One relatively major extractor of corn oil in Europe, Pannonia Ethanol, advertises animal feed as its primary market[20]. UK biofuel feedstock statistics show no reporting of corn oil biodiesel for 2015/16 (UK Department for Transport, 2017).

In the feed market, corn oil is generally used as an energy additive. Unlike calcium soaps from PFAD, corn oil is not a rumen protected feed, and therefore has a primary role in non-ruminant rather than ruminant diets. In the U.S., about 68% of vegetable oils and animal fats in livestock feed are fed to poultry, 23% to swine and 9% to cattle (Riley, 2016). Additional refining of crude DCO can be undertaken to reduce fatty acid content (under the trade name 'Corn Oil ONE') to make DCO a better substitute for soy oil (Jordan et al., 2014).

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[19] http://132.155.58.87/default.asp?path=1,41,11991,22708,22722,22729

[20] http://www.pannoniaethanol.com/en/products#corn-oil

In Europe, Pannonia Ethanol advertises its corn oil as a swine and poultry feed.

3.2.3. *Alternatives*

In the US biodiesel market, the most likely alternative feedstock would be soy oil, which is the primary biodiesel feedstock in the US (by volume used). Other possibilities would be canola oil and other by-product biodiesel feedstocks (such as animal fats and UCO). Within the RFS advanced biofuel mandate, sugarcane ethanol may also be an alternative, but the ethanol blend wall effectively provides a premium to the supply of non-ethanol fuels (Searle, Sanchez, Malins, & German, 2014), making this less likely.

In animal feed, fatty feedstuffs have specific dietary roles. As shown below in Figure 6, vegetable and animal oils and fats have systematically higher value per unit of metabolisable energy than cereal feed. It is therefore not economic to feed vegetable oils to livestock simply for the sake of the energy content. "Fats and oils have been added to rations to reduce the health stress of eating dusty and/or very finely processed feeds, to reduce the incidence of bloat, or to increase the energy density in the ration".[21] Fatty materials are generally added to animal rations for specific animal types and at specific growth stages when additional energy intake is desired (Amaral-Phillips, Hemken, & Jackson, 1997). It is therefore expected that a reduction in availability of one fatty feed materials for animal rations would result in increased use of other similar fatty materials, rather than of alternative energy feed (such as cereals).

In swine and cattle feed, alternative fatty supplements include animal fats and soy oil (Feed Energy Company, 2017; Troy Shoen, 2014). For nursery pigs, Jordan et al. (2014) show that Corn Oil ONE is a good substitute for soy oil. Corn oil has a very similar fatty acid profile to soy oil, as shown in Table 8. Indeed, Corn Oil ONE is explicitly marketed (in the U.S. context) as a soy oil alternative.[22] The Feed Energy Company (Norwood, 2012) note that "the chemical makeup of supplemental fats and oils has an important effect on their digestibility". They note that high linoleic acid content, as is found in corn oil, soy oil (Table 8) and sunflower oil, is beneficial in swine diets.

Table 8. Typical fatty acid profiles of corn, soy and sunflower oil, with canola for comparison (ADM, 2016; Chempro, 2017)

Constituent profile	Corn oil	Soy oil	Canola oil	Sunflower oil
Palmitic acid	12.5	11.5	4.1	4.5
Stearic acid	2.5	4.0	1.9	2
Oleic acid	29.0	24.5	63.8	24.5
Linoleic acid	55.0	53.0	8.0	59.5
Iodine value	125	125	109	133

Another option in response to reduced availability of corn oil for feed would be to reduce fatty content in diets, to be replaced by alternate energy feeds such as cereals. However, given the specific role of

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[21] http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/beef11670

[22] See for instance http://www.cornoilone.com/.

fatty supplements in livestock diets, this is considered a less likely response than a switch to alternate fatty feeds.

3.2.4. Prices

Figure 5 shows US price data for corn and other comparable oils as reported by the USDA Economic Research Service (USDA ERS, 2017). These data show corn oil with a historically higher reported price than soybean oil – however, it should be recognised that these data include both edible and inedible (DCO) grades. Edible corn oil has a generally higher price than soy oil, and thus the lower price of DCO is masked in the data. More recently as the production of inedible oil has grown compared to edible corn oil extraction, corn and soy oil prices have become very similar (suggesting that the inedible fraction of the corn oil aggregate has a price a little below that of soy oil). The distillers' corn oil market is not so well documented in Europe, and European price data are not readily available. It seems reasonable to assume that, as in the US, DCO prices in Europe will be well correlated and similar to other lower-cost vegetable oil prices. Similarly, Peiretti, Gai, Brugiapaglia, Mussa, & Meineri (2015) note that corn, soy and sunflower oils all have elevated polyunsaturated fatty acid levels.

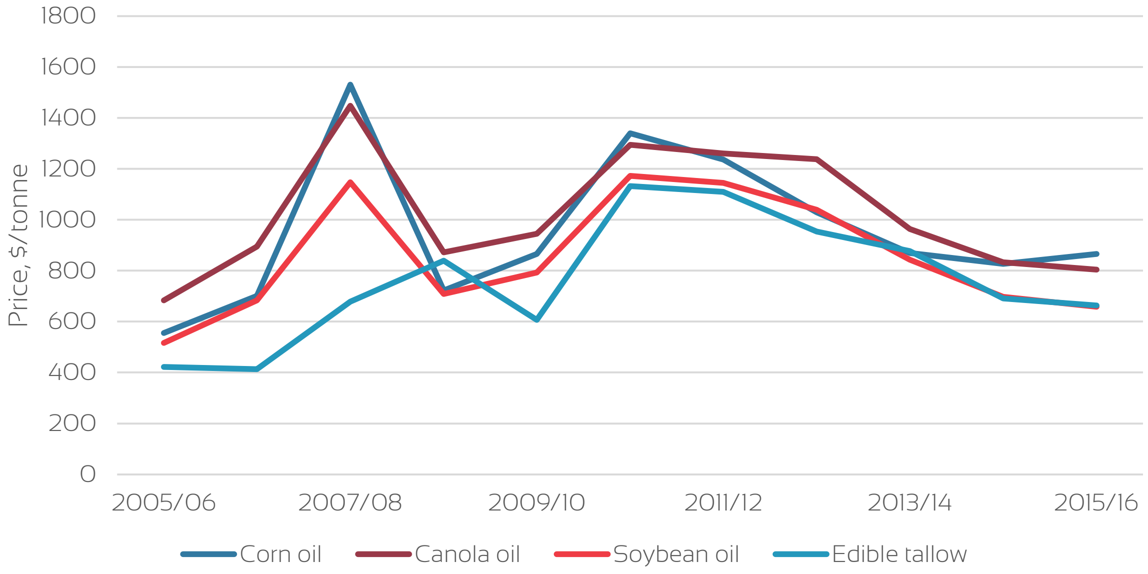

Figure 5. Prices for corn and other oils in the US

From the point of view of DCO as an animal feed ingredient, it is also useful to consider the prices of animal feed commodities in terms of metabolisable energy content. Figure 6 shows that in the period the U.S. prices of all oils considered were between 1.5 and 2.5 times higher than feed corn prices, per unit of metabolisable energy.

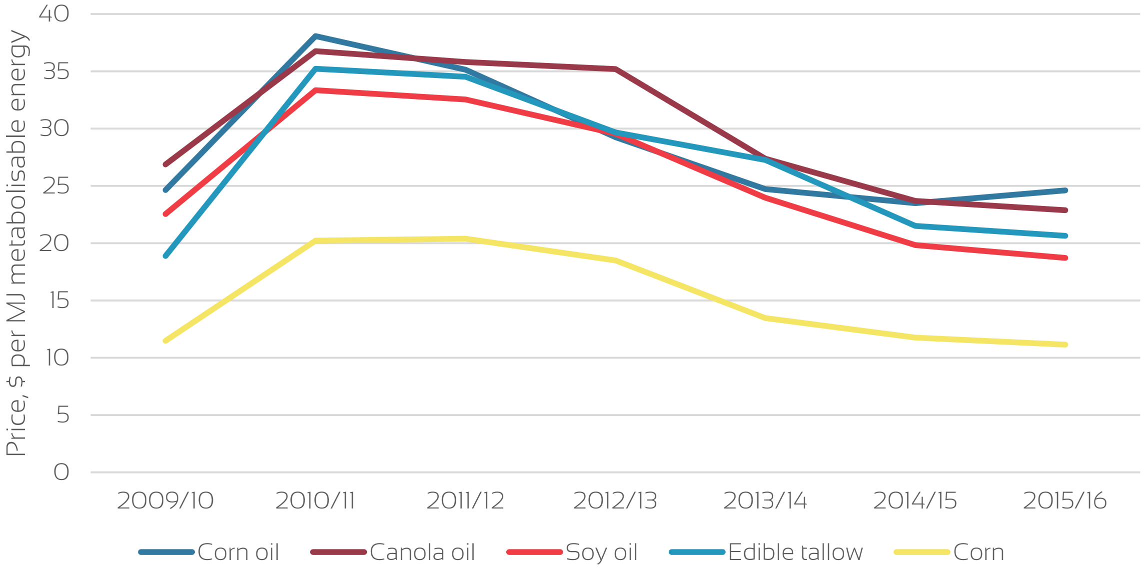

Figure 6. Prices of corn oil and other oils and of feed corn, per GJ of metabolisable energy

Metabolisable energies based on data for swine (Su et al., 2015)

3.2.5. Displacement expectations

Distillers' corn oil is currently almost entirely used for animal feed (either as extracted oil or as a constituent of DGS) and for biodiesel production. For this study, we consider displacement only from non-biofuel uses, and thus assume that all displacement occurs within the animal feed market. Vegetable oils including DCO play a particular role in animal feed rations, and therefore we anticipate that reduced supply of corn oil would be replaced primarily by other vegetable oils. Soy oil has similar properties to DCO, and we understand that it is a favoured alternative to corn oil in both the U.S. (Norwood, 2012) and EU[23]. We also allow for some degree of substitution of sunflower oil, which has similar properties, and of grain feed (wheat) (Table 9).

Table 9. Expected systems and replacement materials affected by increased DCO demand

Displaced system	Substitute 1	Substitute 2	Substitute 3
Remove from feed market (100%)	Soy oil (80%)	Sunflower oil (10%)	Feed wheat (10%)

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[23] Private communication with Premier Nutrition.

3.2.6. Carbon intensity of displacement

Table 10. Summary of indirect emissions for DCO-derived fuels (gCO2e/MJ)

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from distillers corn oil	0.99	30	43 (110)	0	0	0	74 (141)
HVO from distillers corn oil	0.97	32	47 (119)	0	0	0	79 (151)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

The indirect emissions profile for distillers' corn oil use is similar to that for PFADs. Both feedstocks are likely to be displaced out of animal feed markets, and both are likely to be replaced in the market primarily by virgin vegetable oils. The modelled increases in material production and land use change emissions are not as large as for PFAD, but still significant. The implication is that the utilisation of DCO for biofuel feedstock is likely to have a marginally better net climate impact than use of virgin soy or palm oil, but that overall there is likely to be little climate benefit resulting from moving DCO out of feed markets and into biofuel production.

3.3. Crude tall oil

Tall oil, or 'pine oil', is a chemical by-product of the Kraft wood pulping process. Typically, 20-50 kg of tall oil can be generated for every tonne of pulp. Crude tall oil (CTO) is separated from black liquor which is produced as a residue of the kraft chemical pulping process.

The kraft process, originally developed in the late nineteenth century, is the most widely used chemical wood pulping process in the world. In the process, chemical action is used to dissolve the lignin component of wood to leave behind cellulose fibres that can be used in paper manufacture. In kraft pulping, wood chips are digested by addition of 'white liquor', a solution of sodium sulphide and sodium hydroxide, at high temperature and pressure (U.S. EPA Office of Air Quality Planning and Standards, 1995).

The main products of the kraft pulping process are wood pulp and a weak 'black liquor', consisting of lignin residues, hemicellulose and organic chemicals in solution. This black liquor is normally further processed to reduce its water content and to separate out soaps (crude sulphite soap, CSS) which are further processed into tall oil by acidulation. This tall oil may, in turn, be further separated into products including tall oil fatty acids (TOFA), distilled tall oil (DTO), tall oil rosins and tall oil pitch.

Global production of tall oil is limited by global wood pulp production, and is estimated at between 1.6 and 2 million tonnes per year (Peters & Stojcheva, 2017; Peters & van Steen, 2013). Ecofys (Peters & Stojcheva, 2017) estimate that there are up to 850,000 tonnes of additional potential CTO production capacity that could be achieved by increasing acidulation of CSS in regions where it is not yet standard practice. This CSS is currently likely combusted for energy in the recovery boiler at pulp mills with no acidulation plants. This additional potential resource is located almost entirely outside Europe. At least some of this potential is presumably in locations in which there may be existing structural barriers to adoption of acidulation, given that CSS combustion for energy is a relatively inefficient and low value use.

It is reported that around 650,000 tonnes of crude tall oil are produced in the European Union (Peters & van Steen, 2013; Rajendran et al., 2016), although the figure could be as high as 900,000 tonnes, as shown in Figure 7 (Ukkonen & Oy, 2016). EU demand for tall oil is greater than local production, as evidenced by a growing rate of CTO imports from the USA from 2008 to 2013, approximately 100,000 tonnes in 2013 (Peters & van Steen, 2013).

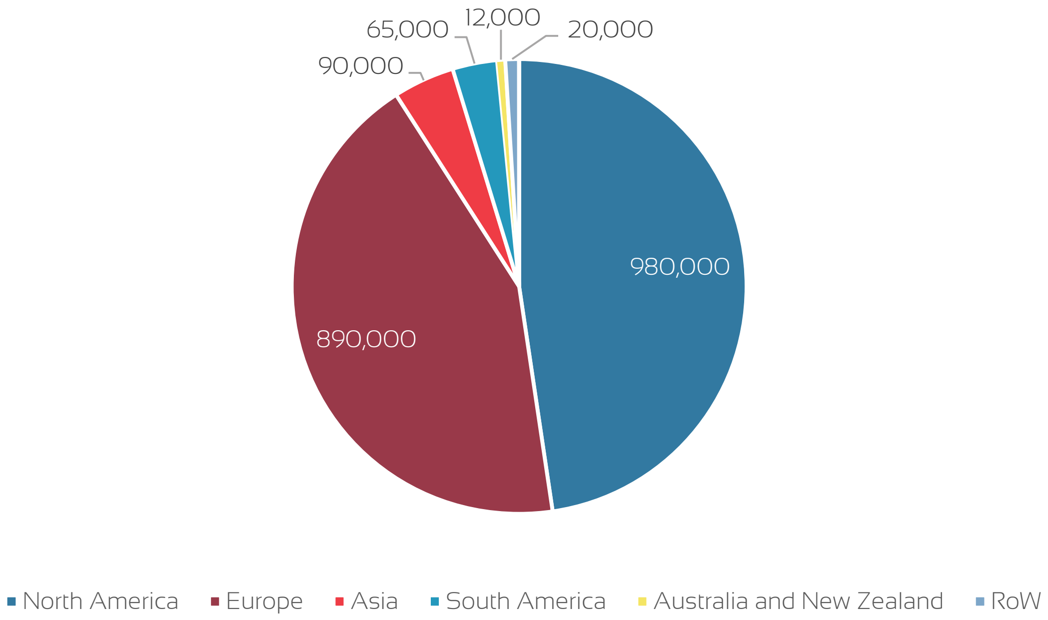

Figure 7. Estimated 2015 tall oil production by region in tonnes, Pine Chemicals Association data (Ukkonen & Oy, 2016)

It is understood that essentially all CTO is put to productive use[24], but, unlike some of the materials considered in this report, the supply of CTO potentially has a degree of elasticity, due to the availability of additional CSS resources that are not currently being acidulated. Additional CTO could be brought to market by acidulating some of this material, either utilising existing excess capacity (Peters & Stojcheva, 2017) or through investment in additional acidulation capacity in the regions in which the CSS is available.

3.3.1. Use as a biofuel feedstock

There are two types of processes for the production of liquid fuels from crude tall oil. The first requires the initial depitching of the crude tall oil, thus removing some of the lower value components before the

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[24] Including energy recovery.

conversion to fuels (e.g. Monnier et al., 1998). The second uses the whole crude tall oil stream without removal of the pitch fraction, although still requiring a washing step to purify the crude tall oil input feed and remove sulphate salts (Knuuttila, Kukkonen, & Hotanen, 2012). The only known facility in Europe producing transport fuel from crude oil is operated by UPM in Lappeenranta, and it is understood that it upgrades the whole crude tall oil input stream, producing *'UPM BioVerno'* renewable diesel, and presumably also a smaller quantity of hydrocarbon co-products in the naphtha and gasoline ranges (Knuuttila et al., 2012). In both cases, hydrodeoxygenation is used to produce hydrocarbon output molecules by removal of oxygen and saturation of carbon-carbon bonds. In the *UPM BioVerno* process, the diesel-range output molecules are subjected to a further isomerisation step to produce EN 590 quality diesel blendstock.

3.3.2. Existing uses

As with many other by-products of the forestry industries, tall oil produced as a by-product of pulping is not disposed of unused, but has a range of existing industrial applications. CTO is currently generally used in one of four ways. The largest use in Europe is distillation to produce inputs for the 'pine chemicals' industry. It may also be combusted directly for energy recovery for the pulp mill lime kiln, or be used as an additive for drilling or mining fluids, and there is already a moderate use for biofuel production.

Tall oil distillation produces four output fractions: tall oil rosins (TOR); tall oil fatty acids (TOFA); distilled tall oil (DTO); and tall oil pitch (TOP). Typical fractional outputs of distillation are shown in Figure 8.

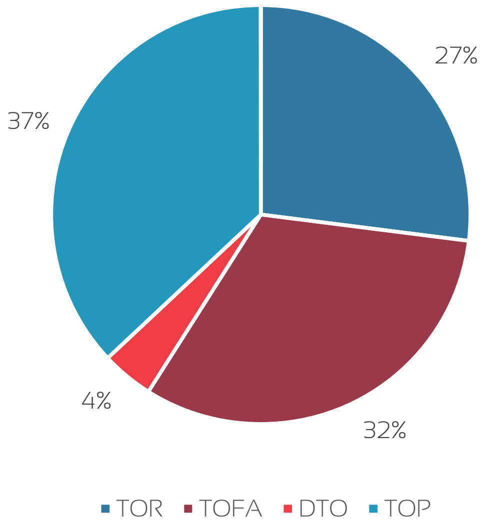

Figure 8. Outputs of crude tall oil distilling

Tall oil rosins are used in printing inks and adhesives, as well as other applications, with consumption in the EU of 325,000 tonnes per year. Tall oil fatty acids have applications including alkyd resin manufacture for plastics and paints, with annual consumption of 170,000 tonnes per year. Distilled tall oil is used in rubber emulsifiers and as a metal working fluid, and may also be subject to energy recovery

(Peters & Stojcheva, 2017). Tall oil pitch is a lower value material primarily used for energy recovery. The pine chemicals industry has predicted modest ongoing growth in CTO production, but that this growth will be accompanied by increasing demand (Baumassy, 2014).

Global CTO distilling capacity is estimated at 1.6 million tonnes per year, something like 20% below global tall oil production, and is believed to run at high capacity (Peters & van Steen, 2013). CTO that is not refined may be used for oil drilling fluid or other niche applications, or be combusted for energy recovery. It has been suggested that the drilling fluid market for CTO could potentially expand significantly (Peters & Stojcheva, 2017), but current oil prices have depressed rates of drilling of new wells for the time being. Estimates of fractional global CTO disposition from the 2013 and 2017 Ecofys reports are provided in Figure 9. Total CTO production was assumed to be about 2 million tonnes in the 2013 report, whereas the 2017 report revises this estimate down to 1.75 million tonnes. This change may not represent a real reduction over time so much as a reassessment based on additional data. The estimated fraction of material being refined is higher in the 2017 report, but the absolute volume is marginally lower (1.4 million tonnes, down from 1.5 million tonnes). Ecofys believe that, "This decrease results from lower oil prices which lowered the price of hydrocarbon rosins which put pressure on the demand for CTO-derived rosin."

The market for distilled tall oil products appears to be quite robust, with industry analysts forecasting increasing global demand for tall oil rosins and TOFA through to 2024 (Baumassy, 2014; Transparency Market Research, 2016), but the market may be stronger in the United States and developing world than in Europe (Baumassy, 2014). Lower oil prices may also have increased competition from hydrocarbon based alternatives (Peters & Stojcheva, 2017).

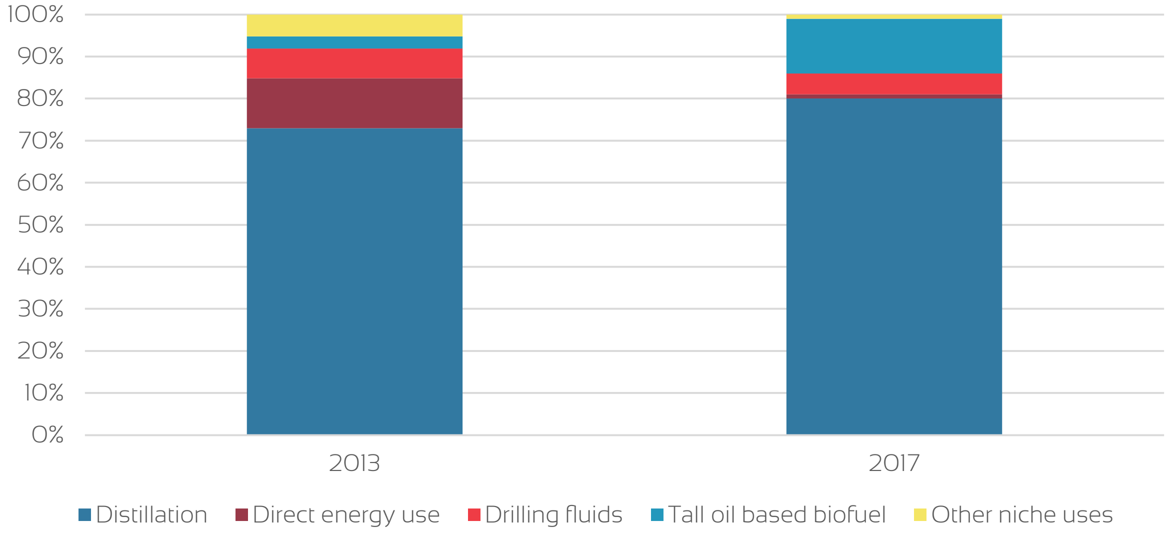

Figure 9. Relative share of existing uses of crude tall oil, as given by 2013 and 2017 Ecofys reports (Peters & Stojcheva, 2017; Peters & van Steen, 2013)

Peters & van Steen (2013) estimate that 220 thousand tonnes of CTO is likely combusted for energy globally every year. It should be noted that this is based on a remainder calculation rather than direct data availability. This quantity would therefore be rather sensitive to changes in assumptions about total CTO availability and CTO use by other sectors, and given lower estimates of total CTO production, the remainder term would disappear. Peters & Stojcheva (2017) assume a lower overall CTO production rate, and therefore estimate a lower quantity sent for energy recovery for heat and power (only 40,000 tonnes). As with the overall CTO production, this may be more to do with data revisions than with real changes over time. There is also an apparent reduction in material used for 'other' applications, in particular a reduction in reported use for mineral flotation in mining operations[25] Several references identify TOFA rather than CTO as the preferred flotation agent, and so this change may reflect a mis-categorisation of this as a use of crude rather than refined tall oil products in the earlier report rather than a real change.

Given a lack of information on the geographical distribution of boiler use of CTO, it is difficult to come to any conclusion about how much of this combustion goes on in Europe, but it seems likely that CTO use for combustion is lower as a fraction in the EU than elsewhere in the world, given the relatively high incidence of CTO distillation facilities near European kraft pulping installations.

3.3.3. Prices

Ecofys (Peters & van Steen, 2013) note that CTO from the kraft process can have a range of characteristics, and that CTO distillers favour material with a higher 'acid number' and higher content of rosin acids. Their reported prices for 'good quality' CTO from 2008 to 2013 are shown in Figure 10. The same report suggests that the price for better quality CTO could be up to 40% higher than the price for lower quality material (for instance they quote €550 per tonne for high quality material as against €400 per tonne for lower quality material).

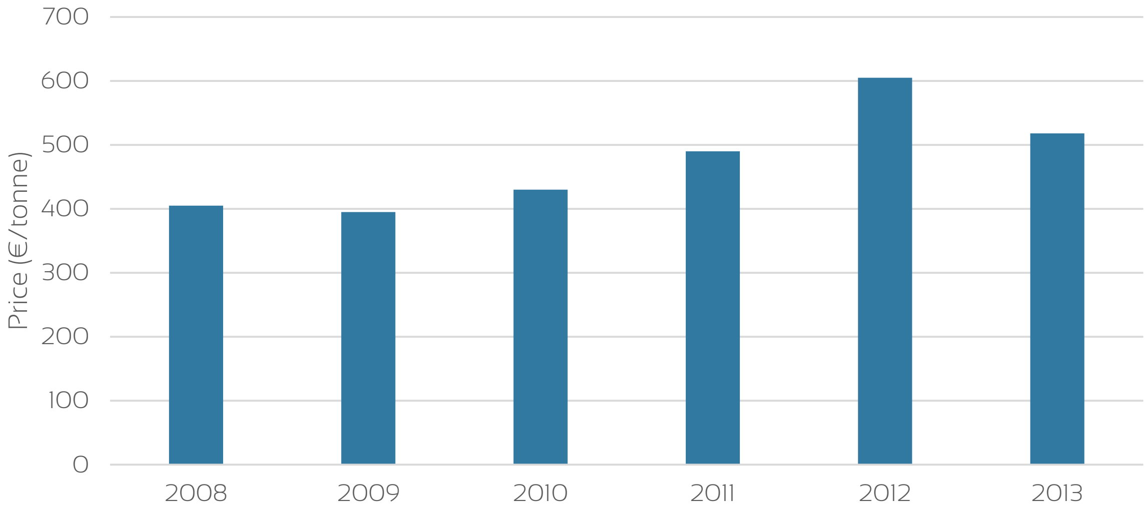

Figure 10. Prices for 'good quality' CTO as reported by Ecofys (Peters & van Steen, 2013)

A report by E4tech (Chudziak & Haye, 2016) provides more detailed price data for the period 2010 to 2015 (Figure 11).

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[25] Tall oil and/or derivatives can be used to aid separation of materials in froth flotation.

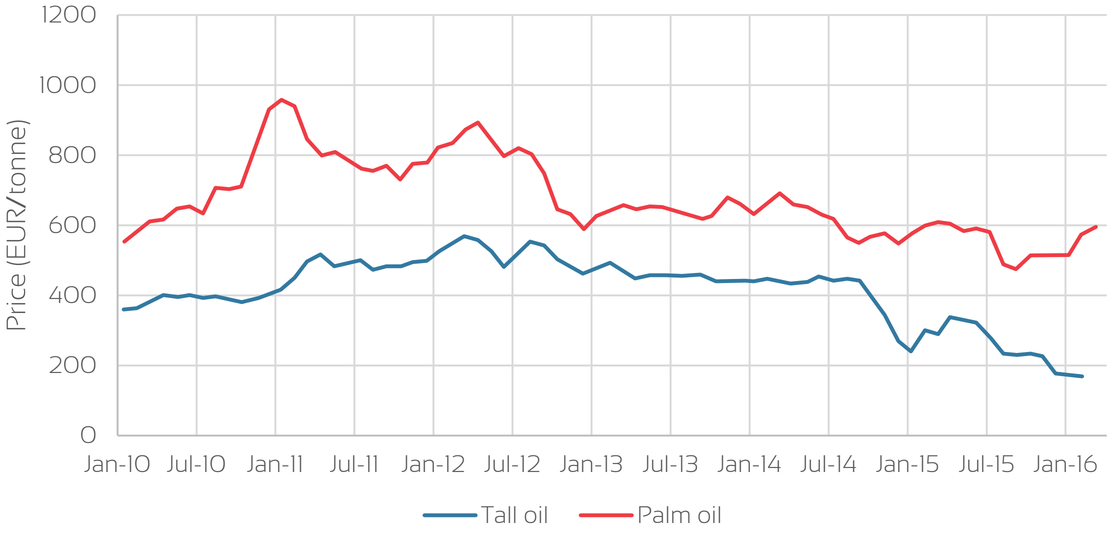

Figure 11. Tall oil price as reported by E4tech (Chudziak & Haye, 2016), with palm oil price for comparison

A later Ecofys study (Peters & Stojcheva, 2017) proposes a formula for identifying the floor price of CTO, based on the minimum value to the pulping facility of using the material for fuel (heating oil price plus value of carbon credits for biomass energy) plus a handling cost for bringing the material to market. The proposed floor price (in €) is:

$$P_{CTO} \geq 0.9 \times P_{BF} + 30 + 2.9 \times P_{carbon}$$

Figure 12 shows reported high quality CTO prices for 2009-11 against the implied floor price, and two comparison fossil commodities (diesel and fuel oil). The implied floor price only approaches the observed price of CTO for limited periods, suggesting that in general CTO has significantly more value to refiners than it does for energy recovery. This could imply that use in energy recovery applications may be relatively elastic to price compared to use in refining (i.e. that refiners are generally able to outbid energy users).

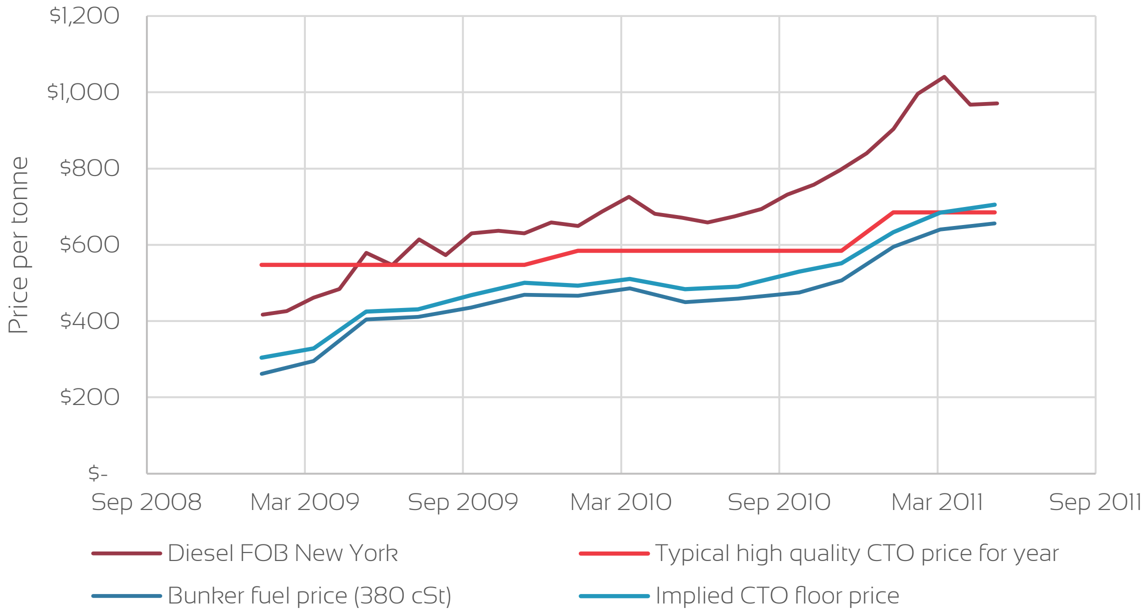

Figure 12. Prices of CTO, bunker fuel and diesel fuel (2009-11) compared to implied CTO floor price from Ecofys formula

Note: the CTO price data in this figure has only annual resolution

It is difficult to obtain price data for the higher value distilled tall oil products (TOFA, TOR, and DTO) in the public domain. TOR achieves the highest prices of the distilled tall oil fractions. Using gum rosin prices as a proxy for TOR[26], it can be inferred that TOR production delivers considerable added value compared to the underlying CTO price (Figure 13). Allowing for a 20% discount on TOR prices compared to gum rosin, this data suggests that TOR traded at a value 25 – 300% higher than CTO during this period, and 20-200% higher than the price of diesel. According to the Fraunhofer Institute (Rajendran et al., 2016), TOFA delivers about 75% of the added value delivered by TOR. This suggests that TOFA would have traded at between 10% below and 100% above the diesel price in this period. In contrast, Fraunhofer report only marginal added value for DTO and TOP, implying that prices for these materials follow the CTO price.[27]

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[26] It is understood that gum rosin prices tend to run higher than but similar to tall oil rosin prices (Flint Group, 2011).

[27] It is slightly surprising that Fraunhofer imply that TOP prices are higher than CTO prices, as TOP has little application other than energy recovery, and a lower heating value slightly below that of CTO. There may be a detail in their analysis on this point that we have not fully understood.

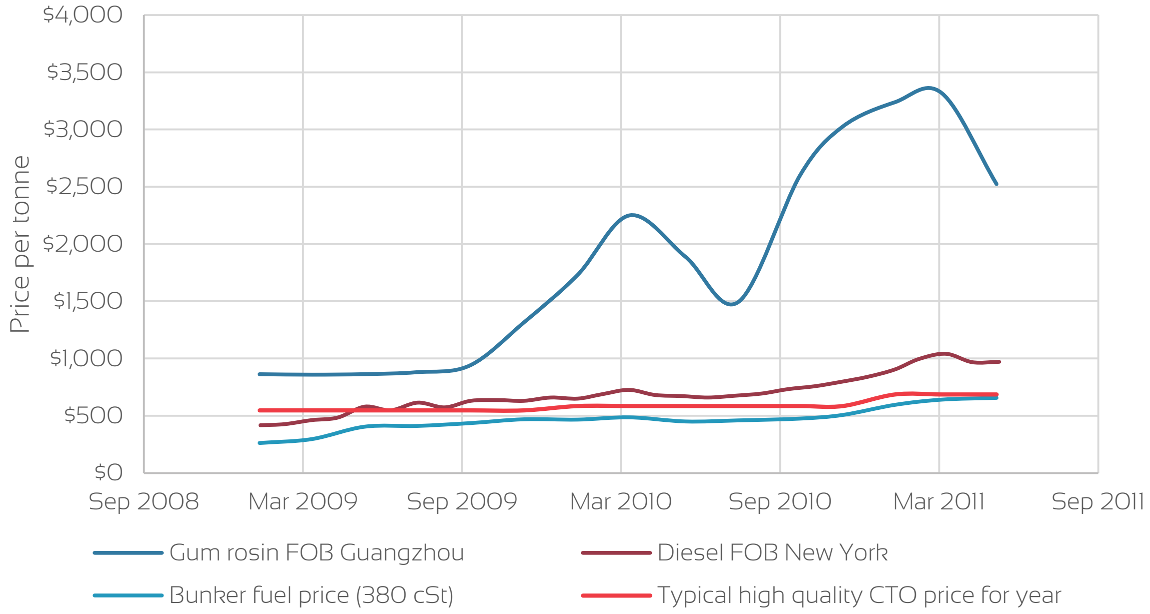

Figure 13. **Gum rosin prices (Flint Group, 2011) compared to FOB prices for diesel and heating oil (IndexMundi, 2017), and to reported typical crude tall oil prices (Peters & Stojcheva, 2017)**

Note: prices converted to USD from EUR where necessary using historical exchange rates from www.xe.com

Typically, 59% of the output of CTO distilling is in the form of the higher value TOR and TOFA fractions. Based on the data given above, we estimate that in the period covered in Figure 13 the combined products of CTO distillation could be sold with a value between 70 and 100% higher than the value of the CTO input. This suggests that rates of CTO distillation may be moderately insensitive to CTO prices, but does not preclude the possibility that a more significant change in CTO price may impact distillation rates.

Some existing users of tall oil have expressed concern relating to the impact on raw material prices of potentially increasing biofuel production from CTO. Flint Group reported in 2016 that rising tall oil prices are a major cause of rising costs for the printing inks industry, drawing a parallel with challenges experienced in 2008 due to rising oil prices (though not explicitly linking this to biofuel demand).[28] Providing an alternate viewpoint, Ecofys (Peters & Stojcheva, 2017) note that imported CTO prices to Scandinavia fell from €550 per tonne in 2015 to €350 per tonne in early 2017, over the same period that up to 230,000 tonnes per year of CTO demand were added by CTO to biofuel facilities. This suggests that the CTO supply has not been unduly tight through this period, implying that there is flexibility in the lower value uses (either CTO combustion for energy, or rates of CTO acidulation). Ecofys explicitly link this observed drop in CTO prices to drops in heavy fuel oil prices (due to falling oil prices). This price behaviour would be consistent with rates of demand for CTO from the distilling sector that are relatively insensitive to price. To date, the growth in biofuel production from CTO does not seem to have unduly impacted the pine chemicals industry.

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[28] http://www.flintgrp.com/en/news-information/press-releases/1595-the-ink-industry-sees-ongoing-raw-material-cost-increases/

3.3.4. Tall oil pitch

At the time of writing, the proposed text for Annex IX of the RED II identifies both tall oil and tall oil pitch as feedstocks for the production of advanced biofuels. Tall oi pitch is the heaviest material produced during tall oil refining, comparable in this regard to heavy fuel oil from oil refining. Tall oil pitch has a lower value role in the market than crude tall oil (or distilled tall oil) and is primarily used for energy recovery, although other potential applications do exist (Rajendran et al., 2016). Tall oil pitch could be used as biofuel feedstock either through hydrotreating or by gasification. Reportedly, Neste Oil is able to use tall oil pitch as feedstock for its hydrotreating process.[29] Given 1.4 million tonnes a year of tall oil being refined globally, we would expect the global supply of tall oi pitch to be around 400 thousand tonnes.

3.3.5. Alternatives

A fairly detailed characterisation of potential alternative materials to refined CTO derivatives is provided by Cashman et al. (2016)[30]. This characterisation is shown in Table 11. Other publications discussing the implications of displacement of CTO to biofuel production also discuss the question (Peters & van Steen, 2013; Rajendran et al., 2016). For tall oil rosin, one alternative is gum rosin, which has generally traded at a higher price than tall oil (Flint Group, 2011). Gum rosin could replace tall oil rosin in applications such as paper sizing[31] and printing inks. It is obtained by tapping pine trees, largely in China. Resin is tapped from trees from the age of about 10 years until they are harvested for timber at around 25 years. Other substitutes may include hydrocarbon resins, alkylsuccinic acid and acrylic resin.

For TOFA and DTO, vegetable oils and animal fats represent a potential substitute. For instance, ICIS chemical use a 2013 briefing to draw attention to convergence between prices for oleic acid (largely tallow-derived) and TOFA, partly driven by increased demand for oil drilling fluids.[32] It is unclear whether TOFA is likely to be substituted in the first instance by primary vegetable oils or by fatty acid distillates. We note that it is generally challenging to fully identify possible chains of substitution between vegetable oil by-products, primary vegetable oils, animal fats and fossil alternatives (Malins, 2014). Cashman et al. (2016) identify only food grade soy oil as a primary bio-alternative to TOFA and DTO in these markets.

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[29] https://www.neste.com/en/neste-oil-uses-tall-oil-pitch-produce-traffic-fuel

[30] It should be noted that these substitution assumptions are referenced to private conversation with executives in the pine chemicals industry, and not explained in detail.

[31] This refers not to the physical size of the paper but rather to the application of coatings for particular paper uses.

[32] https://www.icis.com/resources/news/2013/05/10/9667047/market-outlook-oleic-acid-demand-reshapes-north-american-fatty-acids-market/

Table 11. Substitutes for products of CTO refining as identified by Cashman et al. (2016)

Pine chemical	End market	Primary substitutes	Substitution factor	Substitute % of market share (U.S.)	Substitute % of market share (Europe)
Rosin	Paper size	Alkenyl succinic anhydride (ASA)	1	90	70
	Paper size	Gum rosin	1	10	30
	Rubber	C5 hydrocarbon resins	1	100	100
Rosin ester	Adhesives	Gum rosin ester	1	20	50
	Adhesives	C5 hydrocarbon resins	1	80	50
	Ink	Acrylic resin	1	100	100
TOFA	Oilfield chemicals	Vegetable oils (soybean—food grade)	1	100	100
	Surfactants	Vegetable oils (soybean—food grade)	1	100	100
	Paints/coatings	Vegetable oils (soybean—food grade)	1	100	100
DTO	Surfactants	Vegetable oils (soybean—food grade)	1	100	100
	Paints	Vegetable oils (soybean—food grade)	1	100	100
	Rubber	C5 hydrocarbon resins	1	100	100
Pitch	Fuel	Heavy fuel oil #6	0.91	100	100
Heads	Fuel	Heavy fuel oil #6	0.91	100	100

For TOP, the likely current disposition is combustion for energy, and heavy fuel oil is identified as a likely substitute. Heavy fuel oil is a technically suitable alternate fuel for facilities currently burning TOP (for instance in the limekiln) (Ikonen, 2012). Given that the forthcoming introduction of Marpol VI limits on sulphur in shipping fuel is likely to subdue overall demand for fuel oils (Molloy, 2016), and therefore prices, substitution by heavy fuel oil is likely to be economically appealing in the coming decade (in the absence of further regulation on stationary source emissions that might encourage users to alter practices). Other alternatives however would include natural gas and woody biomass combustion.

3.3.6. Displacement expectations

In assessing the displacement implication a key question is whether additional CTO demand for biofuels would have more impact on the amount of CTO being refined, or on existing users of CTO – i.e. whether the supply of or demand for CTO is more elastic.

On the supply side, there is potential for supply to increase by something in the region of 600 to 850 thousand tonnes of CTO per year by increasing CSS acidulation. There is also an expectation that CTO supply will increase in the next few years due to increased softwood pulping. Ecofys (Peters & Stojcheva, 2017) claim that "It is clear that acidulation varies depending on market demand for CTO". They also note that in principle there is spare acidulation capacity in the global market, but this capacity may not be local to facilities currently combusting CSS for energy. Increasing acidulation rates would result in reduced CSS availability for on-site energy applications. If combusted at the pulp mill, CSS will generally be put through the recovery boiler (Salmenoja, Pynnönen, & Kankkunen, 2016), in order to allow process chemicals to be recovered (these chemicals are otherwise recovered in the acidulation process). CSS has a relatively high moisture content, and thus its combustion is less efficient than combustion of derived CTO. CSS combustion in the recovery boiler could also reduce capacity to combust spent black liquor for process chemical recovery. The recovery boiler is one of the more costly parts of the kraft pulping process, and thus may represent a bottleneck on overall pulp production for many mills. Operators are likely therefore to prefer solutions that avoid CSS combustion in the recovery boiler, providing these are economic (Peters & Stojcheva, 2017; Peters & van Steen, 2013).

On the demand side, the primary uses of CTO that could be displaced are direct energy recovery, refining, and oil drilling applications. In this study, we do not allow for significant displacement from drilling fluid and other niche uses. Additional market research would be necessary to identify whether these uses would be likely to be affected before other uses, and to identify appropriate substitute materials for these uses. Given their limited role in the overall CTO market, this assumption should not fundamentally change the conclusions of this study.

By far the largest use of CTO is refining, using an estimated 1.4 million tonnes of material per year. The CTO used for energy recovery likely reflects lower quality material unsuitable for refining, and may also to some extent reflect cases in which there are structural barriers to accessing alternative CTO markets (for instance pulp mills with relatively high transport costs to distillation facilities). It seems likely that use of CTO for energy recovery would be more responsive to demand changes than demand for refining. There is little evidence that increased utilisation of CTO as biofuel feedstock in recent years has unduly affected the refining market, and therefore we conclude that had biofuel production capacity not expanded in this period it is likely that energy recovery uses for heat and power would have taken up most of the slack, or that rates of acidulation would have reduced.

In the case of expanded capacity for biofuel production from CTO, there is however only a limited extent to which energy recovery for process power could be further reduced. For instance, the UPM plant in Lappeenranta has a capacity to process about 100 thousand tonnes of CTO per year. The total amount of CTO currently used in the EU for energy recovery on site would be enough to supply less than half of such a facility's demand (cf. section 4.3.3).[33]

For a modestly sized tall oil to biofuel industry, say up to four plants with a combined intake capacity of up to 500 thousand tonnes per year[34], we conclude that the primary impact of CTO demand would

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[33] This is distinct from the larger volume of CSS from which energy is recovered globally.

[34] Including the facilities already operational.

be to reduce energy recovery from CSS and CTO, but that at least some impact on refining is also likely. Given that there is at least 600 thousand tonnes of additional potential for CSS acidulation, and that existing use of CSS for energy has low value and is not preferred by pulp mills, it would seem reasonable to expect 60% to come from the supply side. This allows for the likelihood that there are structural reasons (access to acidulation plants, unwillingness to invest, etc.) preventing increased CTO production in some regions, and that therefore some material is likely to continue being burnt as CSS even given significant increases in CTO demand. According to work for the U.S. EPA (Kramer, Masanet, Xu, & Worrell, 2009), the main combustible fuels used in boilers in the U.S. pulp and paper industry are natural gas, biomass, and coal. Based on this study, we assume substitution fractions (by energy content) of 44%, 31% and 24% for natural gas, substitute biomass and coal respectively. When CSS is acidulated to CTO, the lower heating value is improved by evaporation of some of the moisture content (the energy cost of this should be considered in the direct emissions analysis). This effectively improves the efficiency of energy recovery from CTO as compared to CSS, and is included in the calculation.

An additional 20% might be expected to come from reduced energy recovery from CTO. This would reflect a combination of a further reduction on current rates of energy recovery, an assumption that existing biofuel production has already led to reduced rates of energy recovery than would otherwise be seen, and an assumption that some of the additional CTO production expected to come online in the next few years would otherwise end up in energy recovery. As in the case of increased CSS acidulation, this energy would need to be substituted. AS we understand it, CTO combustion is likely largely carried out in the lime kiln. Globally, most lime kiln fuel is either natural gas or fuel oil, with some use of tall oil pitch and other waste, residual or by-product materials (Francey, Tran, & Berglin, 2016; Kramer et al., 2009). Interest has been reported in shifting in future to greater use of biomass fuels and petroleum coke for the lime kiln (Adams, 1999; Francey et al., 2016; Ikonen, 2012), but in this study we take natural gas and fuel oil as most likely substitutes, with replacement split 50:50.

The final 20% might be expected to come from marginal reductions in refining rates due to increased feedstock costs and competition. As reduced CTO distillation results in reduced availability of a range of tall oil distillates, it would be expected to result in increased demand for a relatively large set of replacement materials. Using the characterisation of likely substitutes given in Table 11 (Cashman et al., 2016), along with data from Fraunhofer (Rajendran et al., 2016) on the size of market for each CTO derivative, it is possible to derive estimates of the materials that would replace the derivatives from one tonne of CTO if removed from the refining market. The biofuel technology being considered required depitching of CTO before processing. We therefore assume that no TOP is displaced from the market when CTO is used for biofuel feedstock. Note that the UPM process accepts TOP as a fraction in the feedstock, but that some of this pitch material is returned to the market for energy use from the UPM hydrotreating process. The resulting substitution rates are shown in Table 12.

Table 12. Estimated substitutes for one tonne of CTO derivatives

Replacement material	Amount of replacement material required (kg)
Alkenyl succinic anhydride (ASA)	12.1
Gum rosin	5.2
Gum rosin ester	11.6
C5 hydrocarbon resins	9.0
Acrylic resin	13.5
Soy oil	48.7

The expected displacements are shown in Table 12, with the various substitutes for CTO derivatives described as 'aggregate tall oil distillate substitutes'.

Table 13. Expected displacement effects (tall oil)

Displaced system	Substitute 1	Substitute 2	Substitute 3
Increased CSS acidulation (60%)	Natural gas (for CSS) (RoW) (44%)	Substitute biomass fuel (for CSS) (32%)	Coal (for CSS) (RoW) (24%)
Reduce energy recovery (20%)	Fuel oil (EU) (50%)	Natural gas (EU) (50%)	
Reduce CTO refining (20%)	Aggregate CTO substitutes (100%)		

The composition of 'aggregate CTO substitutes is shown in Table 11

For tall oil pitch, the only significant use of which we are aware is energy recovery, which occurs largely in the lime kiln. We therefore assume that increased use of tall oil pitch for biofuel production would results entirely in reduced availability for energy recovery, and that (as for CTO displacement from the lime kiln) the replacement fuels are fuel oil and natural gas (Table 14).

Table 14. Expected displacement effects (tall oil pitch)

Displaced system	Substitute 1	Substitute 2	Substitute 3
Reduce energy recovery (100%)	Fuel oil (EU) (50%)	Natural gas (EU) (50%)	

3.3.7. *Carbon intensity of displacement*

Table 15. Summary of indirect emissions for CTO-derived fuels (gCO2e/MJ)

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FT diesel from tall oil	0.50	13	10 (27)	8	83	-23	90 (107)
HVO from tall oil	0.98	7	5 (14)	4	42	-12	46 (54)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

As shown in Table 15, the largest indirect emissions term for CTO derived biofuel is increased fossil fuel use. This is primarily due to a presumed increase in natural gas and coal consumption in the U.S. to compensate for reduced CSS consumption, but also reflects a reduction in CTO combustion in the lime kiln at EU pulp mills. In the case of gasification and FT synthesis, the relatively low biofuel yield results in a high indirect emissions estimate, suggesting that, at least for less efficient biofuel processes, it may be preferable from a climate perspective to allow CSS to continue to be combusted for energy than to shift it into biofuel production for the transport sector. There is relatively little renewable rebound assumed, as most energy displacement occurs in the U.S., beyond the scope of the RED, and therefore we do not assume it would need to be replaced with additional renewable energy generation.

Table 16. Summary of indirect emissions for TOP-derived fuels (gCO2e/MJ)

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
HVO from Tall oil pitch	0.79	0	0 (0)	0	87	-73	14 (14)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

Table 16 shows that the use of tall oil pitch is expected to have even higher indirect emissions from fossil fuel replacement. However, because it is assumed that reduced energy recovery from TOP would occur in the EU under the RED, there is a large renewable rebound anticipated, which could almost cancel out the increase in fossil fuel use.

3.3.8. *Sensitivity to forest carbon assumptions*

The role of replacement biomass energy is somewhat limited for the CTO pathway, and therefore it has only modest sensitivity to forest carbon stock assumptions. For an assumption of carbon neutral fuelwood harvests, the indirect emission from forest carbon stock change for the HVO pathway is reduced to 1 gCO_2e/MJ (associated with carbon stock reduction due to residue harvest). For the case of higher carbon stock loss assumptions (Holtsmark, 2012), the indirect emission rises to 11 gCO_2e/MJ. The impact of adjusted forest carbon stock change assumptions is shown for the feedstock and for an example fuel pathway in Table 17 and Table 18 respectively.

Table 17. Impact of forest carbon stock assumptions on indirect emissions associated with tall oil

$kgCO_2e/tonne$	Materials production	Land use change (RED)	Forest carbon stock low	Forest carbon stock mid	Forest carbon stock high	Fossil fuel use	Renewable rebound	Total
Tall oil	234.1	177.1	25.0	137.2	375.9	1506.0	-445.9	1608.5 (1496.3-1847.2)

Table 18. Impact of forest carbon stock assumptions on indirect emissions associated with tall oil derived HVO

gCO_2e/MJ	Materials production	Land use change (RED)	Forest carbon stock low	Forest carbon stock mid	Forest carbon stock high	Fossil fuel use	Renewable rebound	Total
Tall oil derived HVO	6.5	5.0	0.7	3.8	10.5	42.1	-12.5	45 (41.8-51.6)

3.4. Sawdust and cutter shavings

Sawdust and cutter shavings are residues from timber production from roundwood at the sawmill, and at wood finishing/carpentry businesses further down the supply chain. The terminology of wood industry residues is not used entirely consistently across references. The RED II uses the specific terms 'sawdust' and 'cutter shavings'. This could be interpreted to exclude wood chips produced at the sawmill and elsewhere (cutter shavings can be taken to specifically mean shavings from wood planing, which would exclude offcuts from the mill). We do not believe that this is the intention of the Commission in its RED II proposal, nor that it is likely that the legislation would be implemented to make such a distinction, given that the context for identification of these materials is the listing of the, "Biomass fraction of wastes and residues from forestry and forest-based industries." In this report we therefore treat the category sawdust and cutter shavings as inclusive of residual wood chips produced at the mill and elsewhere in the wood products industry, and use the terms cutter shavings and chips somewhat interchangeably. We note that the alternative use profiles will differ between sawdust, cutter shavings and wood chips, and therefore it would be possible to undertake disaggregated indirect emissions assessments for these materials. This was beyond the scope of this study.

Approximately 10-15% of wood volume entering the sawmill is estimated to end up in sawdust, and a further 30-40% may be left as slabs, edges and trimmings, so that only about 50% of wood entering the sawmill leaves as lumber (Food and Agriculture Organisation, 1990). Precise ratios will vary with tree types, regions and production practices. For the Finnish wood products industry, material outputs from the unbarked[35] log are estimated as 45-50% sawn wood, 28-32% wood chips/cutter shavings, 10-15% sawdust and 10-12% bark (Sipi, 2006). Taking into account additional shavings and sawdust from further working of the sawn wood, less than half of the mass of roundwood ends up in wood products.

In 2011, total EU consumption of wood for the sawmill and wood panel industry was estimated at 300 million m^3 of which 262 million m^3 was estimated to come from roundwood (Indufor, 2013). A similar estimate for 2008 of 281 million m^3 of domestic roundwood being consumed by European industry is provided from the EUBIONET project (Keränen & Alakangas, 2011). One source estimates that this results in production of about 120 million m^3 of sawdust, cutter shavings and bark (estimated at 30, 65 and 25 million m^3 respectively) (Pekkanen et al., 2016), excluding material combusted for energy at the sawmill. The 'EU-wood' study suggests a range in sawn wood output from the mill in the range 40-65% depending on EU country and type of tree (Mantau et al., 2010), with a total European sawmill residue production of about 100 million m^3 per year. The EUBIONET numbers for 2008 show 109 million m^3 of sawdust and chips being generated from roundwood processing and leaving the sawmill, plus an additional 40 million m^3 used for heat and power by the sawmill industry itself (Keränen & Alakangas, 2011). Similar numbers are reported for 2013 (Indufor, 2013).

3.4.1. *Use as a biofuel feedstock*

Sawdust and cutter shavings are a potential feedstock for both thermochemical and biochemical cellulosic biofuel production technologies. For instance, in 2014 St1 announced the construction of a demonstration scale (10 million litre) plant in Kajaani, Finland, to produce cellulosic ethanol from sawdust through enzymatic hydrolysis.[36] Sawdust and cutter shavings may represent a more consistent material, less subject to contamination, than residues collected in the forest. Given that materials handling should be simpler for sawdust than for forest residues, utilising sawdust as feedstock may be seen as an opportunity for technology developers to focus on improving their cellulose conversion technologies without having to invest as much time and money into problems related to heterogeneity of woody feedstock and dealing with non-cellulosic material in the intake. It can be argued that the development of sawdust to biofuel technologies may be a useful step towards more truly feedstock agnostic cellulosic biofuel production processes.

3.4.2. *Existing uses*

As noted above, something of the order of 135 million m^3 of sawdust and cutter residues are generated

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[35] I.e. from a log after bark removal.

[36] http://www.st1biofuels.com/company/news/cellunolix-ethanol-plant-to-be-built-in-finland

in Europe annually. The ReceBio task 1 report (Pekkanen et al., 2016) gives the estimated utilisations for this material shown in Table 19.

Table 19. Disposition of sawdust and cutter shavings in Europe (Pekkanen et al., 2016)[37]

	Material flow (million m^3)	Percentage
Energy use at the sawmill	36	27
Fibre and particle board	52	39
Pulp for paper	20	15
Chips for export	9	7
Other bioenergy	18	13

Currently, industrial wood residues are largely used for energy recovery for heat and power or for the production of particle board.[38] Industrial wood residues can be consumed for energy as they are, or pelletised for trade (Indufor, 2013). For instance, sawdust reportedly constitutes a significant fraction of the biomass input into the Drax power station in the UK (Brack, 2017). Some material also goes to the pulping industry, although due to the short fibres in sawdust particles (as distinct from cutter shavings), the sawdust is not an ideal feedstock for pulping. Usage rates will differ between countries, and between the sawdust and cutter shavings components of this feed stream. For instance, Swedish data for 2015 (Edlund, Björklund, & Persson, 2015) show that 91% of wood chips from sawmills were used for pulp and paper, while only 11% of sawdust was. In this report, we follow the categorisations in Annex IX of the proposed RED II, and consider sawdust and cutter shavings as a single combined feedstock.

3.4.3. Alternatives

Essentially all sawdust and cutter shavings in Europe are put to some use; Ecofys comment that, "A consistent view expressed is that there is no excess availability of sawmill residues" (Spöttle et al., 2013). Increased demand for these materials for biofuel production could displace them out of other energy applications, particle board production and/or pulp production (Brack, 2017). A significant fraction of energy in the global forestry industry is currently provided by biomass combustion – over 60% according to the FAO (Miner, 2010). Of the fossil energy used in the wood products sector, nearly half globally comes from natural gas, with another half coming from liquid hydrocarbons, and a small contribution from coal (Miner, 2010). It is understood that the European industry uses very little coal, a higher proportion of natural gas (Ecofys, Fraunhofer Institute, & Öko-Institut, 2009), and that most fuel oil consumed is combusted for the lime kiln. In Europe, removal of industrial residues from energy use

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[37] Note on table: The wood flows reported by Recebio include both domestic wood and imported wood. The reported volume flows detailed in the Recebio task 1 report do not fully reconcile, possibly due to differences in moisture content etc., but we believe that the values reported in the table are a fair characterisation of the different disposition pathways, as indicated by Recebio.

[38] The term 'particle board' can have a quite specific meaning as a type of board, but there is a convention in much of the literature on this topic to use the term 'particle board' as a catch all for various manufactured woody boards that can use sawdust and shavings as input material. We are following this convention, and so the term particle board should be understood broadly in this report.

at the sawmill would therefore likely result mainly in replacement by some combination of increased natural gas use and alternative biomass energy sources. Alternative biomass energy could include the combustion of forest residues – replacing industrial residues with forest residues at the sawmill could make sense in the case that sawdust is considered to have more favourable properties for conversion to biofuel than forest residues. Based on the energy use data in Ecofys, Fraunhofer Institute, & Öko-Institut (2009) we assume that 57% of additional energy comes from substitute biomass, and 43% from natural gas.

Previous lifecycle analysis by the ICCT of the use of sawdust as biofuel feedstock (Baral & Malins, 2014a) assumed based on UK data that most sawdust (90%) would be displaced out of the materials sector. As shown above, the high UK rate of utilisation of sawdust in materials production is not representative for the EU more generally, and therefore this study likely overstated the fraction of material that would be displaced from particle board production. That study concluded that displacement of sawdust would lead to increased primary biomass production (Miscanthus and short rotation willow), and assigned low indirect emissions to sawdust use in biofuel on that basis. In contrast, Chatham House recently recommended that displacement of sawdust from materials production should be prevented to avoid indirect impacts (Brack, 2017). Modelling work by ReceBio suggested that displacement of woody residues out of particle board production would lead to a partial reduction in particle board production volumes – in the 'EU emission reduction' scenario for 2050, an increase in industrial residues use for bioenergy of 9 million m^3 occurred alongside a reduction in particle board production of 4 million m^3. This could suggest that there is a high demand elasticity for industrial wood residues as compared to other materials considered in this report (up to 44% of industrial wood residue use for energy coming from a demand reduction in other use, compared to the 10% that we assume for most feedstocks). However, it should be understood that particle board also uses a quantity of round- and/or pulpwood, and therefore the change in particle board production is likely not only driven by reduced availability of sawdust and shavings, but also by the large increase in use of roundwood for energy (78 million m^3 per year) in the scenario. It should also be noted that the ReceBio study does not assess potential for increase in demand for other materials in response to reduced particle board availability. We therefore do not assume in our modelling a stronger demand response for this than other pathways.

In the pulping industry, reduced availability of sawdust and cutter shavings for would likely primarily result in replacement by increased pulpwood harvest, as the only elastic supply response available to the sector.

3.4.4. Prices

Prices for selected woody materials, quoted for 2009 by EUBIONET, are shown in Table 20. The price of chips and particles is the most relevant to sawdust and cutter shavings. The quoted value of chips and particles is about half that of roundwood.

Table 20. Import/export prices for selected woody materials (Keränen & Alakangas, 2011)

	Export value	Import value	Unit
Roundwood	49 (68)	50 (70)	€ / solid m^3 (USD / m^3)
Chips and particles	31 (43)	23 (32)	€ / solid m^3 (USD / m^3)
Sawnwood	171 (240)	192 (269)	€ / solid m^3 (USD / m^3)
Wood fuel	35 (49)	21 (30)	€ / solid m^3 (USD / m^3)
Wood residues*	50 (70)	36 (50)	€ / solid m^3 (USD / m^3)

**Residues that have not been reduced to small pieces.*

Prices for industrial wood residues show considerable regional variation, partly due to the relatively high cost of transporting bulk commodities. For 1999, EUBIONET reported a price range for bark, sawdust and chips from 0.8 euros per gigajoule in Latvia to 4.2 euros per gigajoule in Denmark. This is nevertheless somewhat below the price range reported for wood chips or pellets at that time (1.6 – 4.5 euros per GJ for chips, 3.3 to 10.6 euros per GJ for pellets) (Alakangas, Hillgring, & Nikolaisen, 2002). Of the other woody materials listed, the price of chips and particles is most comparable to the prices quoted for wood fuel, and somewhat below the reported price for wood residues 'that have not been reduced to small pieces'. This suggests that the value of sawdust and cutter shavings may be primarily determined by its value in energy recovery applications.

3.4.5. Displacement expectations

The ReceBio study for the European Commission (Forsell et al., 2016) assessed several scenarios for European bioenergy consumption using the GLOBIOM model, including the use of industrial wood residues for bioenergy. This study (in which bioenergy was primarily considered for heat and power) found that increased use of bioenergy was likely to reduce particle board production – in 2050, the study found that an increase in the use of industrial by-products for energy of 9 million m^3 was associated with a reduction by 4 million m^3 in wood use for particle board (Pekkanen et al., 2016).

ReceBio also considered the impact of increasing the rates of wood recycling (i.e. of increasing the use of recycled wood for materials applications). The study concluded that increased rates of wood recycling would make industrial wood residues available for bioenergy applications, as recycled wood would be suitable for use in particle board applications currently filled by cutter shavings etc. This suggests that there could be a complementarity between increased cascading of wood-based products and availability of woody materials for bioenergy applications, in which increased energetic use of sawdust and cutter shavings need not impact materials uses strongly. It should be noted however that the rates of wood recycling assumed in the ReceBio study were marginal compared to total wood demand, never accounting for more than 3% of total annual woody inputs to material and energy uses. This results may therefore not be extendable to a large scale industry producing biofuel from sawdust and shavings.

The two largest current utilisations for sawdust and cutter shavings in Europe are particle board production and energy recovery at the sawmill. Energy recovery at the sawmill is the fall back use for industrial woody residues when no other market is available, and the price of wood for energy is below prices of roundwood and other wood for material use, and therefore we consider it reasonable to assume that existing energy uses would be more strongly affected by demand for bioenergy than particle board production would be. In the modelling, we assume that energy uses are displaced twice as strongly as particle board uses (60:30), and that a remaining 10% of material is displaced from pulping Table 21.

For materials uses, we assume that the replacement material would be pulpwood.

Table 21. Projected displacement effects

Displaced system	Substitute 1	Substitute 2	Substitute 3
Reduced energy recovery (60%)	Substitute biomass fuel (57%)	Natural gas (EU) (43%)	
Particle board manufacture (30%)	Pulpwood (100%)		
Pulping (10%)	Pulpwood (100%)		

3.4.6. *Carbon intensity of displacement*

Table 22. Summary of indirect emissions for sawdust and cutter shaving-derived fuels (gCO2e/MJ)

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FT diesel from sawdust and cutter shavings	0.50	15	0 (0)	47	31	-26	67 (67)
Pyrolysis diesel from sawdust and cutter shavings	0.74	10	0 (0)	32	21	-17	45 (45)
Cellulosic ethanol from sawdust and cutter shavings	0.42	20	0 (0)	62	41	-34	88 (88)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

The pathways for sawdust and cutter shavings are associated with significant emissions from forest carbon stock change and from fossil fuels use (Table 22). For the central scenario for substitute biomass carbon intensity, this results in relatively high indirect emissions for all but the most efficient biofuel production, even given a significant renewable rebound.

3.4.7. Sensitivity to forest carbon assumptions

The sawdust and cutter shavings pathways are the most sensitive to assumptions about the carbon intensity of substitute biomass fuels. For the FT diesel pathway, a carbon neutrality assumption on fuelwood harvest would reduce emissions by 46 gCO_2e/MJ (to 22 gCO_2e/MJ in total), while the higher carbon loss assumption increases emissions by 97 gCO_2e/MJ (to 164 gCO_2e/MJ in total). The impact is reduced but still significant for the higher yield biofuel pathways. This reiterates that if considering the use of materials for biofuel feedstock that are likely to result in increased wood harvest, it is vital to manage forest carbon stocks to avoid significant carbon stock losses. In the case that additional wood harvest generates a large carbon debt, the indirect emissions are potentially very large. The impact of adjusted forest carbon stock change assumptions is shown for the feedstock and for an example fuel pathway in Table 23 and Table 24 respectively.

Table 23. Impact of forest carbon stock assumptions on indirect emissions associated with sawdust and cutter shavings

$kgCO_2e/tonne$	Materials production	Land use change (RED)	Forest carbon stock low	Forest carbon stock mid	Forest carbon stock high	Fossil fuel use	Renewable rebound	Total
Sawdust and cutter shavings	141.4	0.0	16.4	449.3	1369.5	293.5	-246.0	638.2 (205.3-1558.5)

Table 24. Impact of forest carbon stock assumptions on indirect emissions associated with sawdust and cutter shavings derived FT diesel

gCO_2e/MJ	Materials production	Land use change (RED)	Forest carbon stock low	Forest carbon stock mid	Forest carbon stock high	Fossil fuel use	Renewable rebound	Total
Sawdust and cutter shavings derived FT diesel	14.9	0.0	1.7	47.3	144.2	30.9	-25.9	67.2 (21.6-164)

3.5. Black liquor

As detailed above in the section on tall oil, black liquor is a residue of the kraft pulping process, containing lignin, hemicellulose, other organic material and spent chemicals used in the kraft process. About 7 tonnes of black liquor (though only about 1.7 tonnes by dry mass) are produced for every tonne of pulp. It is normal to separate out the crude sulphite soap (CSS) from the black liquor, and thence produce tall oil (see above). It is presumed that black liquor for biofuel production would be 'spent black liquor', the residual material remaining after CSS removal. EUBIONET estimates that, in 2008, 70 million m^3 of black liquor were produced by European forest industries (Keränen & Alakangas, 2011). A similar estimate of 60 million tonnes is provided by Indufor (2013).

3.5.1. Use as a biofuel feedstock

The main prospective technology for biofuel production from black liquor is gasification and fuel synthesis (IEA Bioenergy, 2007). In this process, a gasification plant replaces the recovery boiler. Gasification is performed at a temperature above the melting point of the inorganic chemicals contained in the liquor, allowing smelt separation in a way similar to the standard recovery boiler process (and hence production of green and hence white liquor for reuse in the kraft process). After cleaning, the gasifier outputs a synthesis gas largely consisting of carbon monoxide, hydrogen and carbon dioxide.

The development of black liquor gasification technology has been focused on allowing the use of the syngas in a gas turbine to increase energy recovery efficiency and allow a better fraction of power to heat to be recovered. One study (Berglin, Lindblom, & Ekbom, 2003) finds that adoption of gasification technology for heat and power generation could double excess power generation from a typical pulp mill (considering a Swedish example). As an alternative to the use of the syngas for heat and power, it may also be an appropriate feedstock for methanation, methanol or DME production, or FT fuel synthesis – although given that FT synthesis is understood to require a relatively large scale operation to be economically feasible (Turley, Evans, & Nattrass, 2013), this may only be appropriate for larger pulping mills or for groups of mills. If aggregating black liquor from a number of locations, it would be vital to return the recovered pulping chemicals to the mills of origin.

3.5.2. Existing uses

Currently, it is normal for black liquor from the kraft process to be combusted in a 'recovery boiler' – this is a special boiler used to extract energy from the organic components of black liquor (U.S. EPA Office of Air Quality Planning and Standards, 1995). Use of the recovery boiler is an important part of recovering the chemicals required for the kraft process, and provides a disincentive to the export of spent black liquor for biofuel (or other chemicals production). If black liquor were to be transported to a centralised biofuel production facility, the green liquor extracted from the gasification process would need to be returned to the mill.

3.5.3. Alternatives

Increased use of spent black liquor for bioenergy feedstock would reduce its use for heat and power generation by pulp mills. Alternative energy sources would therefore be required. The most likely alternative energy sources for Europe would be other biomass residues (similarly to the case of sawdust above) or natural gas. Berglin et al. (2003) assume that power replacement for a case where all syngas is used for methanol production would be delivered from biomass. In the event of reduced use of black liquor for energy recovery, pulp mills are likely to adopt new energy generation systems that deliver improved efficiency. Berglin et al. (2003) calculate additional requirements for power and fuel resulting from moving black liquor from the recovery boiler to a gasification process for fuels. Per MJ of methanol production, they find that an additional 0.27 MJ of power and an additional 0.12 MJ of fuel are required.[39] We base our substitution requirements on this analysis. The paper assumes that these additional energy needs will be met by increasing combustion of bark or other residues in the bark boiler, and by additional biomass combustion in biomass powered condensing power plants at 35% efficiency. This gives a replacement requirement of about 0.9 MJ LHV of biomass or fossil fuel for every 1 MJ of methanol produced. The pulping industry is generally power self-sufficient, and we therefore assume that any additional power needed will be generated on-site (i.e. we do not allow for the possibility of electricity imports).

3.5.4. Prices

Black liquor is not a routinely traded material, and thus it is not readily possible to obtain pricing information.

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[39] Author's calculation, excluding energy required to run the gasification and methanol synthesis processes, which should be included in the direct LCA.

3.5.5. Displacement expectations

The primary and only displaced system for increased use of black liquor as biofuel feedstock would be energy recovery. In Europe, biomass provides 51% of sectoral energy, natural gas 38%, and other fuels including coal and fuel oil provide the remaining 11% Ecofys (Ecofys et al., 2009). We assume that expansion of coal combustion in unlikely in Europe, and that most fuel oil use is in the lime kiln, and therefore consider only biomass and natural gas as replacement fuels, in the ratio 57:43. It is assumed that fuel production from black liquor would only be undertaken if the economics for the facility as a whole were improved by the investment, and therefore we assume no elasticity of energy demand in the pulp and paper industry to black liquor supply.

Table 25. Proposed displacement effects

Displaced system	Substitute 1	Substitute 2	Substitute 3
Reduced energy recovery	Forestry residues (57%)	Natural gas (EU) (43%)	

3.5.6. Carbon intensity of displacement

Table 26. Summary of indirect emissions for black liquor-derived fuels

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FT diesel from black liquor	0.50	6	0 (0)	18	26	-25	25 (7)
Methanol from black liquor	0.56	5	0 (0)	16	24	-22	22 (6)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

Fuel production from black liquor is associated with relatively modest overall indirect emissions (Table 2). This is influenced by the assumed efficiency gains through implementing alternative energy generation capacity, and by the role of the renewable rebound in cancelling out emissions from increased fossil fuel demand. This suggest that even though displacing black liquor out of existing energy production will require replacement, it may be possible to deliver net carbon benefits across the system by doing so.

3.5.7. Sensitivity to forest carbon assumptions

For the FT diesel pathway, a carbon neutrality assumption on additional fuelwood harvest reduces forest carbon stock emissions by 15 gCO_2e/MJ. For the high carbon stock loss scenario, forest carbon stock emissions become very significant – increasing by 31 gCO_2e/MJ to 49 gCO_2e/MJ. The impact of adjusted forest carbon stock change assumptions is shown for the feedstock and for an example fuel pathway in Table 27 and Table 28 respectively.

Table 27. Impact of forest carbon stock assumptions on indirect emissions associated with black liquor

$kgCO_2e/tonne$	Materials production	Land use change (RED)	Forest carbon stock			Fossil fuel use	Renewable rebound	Total
			low	mid	high			
Black liquor	41.5	0.0	23.8	130.7	357.9	191.2	-180.8	182.5 (75.6-409.7)

Table 28. Impact of forest carbon stock assumptions on indirect emissions associated with black liquor derived FT diesel

gCO_2e/MJ	Materials production	Land use change (RED)	Forest carbon stock			Fossil fuel use	Renewable rebound	Total
			low	mid	high			
Black liquor derived FT diesel	5.7	0.0	3.3	18.0	49.4	26.4	-24.9	25.2 (10.4-56.5)

3.6. Crude glycerine

Glycerine, also referred to as glycerin and (in its pure form) glycerol and by the chemical name 1,2,3-propanetriol, has a variety of chemical applications, as well as applications for feed. The market distinguishes between crude glycerine and purified glycerine, with the latter having substantially higher value. Glycerol has historically played a role as a precursor for explosives production, and from the First World War a synthetic glycerol industry developed to complement the production of glycerol as a soap by-product. After the second world war, processes for glycerol synthesis from propene became widespread, and for the period up to 2003 accounted for about a quarter of glycerol production, the remaining 75% still arising as a soap by-product (Ciriminna, Pina, Rossi, & Pagliaro, 2014). This market was dramatically affected by growth in biodiesel production through transesterification since 2000, with a rapid increase in global crude glycerine supply. Most active glycerol synthesis has now ceased, except for pharmaceutical application requiring very high purity. Given global biodiesel production of about 33 billion litres in 2016[40], glycerol production as a biodiesel co-product is estimated at around 3 million tonnes per year using glycerine yield data from Biograce (2017). This matches 2.9 million tonnes of global production reported by E4tech (Taylor & Bauen, 2014), but runs somewhat higher than reported estimates of global glycerine production (e.g. 2 million tonnes is quoted for 2011 by Ciriminna

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[40] http://www.platts.com/latest-news/agriculture/london/world-biodiesel-productionconsumption-to-rise-26485632

et al., 2014; only about 1.5 millon tonnes is quoted for 2011 by Quispe, Coronado, & Carvalho, 2013). This could be partly explained by continued growth in global biodiesel production in the last five years, but could also suggest that a significant amount of produced glycerine may be being disposed of without reaching the market, for instance for local energy use at the producing facilities. Oleoline (2012) identify about a million tonnes of additional non-biodiesel production capacity, which could suggest that total global glycerine production in 2016 was closer to 4 million tonnes. This compares to 200,000 tonnes a year of global production reported in 2003 (Ciriminna et al., 2014), before the rapid growth of biodiesel production.

In the EU 1,100 thousand tonnes of glycerine is produced every year by the biodiesel industry alone, based on European Biodiesel Board statistics[41] and a glycerine yield on biodiesel production of 0.1 tonnes per tonne biodiesel (BioGrace, 2017). Given that Global Market Insights[42] state that biodiesel accounts for something around 65% of European glycerine production, total crude glycerine production in Europe in 2013 could have been as high as 1,700 thousand tonnes. Other strong biodiesel markets (e.g. the U.S., Argentina, Brazil, Indonesia) may represent potential glycerine exporters.

3.6.1. Use as a biofuel feedstock

The main case of glycerine use for biofuel feedstock in Europe of which we are aware is the company BioMCN, which had developed a technology for glycerine gasification to syngas (H_2 + CO) and methanol synthesis. The facility used was designed for methanol production from natural gas but was converted to run using gasified crude glycerine, reportedly to be sourced from Argentina[43]. It is our understanding that the BioMCN glycerine to methanol operation is no longer active, with the methanol production capacity having been sold to OCI N.V. while the glycerine refining business has been separated off (Zayed & Koot, 2015). A similar technology pathway for glycerine to methanol was trialled in the European Union funded FP7 project Super Methanol: Reforming of Crude Glycerine in Supercritical Water to Produce Methanol for Re-Use in Biodiesel Plants[44].

Beyond methanol applications, glycerine may be suitable as a feedstock for Fischer-Tropsch synthesis following conversion to syngas by gasification or pyrolysis (e.g. Fernández, Arenillas, Díez, Pis, & Menéndez, 2009; Simonetti et al., 2007). However, given the relatively high per-tonne price of glycerine compared to other some other low-cost feedstocks it is unclear without further analysis whether these options are likely to be pursued.

The initial BioMCN methanol synthesis plant was reported to have capacity to produce 200,000 tonnes of methanol per year.[45,46] Given a methanol yield from glycerine of 0.27 kg/kg (base case in van Bennekom, Venderbosch, & Heeres, 2012)[47], operating the BioMCN plant at stated capacity would have

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[41] http://www.ebb-eu.org/stats.php

[42] From Global Market Insights, https://www.gminsights.com/industry-analysis/glycerol-market-size

[43] http://www.biofuelsdigest.com/bdigest/2012/04/18/biomcn-edf-man-partner-to-procure-glycerin-for-advanced-biofuels/

[44] http://cordis.europa.eu/project/rcn/85746_en.html

[45] http://www.just-auto.com/interview/qa-with-biomcn-rob-voncken-ceo_id101248.aspx

[46] Note that E4tech (Taylor & Bauen, 2014) report glycerine demand of 200,000 tonnes from this plant. This may suggest a confusion between input and output in one of the sources, or else that the facility never ran at full capacity.

[47] Note that this yield is quoted for a similar process, but not directly for the BioMCN facility.

required about 750 thousand tonnes of glycerine a year. A first generation Fischer-Tropsch synthesis plant would likely have a similar glycerine intake capacity (assuming a commercial scale production capacity of about 150 thousand tonnes, Turley et al., 2013). A yield of 0.27 kg/kg for glycerine to methanol is equivalent to an energy efficiency of about 35%. IRENA suggest a higher achievable energy conversion efficiency of 50-60% (IEA-ETSAP & IRENA, 2013), which would be consistent with the higher yield case described in van Bennekom et al. (2012), and would imply that only 500,000 tonnes of glycerine was required.

3.6.2. *Existing uses*

About half of global glycerine supply is refined to remove impurities (Ciriminna et al., 2014).

Refined glycerine (glycerol) has a wide range of existing applications. Chemical applications include epichlorohydrin, acrylic acid and acrolein production (Carus, Dammer, Hermann, & Essel, 2014). Indeed, there are reported to be over 1,500 separate uses for glycerol in the chemicals industry (Quispe et al., 2013). Figure 14 shows that the glycerol market has been growing steadily (alongside increasing crude glycerine availability), with the largest share of growth occurring in personal care and pharmaceutical applications.

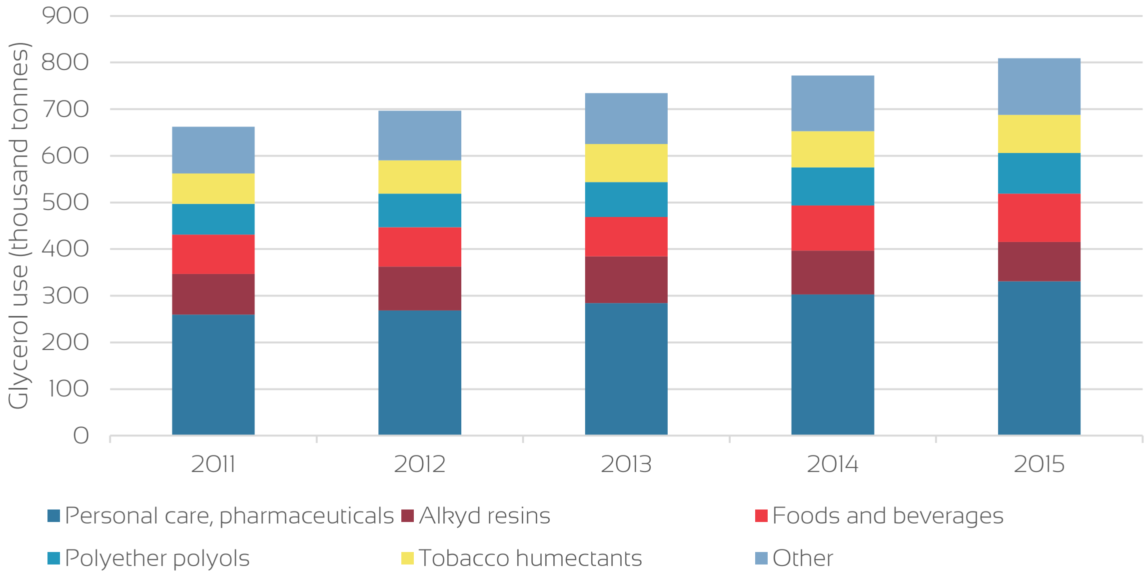

Figure 14. Industry estimate of uses of refined glycerol in Europe, 2011-201548

The market analyst Global Market Insights predicts (given expected growth in biodiesel production) that the market for refined glycerol will continue to grow, and be 50% larger by 2022 than in 2015.[49]

According to Global Market Insights' data, about 730 thousand tonnes of refined glycerol was consumed in Europe in 2013, as shown in Figure 14, substantially less than total crude glycerine production. For

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48 From Global Market Insights, https://www.gminsights.com/industry-analysis/glycerol-market-size

49 Ibid.

a crude glycerine purity of 80%, the demand from glycerol refining could therefore have been met from European glycerine production leaving an excess supply of up to 800 thousand tonnes available directly to crude glycerine markets (or export markets). However, other sources suggest a lower level of European crude glycerine production (e.g. 1 million tonnes is reported by Taylor & Bauen, 2014). They identify European glycerine use as 560 thousand tonnes per year to glycerine refining, 300 thousand tonnes to animal feed and 100 thousand tonnes to heat and power via biogas. It is therefore possible that Global Market Insights may be overstating non-biodiesel production of glycerine in Europe.

Refined material has a high value, and there is therefore no expectation that refined material would be used for bioenergy (it is also currently excluded from Annex IX). It is possible though that increases in crude glycerine demand for biofuel production could result in increases of crude glycerine cost (and reductions in availability) to refineries. However, given that the glycerine market has been characterised by oversupply for several years, it seems likely that the capacity of refiners to pay for crude glycerine goes somewhat beyond the current price bracket. As noted above, the economics of methanol or FT-diesel production from glycerine are likely to be rather more sensitive to feedstock price, and so we would not expect to see substantial displacement of glycerine resources from refineries in the near term – rather, glycerine for biofuel is much more likely in the first instance to be displaced from crude glycerine markets.

Animal feed represents an attractive market at present for crude glycerine from biodiesel, as the impurities typically present in crude glycerine do not prevent it being adequately metabolised (Donkin, 2008). While some concern has been expressed about the potential for methanol contamination in feed glycerine to be passed through the food chain, there is no EU level limit. French and UK food standards agencies, for instance, have set only recommended limits of 0.5% (Nelson, 2007). It has been estimated that about 16% of total glycerine production (which would be of the order of 300-500 thousand tonnes if true globally) goes into animal feed (Ciriminna et al., 2014). The apparent metabolisable energy of glycerine in poultry diets has been reported as 3,800 kcal/kg (Lammers et al., 2008). This is comparable to values for corn (3,800 kcal/kg, Kato, Bertechini, Fassani, Brito, & Castro, 2011) but much lower than for vegetable oils such as soy oil (8,900 kcal/kg, Mateos, 1981).

It has also been reported that crude glycerine (other than energy recovery) has acquired a use in cement manufacture (Ciriminna et al., 2014). Glycerine can be used as a grinding additive, reducing the energy intensity of the cement manufacture process[50] and replacing oil derived alternatives (Ciriminna et al., 2015). Some thermochemical and biological processing options have also been identified for crude glycerine, with glycerol as feedstock for fermentation. These include production of propylene glycol, reforming to hydrogen, and fermentation to citric acid, 1,3-propanediol and ethanol, among others (Ciriminna et al., 2014; Quispe et al., 2013). Oleoline (2012) predicted that by 2014 nearly a million tonnes of glycerine globally would be utilised in 'new' applications, including epichlorohydrin, mono-propylene glycol and anti-freeze manufacture.

As well as feed and material uses, there is some potential for use of glycerine for energy recovery. In principle it could be used as a boiler fuel, although this may be limited by air pollution concerns and technical challenges to combustion (Metzger, 2007). In particular, the low energy density, high self-ignition temperature and potential water content make it difficult to successfully combust glycerol as boiler fuel without specialised equipment (Quispe et al., 2013). We therefore do not believe that direct combustion for heat and power is a significant current use for glycerine, or that it would be likely to be displaced from such use if transferred to biofuel production. A more promising energy recovery route is anaerobic digestion. The Belgian company Organic Waste Systems identifies glycerine as a

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[50] Cf. https://www.decodedscience.org/bioglycerol-use-construction-industry/53790

possible AD feedstock, although there may be chemical limitations to the fraction of glycerine that can be digested (Velghe & Wierinck, 2013). The impurities in crude glycerine that make it cheap enough to consider as a digester feed may simultaneously inhibit bacterial function (Redman, 2010). While it is relatively easy to find isolated examples documented of glycerine use as digester feed, we were not able to find data on rates of use. We believe that the E4tech estimate of ~100,000 tonnes per year for heat and power via biogas could be considered a high-end estimate. In any event, digestion is a low value use, and likely to be responsive to changes in demand from other users.

3.6.3. Alternatives

E4tech (Taylor & Bauen, 2014) identify fossil-derived glycerine and propylene glycol as possible alternative materials following displacement of crude glycerine out of the market, but this may not be correct in all cases.

In animal feed, crude glycerol would likely be replaced by other low cost energy feeds. As noted above, the metabolizable energy content of crude glycerine is similar to feed grains. Glycerine has limited other nutritional value. Crude glycerine trades for much lower prices per tonne and per calorie than vegetable oils, but prices per tonne for crude glycerine are similar to corn prices (Figure 15).[51] Given that metabolisable energy in crude glycerine is also comparable to that for corn, this is consistent with a hypothesis that excess supplies of crude glycerine (i.e. volumes of glycerine not purchased by glycerine refiners) currently displace corn in the animal feed market. It therefore seems reasonable to treat feed grains (corn and wheat) as alternatives to glycerol in the feed market. Glycerine may also compete in the feed market with molasses, as both have a role as a sweetener and potential palatability enhancer.

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[51] Note that a US corn price is compared to a Chinese glycerine price, and therefore the direct comparison should be treated with some degree of caution.

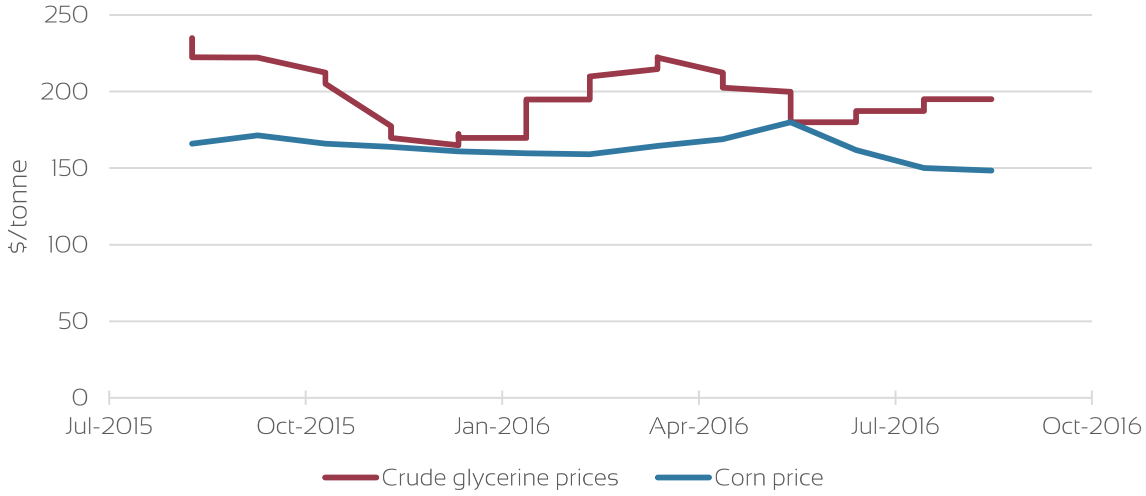

Figure 15. 2015/16 Chinese crude glycerine prices reported by ICIS52 against CBOT corn prices as reported by Indexmundi53

In the cement industry, alternatives to crude glycerine as a grinding agent include ethylene glycol, propylene glycol and polypropylene glycol from fossil sources (Ciriminna et al., 2015; Engelsen, 2008). Unlike the use of glycerine in animal feed, chemical processing options for direct crude glycerine conversion (as opposed to refined glycerol conversion) seem not to be well commercialised to date. Based on the information available, it seems plausible that fossil-derived materials such as propylene glycol are indeed the likely replacements in such chemical applications, but this likely would vary depending on specifics.

3.6.4. Prices

The surge in crude glycerine production over the last 15 years has had a predictably dampening effect on glycerol prices since 2000. Crude glycerine prices fell by a factor of four from 2000 to 2011, as shown in Figure 16 (with, additionally, considerable regional price variation). The significant gap between the price of crude and high purity refined glycerine, by a factor of up to twenty, reflects the relatively high cost of glycerine purification, reportedly at least $150 per tonne (Ciriminna et al., 2014), and the fact that without purification crude glycerine is not appropriate for higher value applications.

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[52] https://www.icis.com/resources/news/2016/09/08/10032327/asia-crude-glycerine-market-in-stand-off-some-sellers-keep-offers/

[53] http://www.indexmundi.com/commodities/?commodity=corn&months=60

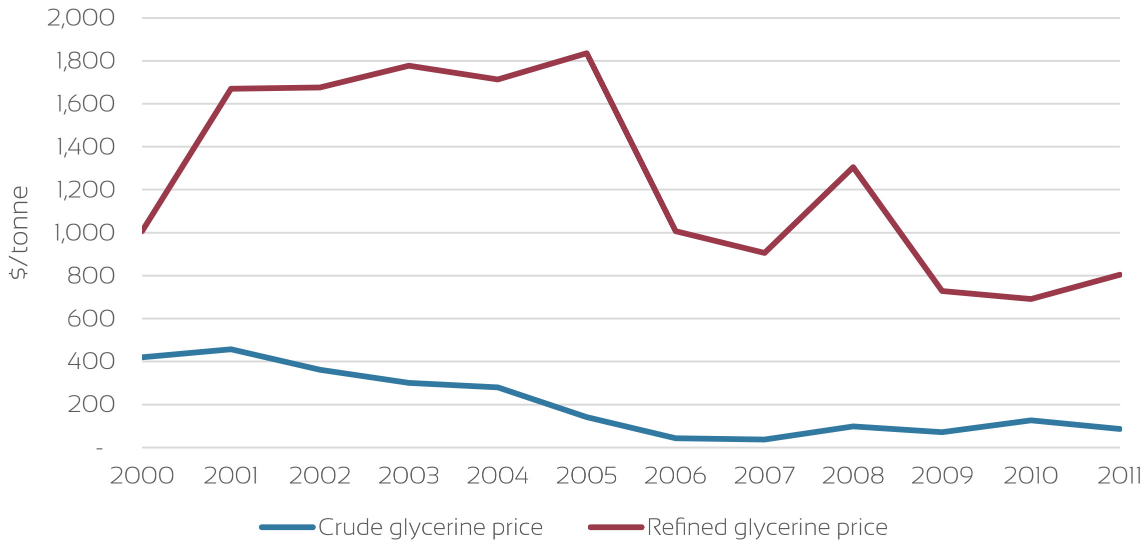

Figure 16. Glycerine prices (refined and crude) 2000-2011 (Quispe et al., 2013)

More recently, E4tech reported crude glycerine price of 253 euro per tonne (Taylor & Bauen, 2014), and Oleoline has reported similar technical crude glycerine prices for Europe, 110-220 euro per tonne for Q3 2016.[54]

Refined glycerol trades at prices on the order of ten times higher than crude glycerine. From this it is clear that feedstock makes only a modest contribution to operational costs for glycerine refiners, and we may therefore conclude that glycerine refining should be relatively insensitive to glycerine price, i.e. that the refining industry has a high willingness to pay.[55] In animal feed and heat and power applications, the opposite is likely to be true. These industries use glycerine primarily because of its low price compared to alternatives, and are therefore likely to be relatively price sensitive. It is less clear what the value is of glycerine for cement and chemicals applications, i.e. whether glycerine brings added value beyond offering a potentially cheaper alternative to fossil derived glycols.

Given typical relative prices for methanol and glycerine, the basic economics of methanol synthesis from glycerine may be challenging. In April 2017, the European methanol price was quoted by Methanex Corporation as 450 euro per metric tonne. Given a methanol yield from glycerine of 0.27 tonnes per tonne, without policy support a glycerine to methanol facility could therefore not currently afford to pay more than 120 euro per tonne glycerine (and given operational and capital costs, rather less in practice). E4tech (Taylor & Bauen, 2014) estimate feedstock cost as 80% of methanol production cost (probably based on limited capital spending, as the BioMCN plant was a converted natural gas to methanol facility). This would reduce maximum ability to pay for crude glycerine to about 95 euros per tonne. This is below recent reported crude glycerine prices (see below). Balegedde Ramachandran, Oudenhoven, Kersten, van Rossum, & van der Ham (2013) similarly suggest that methanol production from glycerine would become attractive only below a glycerine price of about 90 euros per tonne (without policy

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[54] http://www.oleoline.com/index.php/news/crude-glycerine-prices-are-expected-to-rise-for-q32016/

[55] Note however that volumes of refined glycerine appear to have increased with increasing glycerine availability (Ciriminna et al., 2014), suggesting that production has a degree of elasticity to supply.

support). The maximum affordable glycerine price would be increased to about 140 euros per tonne for the higher yield case discussed above, which could significantly improve the business case. E4tech (Taylor & Bauen, 2014) report that production of biofuel from glycerine has the highest cost of any waste-to-biofuel pathway they considered, with the cost dominated by feedstock acquisition.

Given a methanol carbon intensity of 25 gCO_2e/MJ[56], glycerine based methanol could deliver 0.4 tonnes of CO_2 reduction per tonne of glycerine in the lower yield case, or 0.6 tonnes CO_2 per tonne of glycerine in the higher yield case. A carbon price for advanced biofuels of 200 euro per tonne could therefore increase maximum ability to pay for crude glycerine by 80-120 euros per tonne, to 175-215 euros per tonne. Direct or implied carbon pricing could therefore potentially make methanol production competitive for crude glycerine sourcing with at least some other crude glycerine buyers. Nevertheless, even with substantial policy support the economic case for methanol production from glycerine appears to be very sensitive to the price of glycerine feedstock.

3.6.5. Displacement expectations

Based on the information available, it seems likely that an increase in demand for crude glycerine for biofuel production would result primarily in a reduction in crude glycerine use as animal feed. Animal feed use of by-products and residues is likely to be relatively sensitive to price variations (Hazzledine et al., 2011), and animal feed use is considered as a 'disposal application' by the industry (Oleoline, 2012). Within animal feed, we identify feed grains as the most likely substitutes. Glycerine is primarily an energy feed, with similar energy density to cereal feeds.

As discussed above, we would not expect a glycerine-to-biofuel industry to be able to outbid the glycerine refining industry for crude glycerine resources in the near term.

There are other niche uses for crude glycerine in chemicals and cement. These uses have likely been developed at least partly in response to the growing 'glut' of crude glycerine supply associated with an expanding biodiesel industry, and are likely predicated on the low price of crude glycerine, and therefore may also be relatively responsive to increased demand for biofuel feedstock. The use of glycerine in these applications has likely required a higher degree of process modification and investment than is required to introduce glycerine in livestock diets. Alternates in these applications are also likely to be more expensive than animal feed. For instance, one potential alternative identified for crude glycerine in chemical and cement applications is propylene glycol (Ciriminna et al., 2015; Searle et al., 2017; Taylor & Bauen, 2014), which trades for as much as $1,000 per tonne (ICIS, 2012; Oleoline, 2012) against prices consistently below $500 per tonne reported for crude glycerine. We therefore do not expect significant displacement out of these uses. The results for glycerine are likely to be quite sensitive to a higher assumption on displacement out of these uses, and so this question warrants additional examination in future.

While it is our conclusion that glycerine refining would not be heavily impacted by increases in glycerine demand for biofuel, a somewhat opposing viewpoint is expressed in a statement from the Solvay company in 2013:

> *"The proposed changes to the RED/FQD in their current form would have harmful consequences for the development of raw-glycerine-based chemical products. As crude glycerine would be overwhelmingly used for fuel production, this raw material would no longer be available for*

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[56] Average carbon intensity reported for glycerine to methanol under the UK Renewable Transport Fuel Obligation, 2014/15 (UK Department for Transport, 2016).

renewable or bio-based chemistry" (reported by Carus et al., 2014).

However, this statement was made in the context of a proposal that the 'ILUC Directive' should introduce the quadruple counting of biofuels from waste and residual materials, which might have introduced a very substantial price premium for glycerine based biofuel. The system of targets under RED 2 may not provide quite such a large value driver, although it is difficult to confidently compare the value of incentives that have in neither case been implemented. Certainly it is true that diversion of glycerine to biofuel use will remove a potentially low cost feedstock that could be harnessed by future chemicals industry developments. On the other hand, there can be complementarity between the development of technologies for biofuels and biochemical. A developed market for fuel synthesis from gasified glycerine could open up prospects for new chemical pathways using similar technologies in future (cf. Pavlenko et al., 2016). Perhaps pertinently, the glycerine refining arm of the BioMCN operation continues to operate under new ownership, while the glycerine gasification side of the business appears to have been discontinued.

We have developed expected displacement rates based on the utilisations documented by E4tech (Taylor & Bauen, 2014) and on an assumption that use in animal feed will have twice the demand elasticity of use in anaerobic digestion, based on the consideration of responsiveness to price given above. We assume that major feed cereals (wheat, corn and barley) will be displaced in proportion to production, as documented by FAOstat[57]. The resulting displacement rates are shown in Table 29.

Table 29. Displacement effects

Displaced system	Substitute 1	Substitute 2	Substitute 3
Remove from feed market (86%)	Feed wheat (56%)	Feed corn (23%)	Feed barley (21%)
Reduced use in AD (14%)	Natural gas (EU) (100%)		

3.6.6. Carbon intensity of displacement

Table 30. Summary of indirect emissions for glycerine-derived fuels

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
Methanol from glycerine	0.50	19	9 (22)	0	9	-8	28 (42)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

The glycerine pathway has relatively low indirect emissions, largely from materials production and land

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[57] http://www.fao.org/faostat/en/

use change (Table 30). The land use change emissions are more than doubled if based on the GLOBIOM study instead of the RED II ILUC numbers, significantly increasing the overall indirect emissions.

3.7. Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009 of the European Parliament and of the Council

In Europe, animal fats collected as a by-product of the meat industry, or as a result of the mortality of non-meat animals (e.g. zoo animals), are divided into three categories, based on the assessed risk of spreading disease. Category 1 material is considered highest risk, and must be disposed of to landfill or through combustion/incineration. Category 2 material is also treated as high risk, but can be used for soil improvement/fertilisation applications, composted or digested, and production of derivatives for some technical uses. Category 3 animal fats have the lowest risk (and therefore highest value) and can be additionally utilised for oleochemicals production, pet food and animal feed.

In Annex IX of the RED and RED II, only category 1 and 2 animal fats are eligible to be used as feedstock for advanced biofuels. It should be noted however that under the categorisation system, animal fats can be pushed to a lower category through mixing with material of that category, and so given a high enough value for category 1 and 2 material, there may be an incentive to downgrade category 3 material.

3.7.1. Use as a biodiesel feedstock

Animal fats can be transesterified to fatty acid methyl ester biodiesel like other vegetable oils. Animal fat based biodiesel has made a significant contribution to EU member state biofuel targets under the existing RED. It can also be hydrotreated to produce HVO.

3.7.2. Existing uses

Slightly over 2 million tonnes of category 1, 2 and 3 animal fats are produced in Europe every year. Chudziak & Haye (Chudziak & Haye, 2016) report that about 500-750 thousand tonnes is in categories 1 and 2 (Chudziak & Haye, 2016), but (Taylor, 2013) report a higher available quantity (1.2 million tonnes). Availability in Europe is unlikely to increase significantly to 2030.

Category 1 and 2 animal fats have a relatively limited set of potential uses. In addition to use as biodiesel feedstock, they can be used for process fuel at the rendering facility, or used for energy in heat and power more generally. Category 1 and 2 material can also be used in some 'technical' oleochemical applications, although there is a degree of inconsistency in the discursive literature on this point. Article 13 of the Animal By-Products Regulation[58] provides that both category 1 and 2 material may be "used for the manufacture of derived products referred to in Articles 33, 34 and 36 and placed on the market in accordance with those Articles." Article 33 in particular lists a number of oleochemical applications, including cosmetic and medical applications. These uses are somewhat restricted, however, by Commission Regulation (EU) 142/2011, which requires that fat derivatives from category 1 and 2 material may not be placed on the market if intended for use in feed, cosmetic or medicinal applications. In short, there is a significant practical limitation on the use of category 1 and 2 material for oleochemical applications under European law, but not an outright prohibition.

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[58] Regulation (EC) No 1069/2009 Of The European Parliament And Of The Council

There are also some minor exceptions to the prohibition on feeding category 2 material to animals, specifically for cases in which the consumer animals are unlikely to enter the human food chain:

(a) zoo animals;

(b) fur animals;

(c) dogs from recognised kennels or packs of hounds;

(d) dogs and cats in shelters;

(e) maggots and worms for fishing bait;

(f) circus animals.

These feed applications are likely to be too marginal to be pertinent to the questions considered in this report.

For 2014, the European Fat Processors and Renderers Association reported that in category 1 160 thousand tonnes was used for combustion and 350 thousand tonnes used for biodiesel production, while in category 2 40 thousand tonnes was used for biodiesel production and 7.5 thousand tonnes for oleochemicals applications.[59] Ecofys, quoting EFPRA figures, report that category 1 and 2 material constituted 2% of animal fats used for oleochemicals in Europe in 2014 (Chudziak & Haye, 2016).

Use of animal fats for fuel, either at the rendering plant or for power plants, is strongly influenced by the price achievable for animal fats on the market and the comparative price of energy alternatives (fuel oil, natural gas, coal). Chudziak & Haye (Chudziak & Haye, 2016) estimate that 200 thousand tonnes of category 1 & 2 animal fats are used annually for power by rendering plants. Utilisation in the power sector directly is considered low. This is a markedly different conclusion from Taylor (2013), which reports 850 thousand tonnes per year for heat and power in Europe.

Based on the data available, Table 31 provides a characterisation of the disposition of category 1 & 2 animal fats in Europe.

Table 31. Characterisation of typical annual disposition of European category 1 and 2 animal fats

	Biodiesel	Oleochemicals*	Heat and power for rendering	Total*
Category 1 & 2 animal fat use	400	7.5	200	607.5

** The utilisation estimates have been taken from Ecofys (Chudziak & Haye, 2016), with the added recognition of a low rate of use of category 2 material in oleochemicals.*

In addition to impacting existing uses of category 1 & 2 material, it is possible that an expanding biodiesel industry could impact users of category 3 material, for instance through reduced investment in segregation of potentially category 3 material. Table 32 shows current uses of category 3 material. The dominant uses are food and feed, and oleochemicals.

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[59] http://www.rendermagazine.com/articles/2015-issues/august-2015/european-production/

Table 32. Current uses of category 3 material (Chudziak & Haye, 2016)

Current disposition	Quantity, thousand tonnes
Biodiesel	320
Milk replacers	50
Food	190
Pet food	280
Fish food	10
Fur animal feed	10
Oleochemical	580
Other animal feed	600

Demand for animal fat based biodiesel could also see increased imports (indeed, substantial quantities have been imported since 2010 under the double counting incentive). Imported material will have a different alternative use profile than EU material. It may be that due to differences in handling rules, material that would have a general character of being high quality (category 3 in Europe) could acquire a category 1 or 2 characterisation on import. The animal by-product handling rules are quite conservative in this regard, and prior to 2011 it is our understanding that all imported material had been considered as category 1. The UK Government has handled the concern that imported biodiesel from high quality material would be double counted (against the spirit of the regulation) by requiring suppliers to report category based on the material characteristics at source, regardless of any possible recategorisation on import. Rules of that sort, if implemented, would ensure that biodiesel from feedstock with category 3 characteristics would not be 'downgraded'. Without such rules, the profile of alternatives for imported biodiesel from animal fat may have more in common with the alternatives for EU derived category 3 material than category 1 & 2 material.

3.7.3. Alternatives

For rendering plants energy, the obvious alternative to animal fat combustion is fuel oil, as these materials should be readily substitutable in existing equipment. Alternatives like natural gas would require more boiler investment, and may reduce flexibility to return to animal fat as fuel in future. Brander et al. (2009) give an average value for the carbon implications of displacing animal fat from bioheat based on the average carbon intensity of gas and fuel oil use – 3.15 tonne CO_2e per tonne animal fat. E4tech (Chudziak & Haye, 2016) include a scenario in which increased use of animal fat for biodiesel drives substitution with fossil fuel in the rendering sector, giving an emissions estimate of 3.0 to 3.7 tonnes of CO_2e per tonne animal fat[60].

In food and feed applications, relevant only for category 3 material, the situation is similar to the case of displacing DCO from animal feed (section 4.2.3). Vegetable oils would provide the closest substitutes, and with category 3 animal fats and palm oil having similar fatty acid profiles and prices palm oil would be one possibility. It may also be that a reduction in category 3 animal fat availability would lead to a shift in feeding patterns and increased reliance on grains for energy. E4tech (Chudziak & Haye, 2016) identify palm and rapeseed as the most likely substitute oils (along with palm fatty acids, which are

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[60] Note that there is a typographical error in the published report. We have confirmed with E4tech that the values quoted here are correct.

discounted from consideration in our analysis as they have rigid supply). Brander et al. (2009) identify a "Blend of vegetable oils and derivatives" as the likely substitute in the feed sector, and palm oil in the food sector. It seems reasonable to assume that the primary replacement in food and feed markets would be palm oil, the secondary replacement rapeseed oil. As with DCO, in the case of reduced availability there may also be a shift away from fatty feed supplements towards increased use of starchy energy feeds.

In the oleochemicals industry, there has been a shift over the last decade from using European animal fats to using palm oil as feedstock (Chudziak & Haye, 2016). Palm oil is a preferred alternative to animal fats for these applications, as it has properties relatively similar to animal fats, and is generally the cheapest available virgin vegetable oil. Brander et al. (Brander et al., 2009) identify palm oil as the likely substitute for oleochemical uses, and split it into two cases – substitution by palm oil in European manufacturing facilities, and displacement of production out of Europe to the Far East entirely. In the latter case, there may also be a more general change in the energy use and emissions characteristics of the process itself, beyond changes in carbon intensity associated with the feedstock material. There is a degree of consensus in the literature that palm oil represents the most likely substitute material for oleochemical applications in general, and is therefore a reasonable assumption as an oleochemical substitute for category 3 material. It is less clear how applicable this is to category 1 or 2 material, given that we have been unable to identify what the specific oleochemical applications are for those materials. In the absence of an alternative hypothesis, palm oil seems the most reasonable assumption though.

3.7.4. Prices

Animal fat prices are closely correlated to prices for vegetable oils. E4tech quote an example price hierarchy as 320 euros per tonne for category 1 and 2 animal fat, 360 euros per tonne for category 3 animal fats and 400 euros per tonne for palm oil (Chudziak & Haye, 2016). They also provide a characterisation of prices over time, as seen in Figure 17. While in general palm oil prices are higher than those for even category 3 animal fats, historical data show that this picture has not been uniform over time (Alberici & Toop, 2013; Chudziak & Haye, 2016; Ecofys, 2012). Prices vary over time and geographically – E4tech report a price of about 560 euro per tonne for category 1 & 2 animal fats (Taylor & Bauen, 2014).

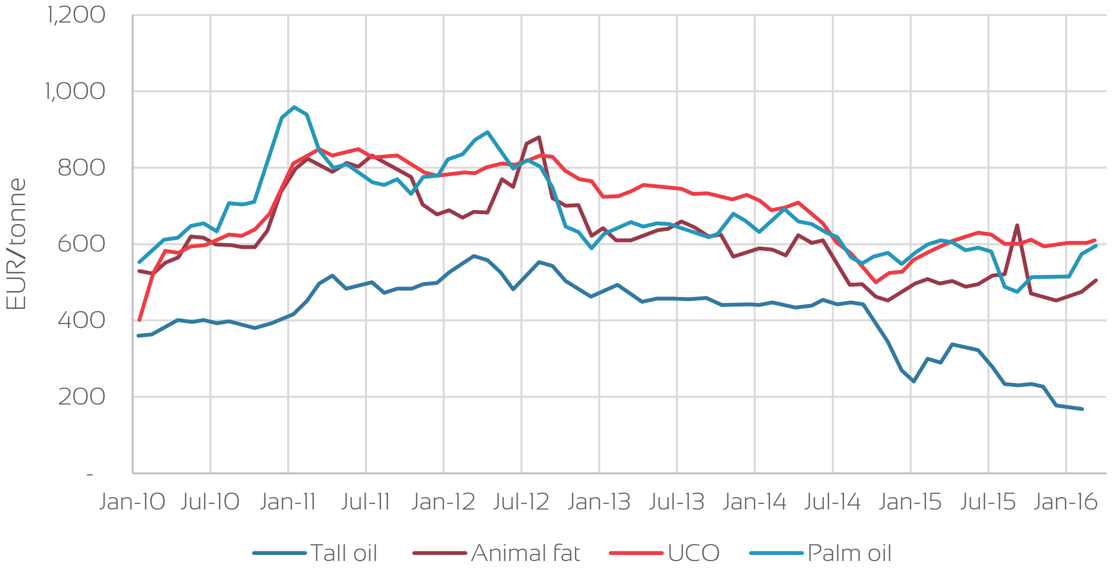

Figure 17. Animal fat prices compared to other oils and fats (Chudziak & Haye, 2016)

Under the current RED framework, biodiesel from animal fats is eligible, like biodiesel from used cooking oil, to be double counted for compliance with renewable energy targets in transport. This double counting has likely improved the relative price of category 1 and 2 animal fats compared to category 3. Nevertheless, a significant price differential has remained with category 3 animal fats commanding a higher value than other grades, and used cooking oil commanding a higher price than low grade animal fats (Alberici & Toop, 2013). This supports a conclusion that there continues to be more value available for non-energy applications of [downgraded] category 3 animal fats than for the use of category 3 animal fats for biodiesel production.

3.7.5. Displacement expectations

In the context of European animal fats, the primary displacement effect expected due to increased utilisation of category 1 & 2 material for biodiesel is a reduction in the use of that material for fuel applications at the rendering plant. This reflects the fact that oleochemical uses of category 1 & 2 material account for only very marginal volumes (Table 31), and the only other major use in Europe is existing biodiesel production. Fuel oil is the cheapest substitute fuel that could be readily used in existing infrastructure, and therefore it is assumed that 75% of replacement fuel would be fuel oil. With additional investment, renderers may also consider transitioning to natural gas, which we assume meets 25% of additional demand.

The secondary displacement effect within the European context would be increased classification as category 1 & 2 of material that has the potential to be placed in category 3. This could occur through reduced investment in material separation, reduced investment in supply chain segregation and in principle through active decisions to mix category 3 material with lower grade material in order to downgrade it. Anecdotal evidence of this practice has been reported by Hermann-Josef Keller of Emery

Oleochemicals, "In England, Cat 3 fats are added to Cat1 fats in order to increase the amounts for fats eligible for double counting" (Carus et al., 2014).

Palm oil is the cheapest primary oil, and the one with the most similar properties to animal fats. It is an established alternative material to animal fats in many oleochemical applications for Cat 3 material. It is therefore assumed that 75% of additional vegetable oil demand would be met by palm oil. Given that displacement will occur in the first instance within the EU, we also allow for a degree of replacement by EU-produced rapeseed oil. These assumptions are shown in Table 33.

Table 33. Expected displacement and substitutes

Displaced system	Substitute 1	Substitute 2	Substitute 3
Category 1 & 2 material for heat and power (80%)	Fuel oil (75%)	Natural gas (25%)	
Reduced classification as category 3 (20%)	Palm oil (75%)	Rapeseed oil (25%)	

3.7.6. Carbon intensity of displacement

Table 34. Summary of indirect emissions for animal fat-derived fuels

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from animal fats	0.96	8	10 (34)	0	58	-46	30 (54)
HVO from animal fats	0.97	8	10 (35)	0	60	-48	31 (56)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

The animal fat pathways are associated with large indirect emissions from increased fossil fuel use. These increases may be largely offset by the renewable rebound effect, however, for the case of animal fats sources from EU production. There is also a significant land use change term, especially when using values from GLOBIOM.

4. Review of results

Table 35. Tabulated indirect emissions outcomes (gCO2e/MJ)

	No ILUC				RED II				GLOBIOM			
Feedstocks:	Materials only	Materials and forest carbon	Materials, forest carbon and fossil fuel	All	Materials and LUC	Materials, LUC and forest carbon	Materials, LUC, forest carbon and fossil fuel	All	Materials and LUC	Materials, LUC and forest carbon	Materials, LUC, forest carbon and fossil fuel	All
Animal fats derived FAME	8	8	66	20	18	18	76	30	42	42	100	54
Tall oil derived HVO	7	10	52	40	11	15	57	45	20	24	66	54
Tall oil pitch derived HVO	0	0	93	15	0	0	93	15	0	0	93	15
Glycerine derived methanol	19	19	28	20	28	28	37	28	41	41	50	42
Sawdust and cutter shavings derived FT diesel	15	62	93	67	15	62	93	67	15	62	93	67
Black liquor derived FT diesel	6	24	50	25	6	24	50	25	6	24	50	25
Distillers corn oil derived FAME	30	30	30	30	74	74	74	74	141	141	141	141
PFAD derived HVO	39	39	47	47	84	84	92	92	213	213	221	221

Where the sum of indirect emissions is over 50 gCO_2e/MJ, cells are shaded red. Where emissions are between 20-50 gCO_2e/MJ, the cells are shaded yellow.

Results in this table use our central scenario for carbon intensity of additional fuelwood harvest (see section 3.5)

The indirect emissions estimates calculated in this report are summarised in Table 35, showing only one fuel pathway for each feedstock. The cases where the estimated indirect emissions are higher than 50 gCO_2e/MJ are highlighted in pink, while cases with indirect emissions between 20-50 gCO_2e/MJ are highlighted yellow. It is quickly apparent that all of the feedstocks considered can be associated with significant indirect emissions for some combinations of assumptions and system boundaries. For the ILUC estimates from GLOBIOM, if one excludes the renewable rebound effect all pathways shown have indirect emissions of 50 gCO_2e/MJ or greater.

This reiterates the conclusion reached in many previous studies (e.g. Brander et al., 2009; Chudziak & Haye, 2016; ICF International, 2015; Searle et al., 2017; Taylor, 2013) that indirect emissions from using by-product and residual materials are likely to be significant in many cases, and should not be ignored when setting renewable fuels policy. For the case of PFADs and distillers' corn oil, the strong links expected to virgin vegetable oil markets mean that these feedstocks inherit directly the sustainability problems of virgin vegetable oils as biodiesel feedstocks. In general, policy makers should be extremely cautious about legislating to encourage fatty and oily materials to be processed into biofuel, as removing these types of material from existing productive uses could easily raise the same sustainability concerns as incentivising production of first generation food based biodiesel.

When reading the results presented in this paper, it is very important that the reader should understand that the numbers presented here represent very different system boundaries than are reflected in the default carbon intensity values in the RED (and proposed RED II), and in other attributional lifecycle analyses. Lifecycle analysis is governed by conventions, and challenging those conventions can result in quite different answers. For instance, in this study we have considered the indirect emissions implication of shifting a resource from an existing energy recovery application to a biofuel application. In conventional regulatory LCA, it is normative that we assume that moving a renewable energy resource from one country or sector to another represents a 'gain'. For instance, it is normal to report a carbon saving in Europe when sugarcane ethanol is imported from Brazil and used – regulatory LCA does not consider whether that ethanol would otherwise have been used in Brazil. By convention, the EU would report an additional emissions saving, even if that saving is only achieved by an increase of emissions from fossil fuels in Brazil. This convention stems in part from the use of national emissions inventories under climate change treaties, and partly from the need to set metrics that create an incentive to support renewables. By assessing displacement emissions in this report, we do not mean to say that these conventions of lifecycle accounting are wrong – but we do hope to draw attention to the fact that they can mask overall system dynamics.

The indirect emissions listed in this report as fossil fuel use represent the opportunity cost of moving a resource from one use to another. We have ascribed indirect fossil fuel use emissions to biofuel pathways. One could equally calculate the reverse version of this opportunity cost (the opportunity cost of preventing a resource being used for biofuel) and assign it to the existing use. In this case, one could produce numbers suggesting that neither the existing use nor the biofuel use has climate benefits (cf. Brander et al., 2009). Clearly, it would be wrong to conclude that biomass resources should not be used in either sector. On the other hand, it is appropriate to ask what the net benefit is to the use of public policy to move a resource from one use or sector to another. Where fossil fuel emissions are high in this report, it is an indication that there may be little net climate benefit to shifting resources from existing energy recovery use.

This said, EU renewable fuel policy clearly places a premium on emissions reductions in the transport sector, and thus EU policy makers may decide that it is appropriate to use policy to take a resource from heat and power uses and shift it to transport uses. In this report, the renewable rebound term represents the fact that the EU policy framework is structured in such a way that if renewable energy generation is reduced in one place, it must be increased elsewhere to compensate. For example, black liquor combustion is a major renewable energy source at the moment – but if that black liquor were gasified for biofuel production, additional renewable heat and power capacity would be needed to meet targets. Where we have reported a large renewable rebound term, this reflects an expectation that shifting some biomass resources into transport will mean that new renewable energy capacity must be added elsewhere.

Policy mediated effects of this sort are not usually included in lifecycle analysis, even in consequential lifecycle analysis, and one should be cautious in interpreting these results. We believe though that it is important to recognise that some of the 'opportunity cost' problems mentioned above may be remediated through existing policy regimes.

The results presented in this report for biofuel pathways with different yields highlight the importance of efficient biofuel conversion in reducing the magnitude of indirect emissions effects. It is conventional for materials treated as wastes and residues to be ascribed zero feedstock production emissions. This means that it is possible in principle to report a very low carbon intensity even for a very inefficient biofuel production process, so long as the conversion energy used comes from low carbon sources (or emissions are offset by co-product or electricity export credits etc.). However, when the feedstock is associated with indirect emissions, these emissions double if the biofuel yield is halved, and so on, and thus indirect emissions are very sensitive to fuel production efficiency. It should therefore be remembered that the fuel pathway emissions intensity values given in this reprot are based on typical yields, and should ideally be recalculated usinf facility specific yield data for actual biofule projects. In this report, processes assumed to have a better energy conversion efficiency have much lower indirect emissions in gCO_2e/MJ. The business advantages of more efficient production are obvious, the results in this report provide a useful reminder that the environmental advantages may be large as well, but could sometimes be masked by methodological LCA choices.

By presenting results in this report in units of gCO_2e/MJ, we are effectively inviting readers to add our indirect emissions results to direct emissions results such as those provided in the proposed RED II. Doing so introduces a degree of methodological inconsistency, but can nevertheless be a useful exercise when trying to understand the overall climate impacts of given biofuel production technologies. We would warn again though that great caution should be exercised in interpreting the results of such a calculation. Where a direct LCA shows that a biofuel delivers no carbon saving, this strongly suggests that there is no environmental advantage in producing that biofuel. In contrast, if adding our value for indirect fossil fuel emissions to an attributional value for direct emissions results in a carbon intensity above that of a comparison fossil fuel, it means only that the biofuel use of that feedstock has no greater environmental value than its existing energetic use. These conclusions are similar, but they are not the same. In particular, we would urge great caution in applying emissions saving thresholds to values taken from this report, where the thresholds were originally conceived for application to direct emissions estimates.

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Annex A. Description of feedstock indirect emissions analysis

In this annex, we detail the assumptions made at each step of our indirect emissions analysis. The explanations behind the assumptions are generally detailed in the main text, although some explanatory notes have been included below for ease of reference.

The emissions associated with additional demand for replacement materials are split into four categories. Materials production emissions are the emissions associated with producing an additional supply of materials with elastic supply. This includes lifecycle stages such as cultivation, transport and processing. The exception is fossil fuels, where we have grouped all lifecycle stage emissions, including extraction, processing and combustion, into the fossil fuel use category. The land use emissions category includes estimated indirect land use change emissions, and we have considered two sets of estimates – one based on the values in Annex IX of the RED II proposal (European Commission, 2016b), one based on modelling for the European Commission with GLOBIOM (Biggs et al., 2016; Valin et al., 2015). Finally, there is a 'renewable rebound' category. This category recognises that displacing renewable materials out of energy recovery in heat and power creates a need for additional renewable energy to meet EU renewable energy targets. The same emissions credit is applied for all cases in which fossil fuel use for heat and power is expected to replace biomass in the EU. We assume that the 2030 marginal renewable energy mix will be split 50:50 between biomass energy and other zero-carbon renewables (wind, solar, geothermal). The average emissions reduction associated with biomass energy is taken to be 66 gCO_2e/MJ[61]. The marginal power source displaced by additional zero carbon electricity generation is taken to be efficient natural gas power, with a greenhouse gas intensity of 111 gCO_2e/MJ. It is assumed that the average energy efficiency (LHV) of energy generation from displaced biomass resources would be 50%. This gives a renewable rebound credit of 44 gCO_2e/MJ of energy (LHV) in the displaced biomass.

Where emissions intensities are quoted in source documents in units other than per tonne of material, they have been adjusted appropriately. For instance, the ILUC emissions estimates from RED II and GLOBIOM have been adjusted from values per megajoule of biofuel supplied to values per megajoule of feedstock material.

The main results shown below use ILUC emissions from RED II unless otherwise indicated.

Note that in all cases this analysis only considers the indirect emissions due to displacement. 'Direct' emissions from production and processing of feedstock and biofuels must be considered separately.

A.1. Palm fatty acid distillate (PFAD)

Step 1. Material definition and biofuel yields

PFADs are the fatty acid fraction removed from palm oil during the refining process. They can be trans-esterified into FAME, or hydrotreated to HVO. Based on comparative yield results for FAME production

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[61] Authors calculation of average emissions intensity reduction delivered by biomass energy scenarios documented in Matthews et al., (2015)which was stated as \u201cto quantify the global emissions of prominent GHGs (CO2, CH4 and N2O

from PFAD and CPO (Laosiripojana, Kiatkittipong, Sutthisripok, & Assabumrungrat, 2010), we assume that FAME yields from PFAD are 95% of FAME yields from palm oil (BioGrace, 2017), 0.95 tonne per tonne feedstock. For HVO, we take a yield of 0.97 tonnes per tonne, as for palm oil (BioGrace, 2017).

Step 2. Potential demand from RED II

Global PFAD production is estimated at 2.5 million tonnes. This is less than global vegetable oil hydrotreating capacity. Given strong incentives (i.e. if included in Annex IX part A of RED II), the biofuel industry could likely absorb the majority of this material, although supply chain limitations may prevent full utilisation.

Step 3. Existing uses

PFAD is currently utilised in manufacture of oleochemicals and soaps, in livestock feeds (in particular as rumen protected fats) and as boiler fuel.

In soaps, oleochemicals and rumen protected animal feed, the most similar alternative feedstock material is likely to be palm oil in many cases. Shifting to palm oil would represent a feedstock cost increase of 10-20%, but we are not able to clearly identify any difference in capacity of these different sectors to absorb a price increase in PFAD.

The combustion of PFAD as boiler fuel is perceived by the industry as an undesirable (low value) use, and thus may in principle be expected to be more sensitive to changes in demand from other sectors. On the other hand, where PFAD is currently being used for energy recovery at the palm mill, this may reflect a lack of access to markets or other structural barriers to alternative disposition, and so the resource currently subject to energy recovery may not be readily available to biofuel producers.

We were not able to identify statistics providing an indication of relative rates of utilisation of PFADs in each use sector. Endicott Biofuels and Sabine Biofuels (2013) argued that reduced PFAD availability in the US would result entirely in displacement from the feed market.

Step 4. Potential substitutes

In soaps and oleochemicals, given the relatively similar chemical composition (in terms of length of carbon chains) and availability in the regions currently utilising PFADs, palm oil is expected to be the primary replacement material. There may also be some degree of replacement by other oils such as rapeseed and soy, but this is considered likely to be a relatively minor contribution, not least because these oils have persistently higher prices than palm oil (Malins, 2013). It seems reasonable to assume that the substitution ratio in these uses will be approximately one to one, and one for one replacement is assumed in our analysis regardless of the substitute oil.

In animal feed, palm oil and soy oil have been identified as potential alternative bases for rumen protected calcium salt production. As palm oil has a more similar fatty acid composition to PFAD than soy does, we assume that palm will be the primary replacement material. In the absence of available data on relative market size, we assume that reduced supply of PFAD will have result in three times more additional palm oil demand than additional soy oil demand. As in the soap and oleochemicals markets, we assume one to one displacement of PFAD by alternative oils. Given the specific acknowledged role of rumen protected fats in ruminant diets, we discount the possibility that PFAD based animal feed would be replaced by starchy feeds. This question warrants further investigation in future studies, however.

In the case of PFAD use as boiler fuel, we presume that the replacement material would be fuel oil, as a low cost alternative fuel that could be combusted in the same facilities as PFAD. We assume that the substitution ratio would run with lower heating value.

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle et al., 2017).

Step 6. Displacement assumptions

In the absence of clear data about rates of utilisation or willingness to pay for PFAD in oleochemicals and soaps vs. animal feed, we assume that displacement will be equal from the two systems. We also assume a lower rate of displacement from use as boiler fuel. Our final displacement assumptions are shown in Table A.

Table A. Assumed fractional displacement of other dispositions by increased biofuel demand for PFAD

Displaced system	Assumed displacement fraction
Remove from oleochemicals and soaps market	45%
Remove from feed market	45%
Reduced energy recovery	10%

Table B shows our assumptions about the materials that are likely to replace PFAD in these uses.

Table B. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of PFAD)	Resulting assumed change in material demand (tonne per tonne of PFAD used for biofuel)*
Remove from feed market	Palm oil	80%	1.00	0.32
	Soy oil	20%	1.00	0.08
Remove from oleochemicals	Palm oil	80%	1.00	0.32
	Soy oil	10%	1.00	0.04
	Rapeseed oil	10%	1.00	0.04
Boiler fuel	Fuel oil (RoW)	100%	0.9	0.08

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change.*

Step 7. Greenhouse gas intensity of replacement systems

The greenhouse gas emissions intensities of vegetable oils production and of fuel oil use are taken from Biograce (2017).

Table C. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stocks	Fossil fuel use	Renewable rebound
Rumen protected livestock feed	Palm oil	1,781	2,022	8,492			
	Soy oil	1,496	2,022	5,514			
Oleochemicals and soaps production	Palm oil	1,781	2,022	8,492			
	Soy oil	1,496	2,022	5,514			
	Rapeseed oil	1,297	2,022	2,390			
Boiler fuel	Fuel oil (RoW)					3442	-1798

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of PFAD used as biofuel feedstock are shown in Figure 17.

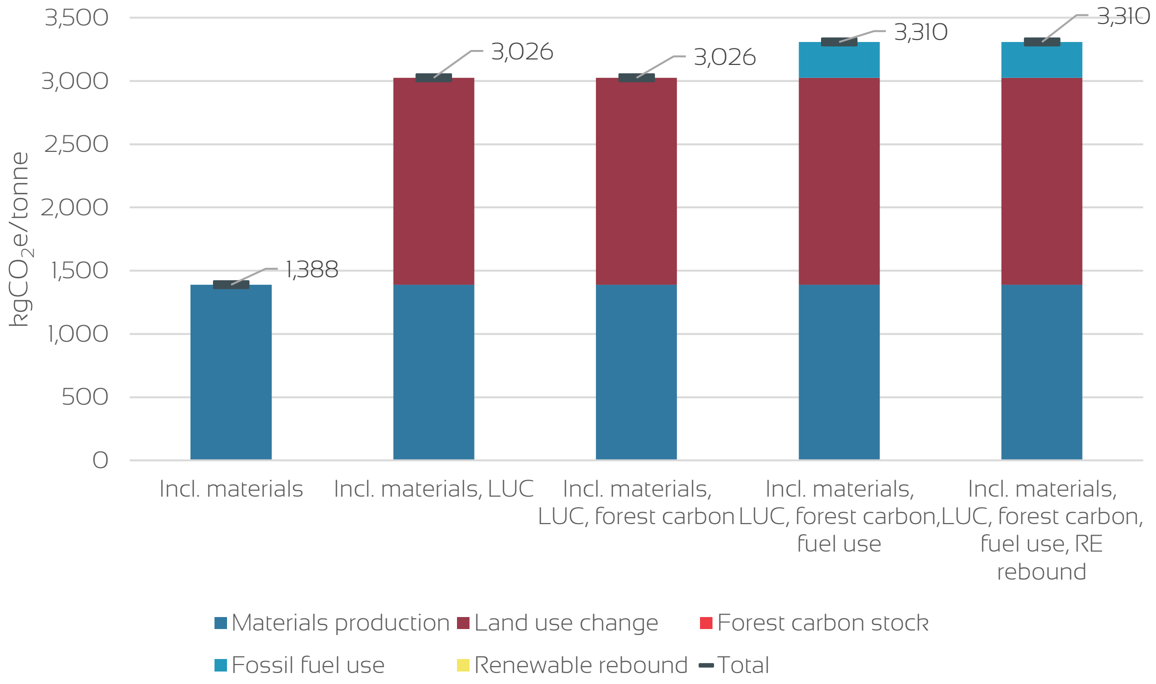

Figure A. Estimated indirect emissions associated with increased demand for PFAD, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure B.

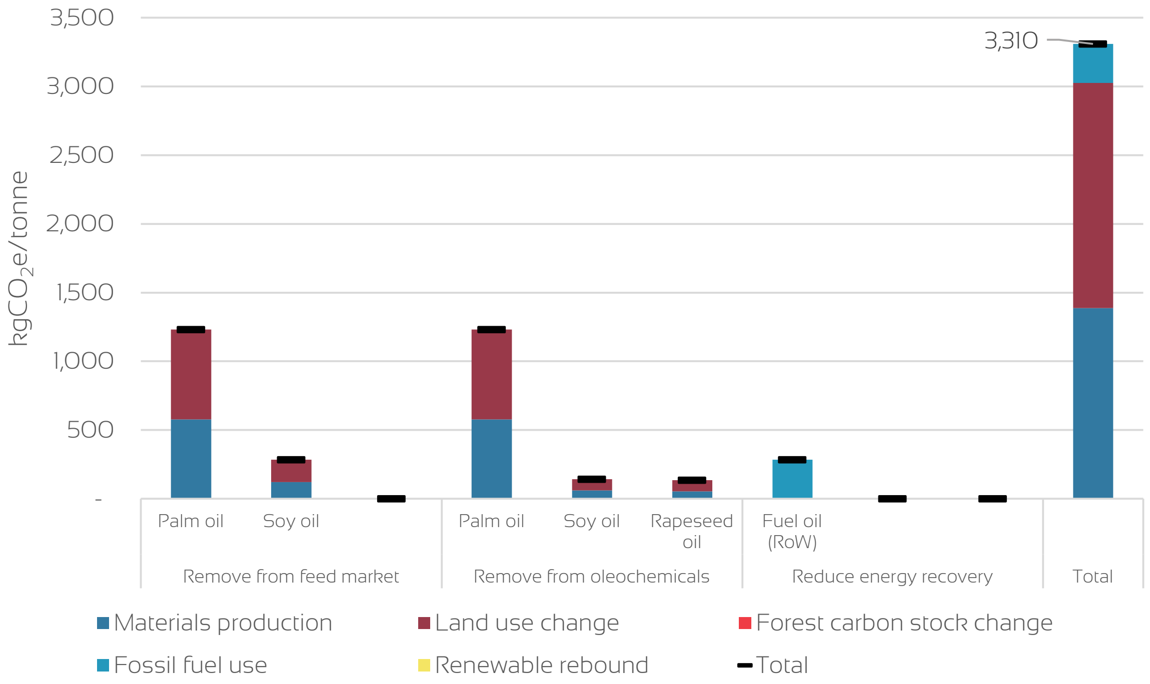

Figure B. Contribution of substitute materials to the indirect emissions profile of PFAD

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for PFAD derived fuels are shown in Table D. The emissions for the HVO pathway are illustrated in Figure C.

Table D. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from PFAD	0.94	38	45 (171)	0	8	0	90 (217)
HVO from PFAD	0.97	39	46 (175)	0	8	0	92 (221)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

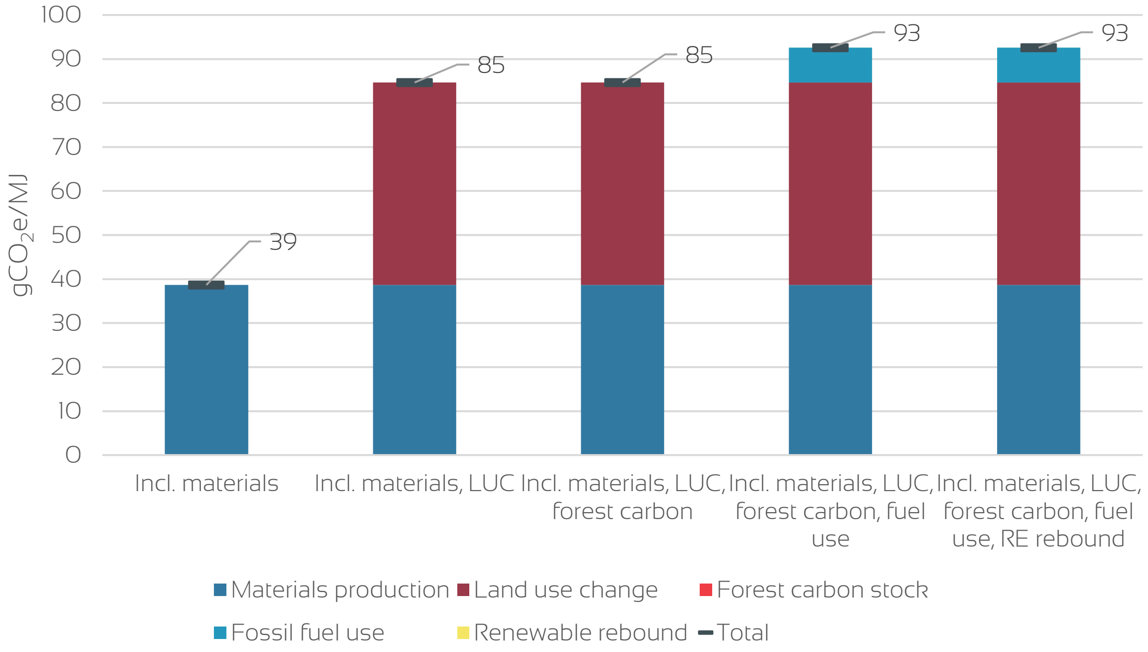

Figure C. Estimated indirect emissions from PFAD-derived HVO

A.2. Distillers' corn oil (DCO)

Step 1. Material definition and biofuel yields

Distillers' corn oil is oil extracted from distillers' grains and solubles produced as a co-product of ethanol refining. DCO can be used as feedstock for either FAME or HVO production. In the U.S., 95% of the corn ethanol industry has now implemented corn oil extraction from DGS (Riley, 2016). The statistics for Europe are less clear, but certainly there is much less potential to increase DCO extraction rates than to use existing DCO supplies.

The FAME yield from DCO is assumed to be the same as for other vegetable oil feedstocks, one tonne of fuel per tonne oil. The HVO yield is also assumed to be the same as for other vegetable oil feedstocks, 0.82 tonnes of fuel per tonne of oil.

Step 2. Potential demand from RED II

European maize ethanol production was estimated at 3.1 billion litres in 2014 (ePure, 2014). Presuming all of this was dry milled (i.e. resulted in production of distillers' grains) then the annual potential corn oil supply in Europe would be about 85,000 tonnes.[62] This could readily be absorbed by biofuel demand under the RED II. This is much lower than U.S. DCO production, estimated at about 3 million tonnes for

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[62] Given a potential corn oil yield of 0.028 kg per litre of ethanol production (California Air Resources Board, 2014).

2016/17 (Integrated Policy Group, 2014). In principle, 3 million tonnes of feedstock could be absorbed by EU demand (if DCO was included in Annex IX part A of the RED II) but in practice there would be considerable competition from the U.S. biofuel market, where DCO based biodiesel has a strong value proposition under the RFS and California LCFS.

Step 3. Existing uses

Currently, DCO is used more or less entirely for biodiesel production (largely in the U.S.) and for livestock feed. For this report, we do not consider transfer of biofuel between markets as a displacement option, and therefore the only source we consider is the livestock feed market. Supply of corn oil in the EU is modest, and could reduce if production of maize ethanol is reduced due to either the reduced incentives for food-based ethanol under RED II, or to competition with cellulosic ethanol under the blend wall. The U.S. therefore represents by far the most significant source of potential DCO supply.

Step 4. Potential substitutes

DCO is used primarily in swine and poultry rations to deliver supplementary energy, complementing cereal feeds. This dietary function could equally be filled by other fatty feed materials, in particular vegetable oils or animal fats. One potential substitute for corn oil in animal feed rations would be soy oil, which has a similar fatty acid profile and nutritional profile to DCO, especially if the DCO has been refined to reduce free fatty acid content. In the U.S, soy oil seems to be by far the most likely substitute for DCO in animal feed, but in Europe there is less evidence from the literature, though we understand that soy oil is widely used in the UK[63]. It is possible that in addition to soy oil, vegetable oils that are produced in Europe in higher volumes (such as rapeseed or sunflower oil) may also be potential substitutes. Of these, sunflower oil has the more similar fatty acid composition.

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Step 6. Displacement assumptions

It is assumed that all DCO used for biofuel production would otherwise have been used as animal feed, either as extracted oil or as a constituent of DGS. We do not assess the net emissions implications of displacing biodiesel from the U.S. market to the EU market. Animal feed is therefore the only displaced system, as shown in Table E

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[63] Private communication with Premier Nutrition.

Table E. Assumed fractional displacement of other dispositions by increased biofuel demand for Distillers' corn oil (DCO)

Displaced system	Assumed displacement fraction
Animal feed	100%

It is assumed that DCO would largely be replaced by increased use of alternative fatty materials with similar properties – soy oil and sunflower oil. Soy oil is documented as being a comparable feed material to DCO, and in the U.S. (where most of the potential DCO supply is located) seems to be the dominant likely replacement. We therefore assume that soy oil replaces the majority of DCO. We then allow for equal quantities of replacement by sunflower oil[64] (as an alternative fatty replacement) and feed wheat (reflecting the case in which dietary patterns shift if fatty feed components become more expensive). Table F shows our modelling assumptions about fractional replacement rates for DCO. Substitution ratios are based on metabolisable energy in growing swine (Norwood, 2012).

Table F. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of Distillers' corn oil (DCO))	Resulting assumed change in material demand (tonne per tonne of DCO used for biofuel)*
Animal feed	Soy oil	80%	1	0.72
	Sunflower oil	10%	1	0.09
	Feed wheat	10%	2.5	0.23

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change.*

Step 7. Greenhouse gas intensity of replacement systems

The greenhouse gas intensities of vegetable oil and feed wheat production have been taken from Biograce (2017).

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[64] We take sunflower oil as the second most likely replacement, because its properties are more similar to DCO than those of rapeseed oil are. The greenhouse gas implications of rapeseed and sunflower oil demand increase are similar.

Table G. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stocks	Fossil fuel use	Renewable rebound
Remove from feed market	Soy oil	1496	2022	5514			
	Sunflower oil	29	2022	2022			
	Feed wheat	359	166	470			

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of DCO used as biofuel feedstock are shown in Figure D.

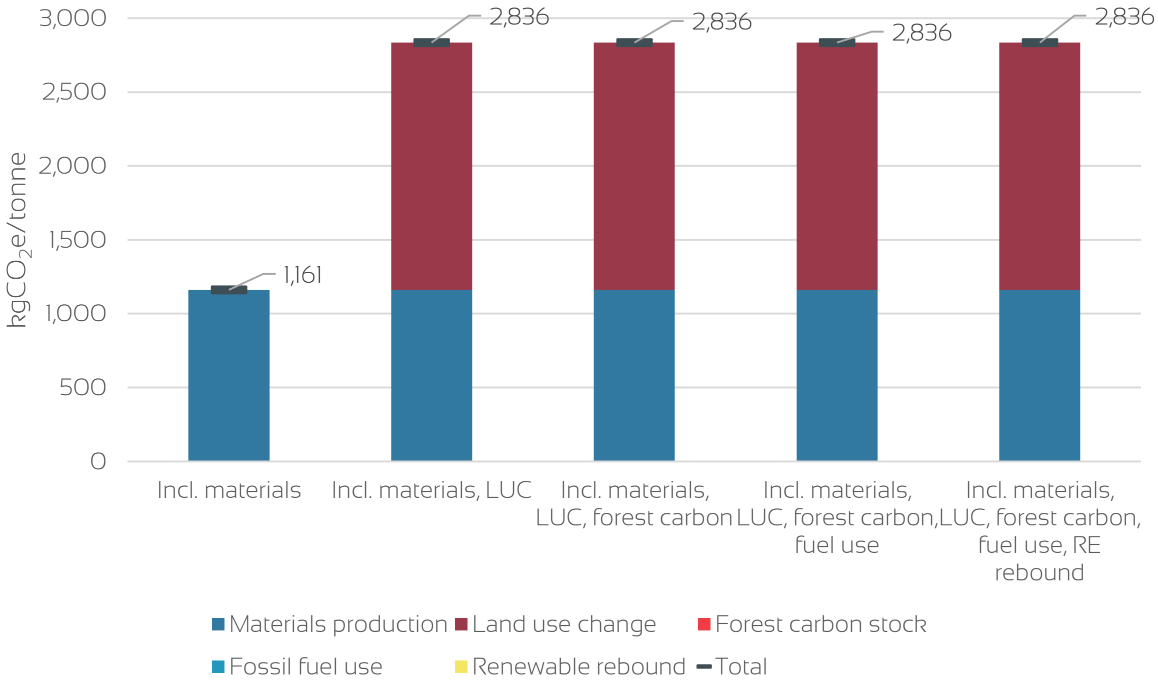

Figure D. Estimated indirect emissions associated with increased demand for DCO, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure E.

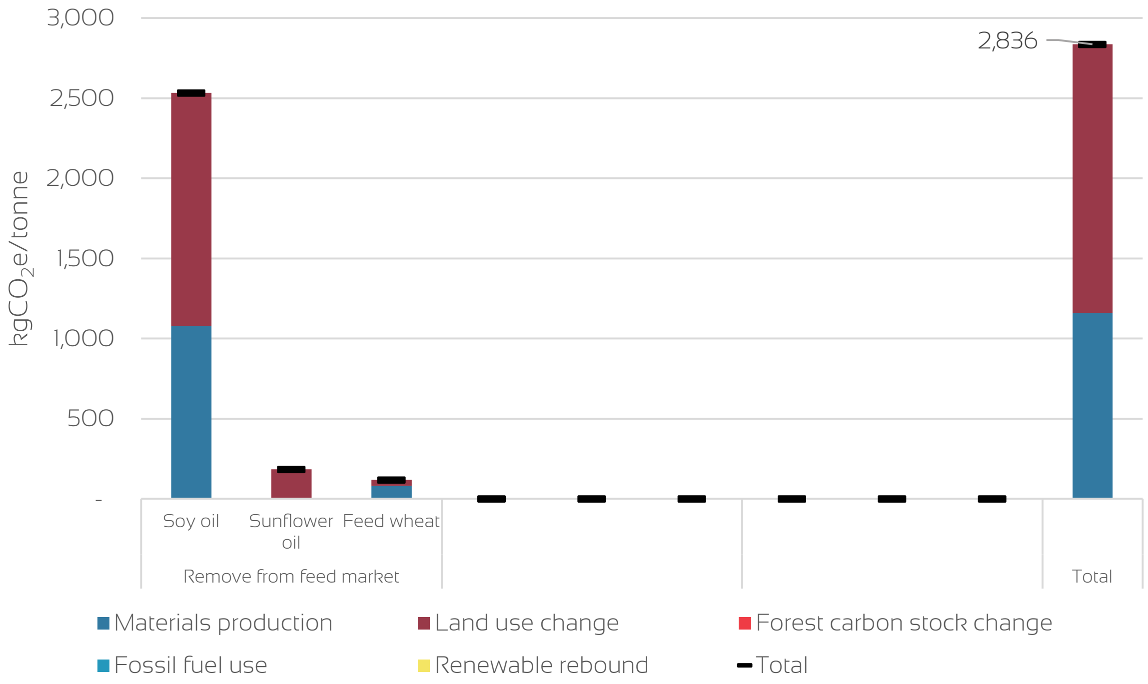

Figure E. Contribution of substitute materials to the indirect emissions profile of DCO

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for DCO derived fuels are shown in Table H. The emissions for the FAME pathway are illustrated in Figure F.

Table H. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from Distillers corn oil	0.99	30	43 (110)	0	0	0	74 (141)
HVO from Distillers corn oil	0.97	32	47 (119)	0	0	0	79 (151)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

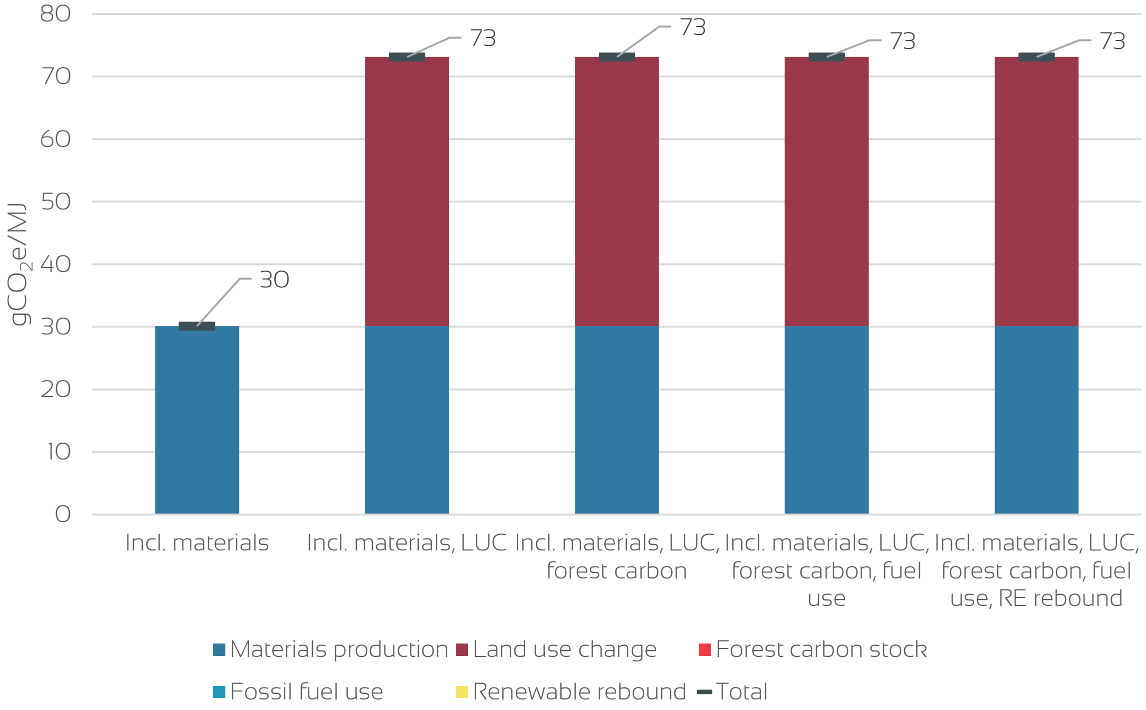

Figure F. Estimated indirect emissions from DCO-derived FAME

A.3. Crude tall oil (CTO)

Step 1. Material definition and biofuel yields

Crude tall oil is the material produced by the acidulation of crude sulphite soap, which is a residue of the kraft pulping process. Crude tall oil (CTO) is distinct from 'distilled tall oi' (DTO), which is one fractional output from the crude tall oil distillation process. Crude tall oil is distinguished by its composition, notably its rosin and fatty acid content. A tall oil with high rosin and fatty acid content (generally resulting from pulping of a higher fraction of soft wood) has more value to the CTO refining industry. Biofuel production from CTO may also be somewhat sensitive to the composition of the tall oil, but is likely to be able to utilise CTO that may have limited value to distillers.

The primary biofuel production processes proposed (and implemented) for CTO involve hydrodeoxygenation by hydrogen addition to produce hydrocarbon molecules. The added hydrogen is likely at the current time to be derived from fossil natural gas. We are aware of two variants of this hydrotreating process. The first (Monnier et al., 1998) requires initial depitching of the tall oil. The second (Knuuttila et al., 2012) uses more or less the whole tall oil stream[65].

For the former process, we take a yield of 0.81 tonnes synthetic diesel for every tonne of depitched

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[65] We understand that even in this latter case some removal of heavy end pitch may be implemented before processing.

crude tall oil (Cashman et al., 2013). For the latter process. For the second process, we were not able to obtain yield data. We therefore consider only the former process in our analysis. We note that in reality neither process will deliver a stream consisting entirely of diesel grade molecules, and that the diesel output is likely to be accompanied by renewable naphtha, and potentially other niche streams. Naphtha could be used as petrol blendstock, or as a chemical intermediate. Here we treat the process as if it delivered only synthetic diesel, as a simplification. In a more detailed LCA, it would be possible to consider the full range of co-products and apply allocation or system expansion rules.

Step 2. Potential demand from RED II

Current demand for CTO for hydrotreating and fuel production is estimated at 230,000 tonnes per year (Peters & Stojcheva, 2017). This is largely driven by two facilities, operated by SunPine in Piteå and UPM in Lappeenranta, each with a production capacity of about 100,000 tonnes of renewable fuel per annum. It is unlikely that any additional commercial scale facilities would be smaller than these, as the economics of production rely on harvesting economies of scale. Potential renewable fuel demand under the RED II is much larger than global CTO production, so given a strong enough value proposition it is conceivable that most CTO could be diverted to fuel production. In practice, it seems unlikely that the biofuels industry would be able to support the feedstock prices necessary to systematically outbid the CTO distilling industry. A total of four CTO hydrotreating facilities of around this would support demand for about 500,000 tonnes of CTO for biofuel.

Step 3. Existing uses

The CTO refining industry uses about 1.4 million tonnes of CTO per year (Peters & Stojcheva, 2017). Demand for distilling is focused on 'higher quality' CTO, i.e. material with a relatively high rosin and fatty acid content, delivered from pulping primarily softwood trees. Some European CTO does not have the correct properties for distilling, and therefore the European distilling industry imports higher quality CTO from the US for blending in order to achieve the desired average properties. Displacement from CTO distilling could occur both inside and outside of the EU.

A smaller fraction of CTO (perhaps only 120,000 tonnes per year, Peters & Stojcheva, 2017) is used in oil drilling applications and for energy recovery. The material used directly for energy recovery is likely to be dominantly of a lower quality, and thus of lower value to distilling. The drilling industry emphasises the fatty acid content of tall oil (Georgia-Pacific Chemicals, 2017; Schlumberger, 2017), but it is unclear to us how sensitive these applications are to CTO quality.

Step 4. Potential substitutes

Increased acidulation of CSS would result in less energy recovered, and this energy would generally need to be replaced. As almost all CSS in Europe is acidulated, this energy replacement would happen elsewhere, in particular the United States and potentially Russia. Any shifts in fuel use would therefore be outside the purview of the Renewable Energy Directive. Additional energy could be supplied through fossil fuel combustion (fuel oil or natural gas) or potentially through increased combustion of biomass materials. We assume that 44% of replacement energy comes from natural gas, 32% from alternative biomass sources, and 24% from coal, based on (Kramer et al., 2009).

There is also potential for reductions in energy recovery from CTO itself. This could occur in Europe, but it could potentially also occur in the U.S. and Russia etc. Here, we consider only reductions in CTO combustion occurring in the EU. Again, this energy would need to be substituted. CTO combustion is likely largely carried out in the lime kiln. Globally, most lime kiln fuel is either natural gas or fuel oil, with some use of tall oil pitch and other waste, residual or by-product materials (Francey et al., 2016).

Reduced tall oil refining would result in reduced supply of tall oil derivatives. Table 11 shows expected substitute materials for tall oil derivatives, and the fraction of total tall oil derivative supply expected to be substituted by each. These substitution fractions are based on combining data from Cashman, Moran, & Gaglione (Cashman et al., 2016) and Rajendran et al. (2016).

Table I. Estimated substitutes for one tonne of CTO derivatives

Replacement material	Amount of replacement material required (kg)
Alkenyl succinic anhydride (ASA)	12.1
Gum rosin	5.2
Gum rosin ester	11.6
C5 hydrocarbon resins	9.0
Acrylic resin	13.5
Soy oil	48.7

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Step 6. Displacement assumptions

For a moderate increase in the size of the CTO to biofuel industry (adding a further two commercial facilities, and raising CTO demand to up to 500 thousand tonnes per year), it is considered likely that the primary response to additional demand would be a reduction of the use of CSS and CTO for energy recovery. This reflects the fact that these energetic uses have rather lower value than refining uses, and that the refining industry ought to be relatively insensitive to prices changes. It is consistent with the observation that the existing level of CTO demand for biofuel seems to have had limited impact on the refining industry to date. We assume that the replacement fuels will be fuel oil and natural gas in equal measure.

While energy recovery is expected to be the primary response, given the dominance of the CTO refining market as a user of CTO (about three quarters of global disposition) it seems unlikely that a significant growth in biofuel supply could be achieved without some impact on the refining industry. We therefore assume that a fraction (20%) of material used for biofuel would result in reduced refining. We assume substitute materials based on current disposition of tall oil derivatives and alternate materials identified by Cashman, Moran, & Gaglione (Cashman et al., 2016) and Rajendran et al. (2016).

Note that the total amount of material that could be displaced out of energy recovery uses is limited, and therefore a larger market development for CTO biofuel may be expected to impact more strongly on the refining industry. Further biofuel expansion beyond 500 thousand tonnes of demand would therefore be expected to have a rather different displacement profile.

Table J shows our assumptions about displaced systems.

Table J. Assumed fractional displacement of other dispositions by increased biofuel demand for Crude tall oil (CTO)

Displaced system	Assumed displacement fraction
Additional CSS acidulation	60%
Reduced energy recovery from CTO	20%
Reduced CTO refining	20%

Table K shows our assumptions about the materials that are likely to replace CTO in these uses. Based on the assumption that increased acidulation will occur primarily in the U.S. (as the primary current source of CTO exports to Europe) alternative fuel assumptions are based on Kramer et al. (2009). We assume that the thermal efficiency of the recovery boiler is comparable to that of other boilers (Vakkilainen & Ahtila, 2011).

Table K. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of CTO)	Resulting assumed change in material demand (tonne per tonne of CTO used for biofuel)*
Additional CSS acidulation	Natural gas (for CSS) (RoW)	44%	0.69	0.16
	Substitute bio-mass fuel (for CSS)	32%	1.79	0.31
	Coal (for CSS) (RoW)	24%	1.28	0.17
Reduced energy recovery from CTO	Fuel oil (EU)	50%	0.90	0.08
	Natural gas (EU)	50%	0.73	0.07
Reduced CTO refining	Alkenyl succinic anhydride (ASA)	8%	1.0	0.01
	Gum rosin	4%	1.0	0.01
	Gum rosin ester	6%	1.0	0.01
	C5 hydrocarbon resins	8%	1.0	0.01
	Acrylic resin	9%	1.0	0.02
	Soy oil	33%	1.0	0.06
	Fuel oil	32%	0.90	0.05

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change.*

Step 7. Greenhouse gas intensity of replacement systems

Greenhouse gas emissions intensity for soy oil, fuel oil and natural gas are taken from Biograce (2017). Greenhouse gas emissions data for CTO distillate replacements are taken from Cashman et al. (Cashman et al., 2016). In the case of reduced CTO distillation, there is not only a change of materials but a change of process, as distillation is no longer required. Emissions reflect the net change once emissions associated with CTO distillation are subtracted (Cashman et al., 2016).

Table L. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stocks	Fossil fuel use	Renewable rebound
Increased CSS acidulation	Natural gas (for CSS) (RoW)					3380	
	Substitute biomass fuel (for CSS)	141			444		
	Coal (for CSS) (RoW)					2716	
Reduce energy recovery	Fuel oil (EU)					3442	-2589
	Natural gas (EU)					3380	-3197
Reduce CTO refining	Alkenyl succinic anhydride (ASA)	2167					
	Gum rosin	461					
	Gum rosin ester	1934					
	C5 hydrocarbon resins	482					
	Acrylic resin	2628					
	Soy oil	308	2022	5514			
	Fuel oil (EU)					2194	-1798

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of CTO used as biofuel feedstock are shown in Figure G.

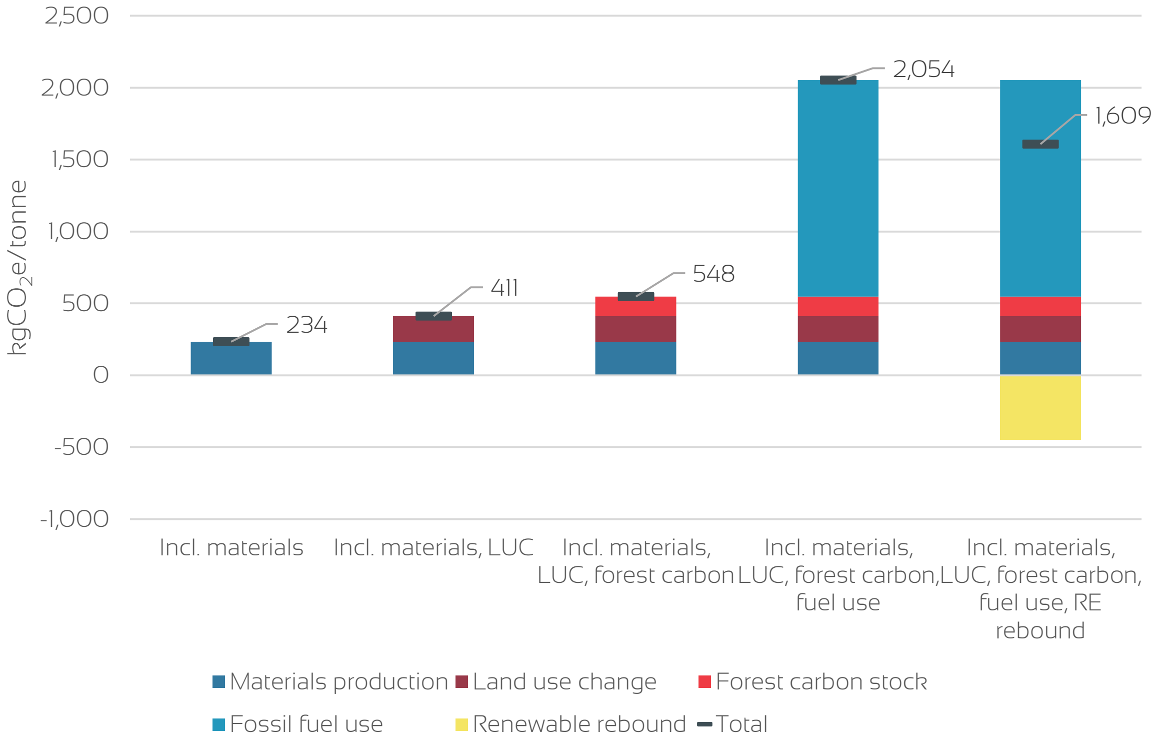

Figure G. Estimated indirect emissions associated with increased demand for CTO, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure H.

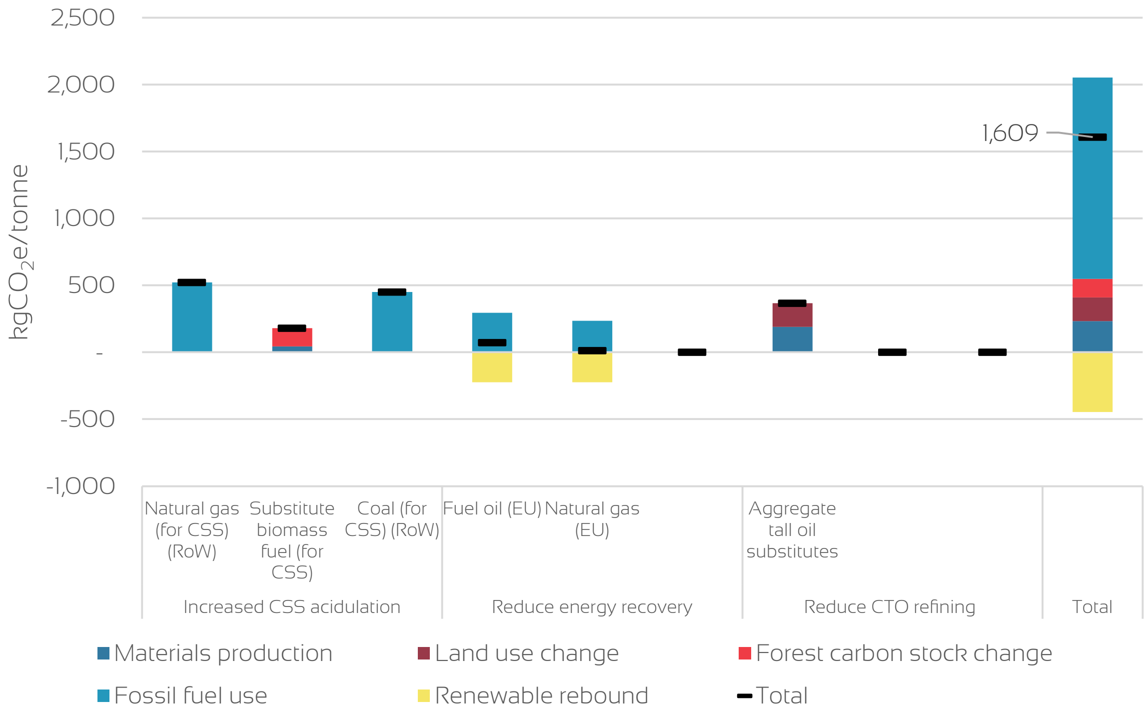

Figure H. Contribution of substitute materials to the indirect emissions profile of CTO

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for CTO derived fuels are shown in Table M. The emissions for the HVO pathway are illustrated in Figure I.

Table M. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FT diesel from Tall oil	0.50	12	9 (25)	7	78	-23	83 (99)
HVO from Tall oil	0.92	7	5 (14)	4	42	-12	45 (54)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

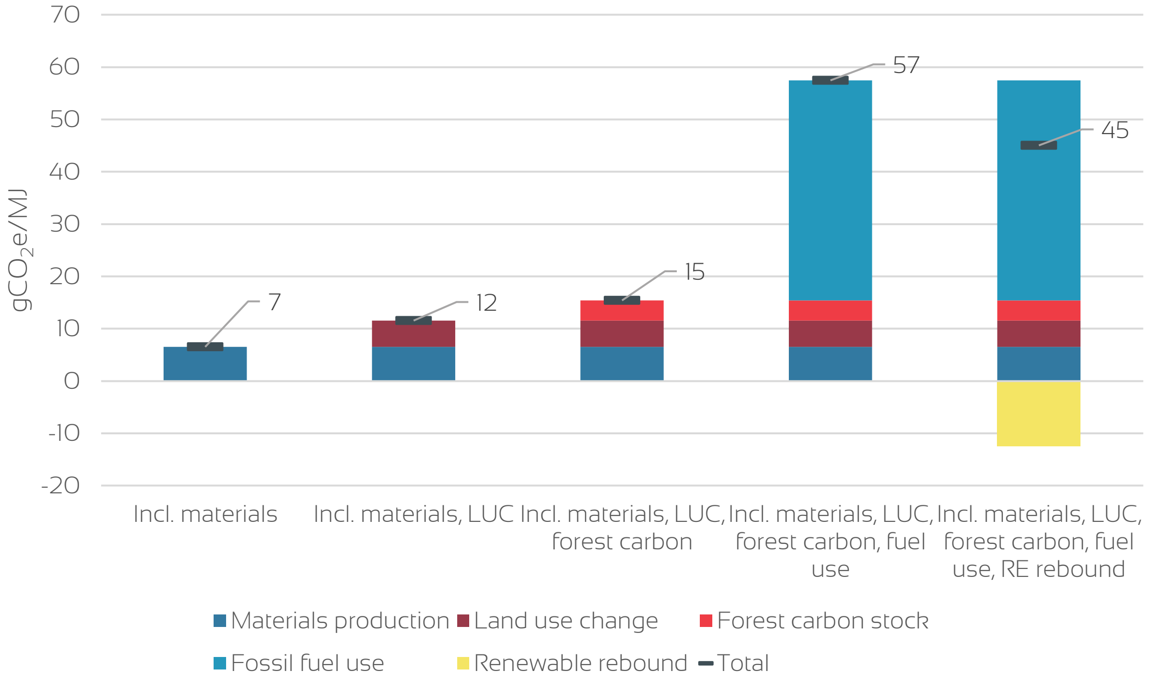

Figure I. Estimated indirect emissions from CTO-derived HVO

A.4. Tall oil pitch (TOP)

Step 1. Material definition and biofuel yields

Tall oil pitch is the heavy end material left over by tall oil distillation. There are no published data for biofuel yields from tall oil pitch, but it is understood that pitch is a more difficult feedstock. For tall oil pitch hydrotreating, we therefore assume that the achievable yields would be only 80% of yields achievable from crude tall oil – 0.29 tonnes synthetic diesel per tonne TOP. As with CTO hydrotreating, we take the simplifying assumption that synthetic diesel is the only output stream.

Step 2. Potential demand from RED II

Current uses for tall oil pitch are relatively low value. Given an adequate incentive for its use as biofuel feedstock, it is therefore plausible that a significant fraction of the global supply (about 400,000 tonnes per year) could be diverted for biofuel production. Neste oil has about 2.4 million tonnes of existing hydrotreating capacity, and have reported that they are able to run tall oil pitch as a feed. If they were able to run toil oil pitch as up to 25% of hydrotreater feed, then in principle they would already have enough capacity to absorb estimated global TOP production. It is unknown what the status is of Neste's programme to increase TOP use as biofuel feedstock, but their website notes that they currently "aim at further enabling" its use, suggesting that there are still limitations on their process.

Step 3. Existing uses

The substantial majority of TOP is currently combusted for energy recovery. Using more TOP as biofuel feedstock would reduce utilisation in these existing energy recovery systems.

Step 4. Potential substitutes

Tall oil pitch is likely to be combusted in the lime kiln. As discussed in the case of energy recovery from CTO, we assume that the replacement fuels would be 50% natural gas and 50% fuel oil.

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Step 6. Displacement assumptions

The displacement and substitution assumptions on TOP are shown in Table N and Table O.

Table N. Assumed fractional displacement of other dispositions by increased biofuel demand for Tall oil pitch (TOP)

Displaced system	Assumed displacement fraction
Energy recovery	100%

Table O. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of Tall oil pitch (TOP))	Resulting assumed change in material demand (tonne per tonne of Tall oil pitch (TOP) used for biofuel)*
Energy recovery	Fuel oil (EU)	50%	0.94	0.42
	Natural gas (EU)	50%	0.76	0.34

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change.*

Note that if TOP could be replaced as fuel for the lime kiln with a renewable alternative (such as forestry residues), there would be a significantly different indirect emissions profile. In principle, it should be relatively straightforward for a pulp mill to document evidence of a shift to renewable fuel rather than fossil fuel.

Step 7. Greenhouse gas intensity of replacement systems

Emissions for fuel oil and natural gas are taken from Biograce (2017).

Table P. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stock	Fossil fuel use	Renewable rebound
Energy recovery	Fuel oil (EU)	0	0	0	0	3442	-1798
	Natural gas (EU)	0	0	0	0	3380	-2220

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of TOP used as biofuel feedstock are shown in Figure J.

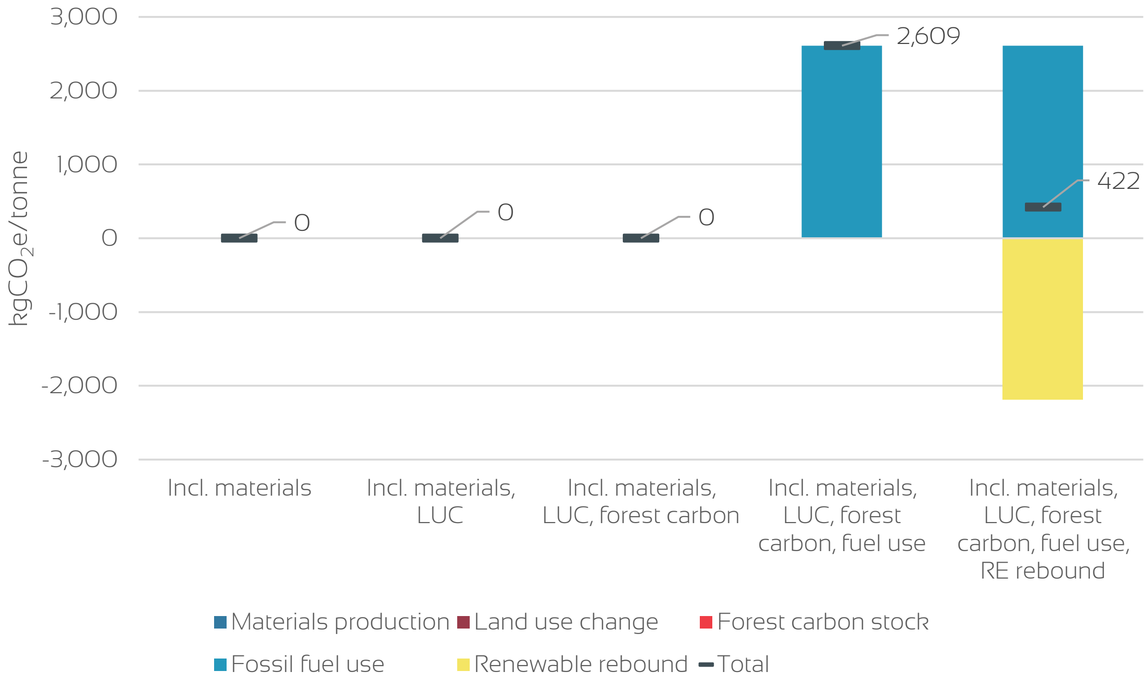

Figure J. Estimated indirect emissions associated with increased demand for TOP, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure K.

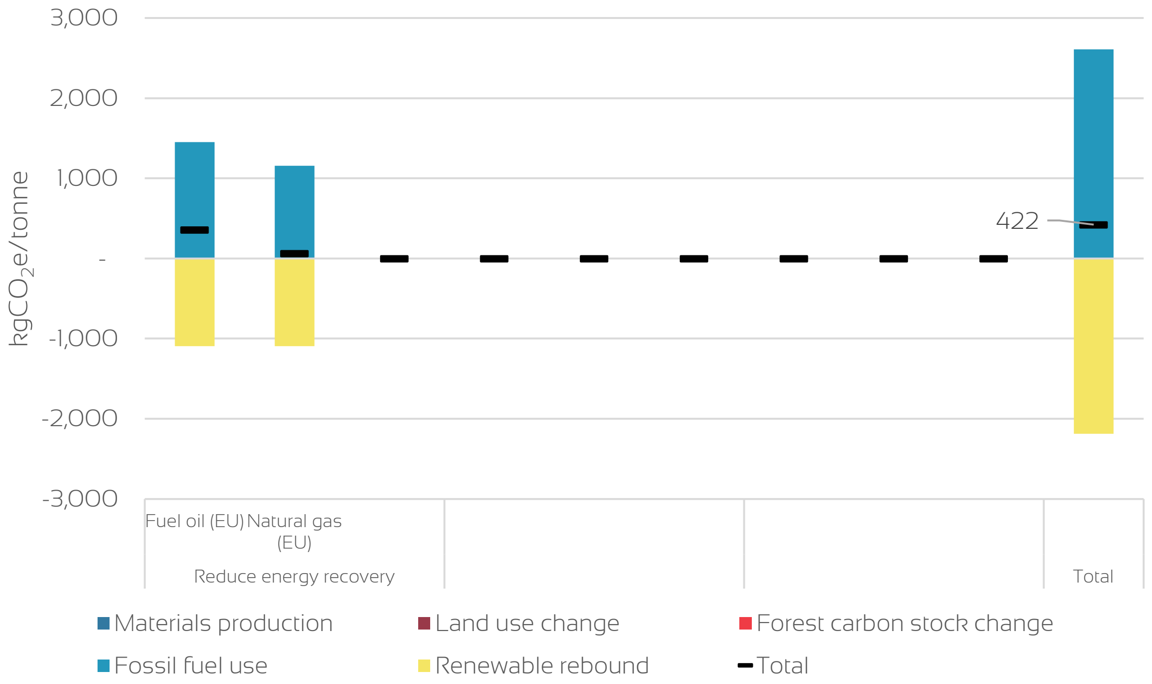

Figure K. Contribution of substitute materials to the indirect emissions profile of TOP

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for TOP derived fuels are shown in Table Q. The emissions for the HVO pathway are illustrated in Figure L.

Table Q. Summary of indirect emissions for relevant fuel pathways

	Materials production	Land use change	Fossil fuel use	Renewable rebound	Total
HVO from TOP	0	0 (0)	87	-51	37 (37)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

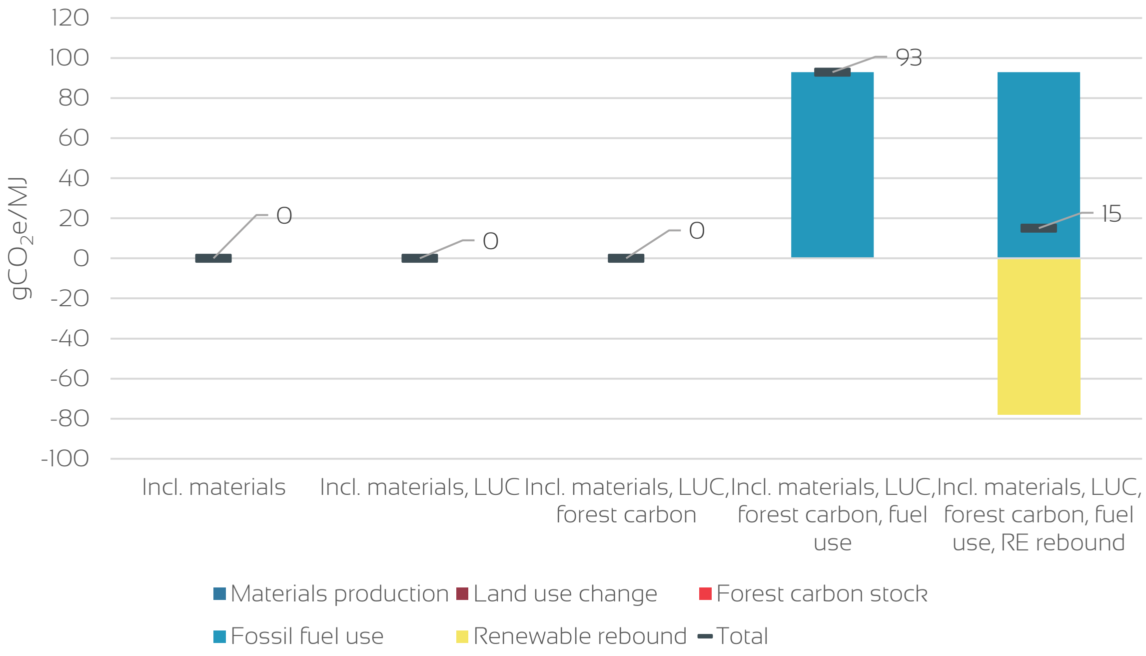

Figure L. Estimated indirect emissions from TOP-derived HVO

A.5. Sawdust and cutter shavings

Step 1. Material definition and biofuel yields

Sawdust and cutter shavings are industrial residues resulting from sawmilling. They account for in the region of 50% of woody material entering the sawmill, depending on tree species and sawmill outputs. In this study, we have interpreted the term 'cutter shavings' broadly to include wood chips and offcuts from the sawmill. Sawdust and cutter shavings could be used as feedstock for any cellulosic biofuel production process. For cellulosic ethanol production. We take a yield of 0.3 tonnes biofuel per tonne feedstock for cellulosic ethanol from sawdust and shavings (Baral & Malins, 2014b) and a yield of 0.22 tonnes biofuel per tonne feedstock for FT diesel[66] (Edwards et al., 2013).

Step 2. Potential demand from RED II

The potential supply in the EU of sawdust and cutter shavings is of the order of 50 million tonnes. Ten large commercial (150 thousand tonne per year) biofuel facilities would require up to 7 million tonnes of woody feedstock per year. In the near term, it is therefore unlikely that biofuel demand could exhaust the potential supply of sawdust and shavings.

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[66] As elsewhere in the report, we treat the output stream as 100% diesel – in reality, it would include other hydrocarbons.

Step 3. Existing uses

Sawdust and cutter shavings are used primarily for energy recovery (at the sawmill or in bioenergy plants), for production of particle board, and by the paper pulping industry. Disposition varies considerably throughout Europe depending on types of wood and the nature of local industry.

Step 4. Potential substitutes

In energy recovery, sawdust and cutter shavings are likely to be replaced by a similar range of materials as are expected to replace black liquor (see below). Biomass provides about 50% of power for the

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Step 6. Displacement assumptions

We assume that sawdust and cutter shavings will be displaced out of existing uses in proportion to the existing rates of utilisation documented in Pekkanen et al. (2016) (Table R).

Table R. Assumed fractional displacement of other dispositions by increased biofuel demand for sawdust and cutter shavings

Displaced system	Assumed displacement fraction
Energy recovery	45%
Fibre and particle board	40%
Pulping	15%

Table S shows our assumptions about the materials that are likely to replace sawdust and cutter shavings in these uses.

Table S. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of sawdust and cutter shavings)	Resulting assumed change in material demand (tonne per tonne of sawdust and cutter shavings used for biofuel)*
Reduce energy recovery	Substitute bio-mass fuel	50%	1.00	0.20
	Natural gas (EU)	25%	0.38	0.04
	Fuel oil (EU)	25%	0.47	0.05
Fibre and particle board	Pulpwood**	100%	1.0	0.36
Pulping	Pulpwood	100%	1.0	0.14

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change*

***Properly, pulpwood means word for use by the pulp industry. Here we use the term to denote lower value harvested wood including for fuel and material uses, as distinct from roundwood for timber. .*

Step 7. Greenhouse gas intensity of replacement systems

Greenhouse gas emissions intensity of collecting and transporting forestry residues is taken from RED II, land use change emissions from Valin et al. (2015). Intensities for natural gas and fuel oil are taken from Biograce (2017). Carbon intensity for pulpwood is taken from (Jonker, Junginger, & Faaij, 2014).

Table T. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replace-ment materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stock	Fossil fuel use	Renewable rebound
Reduce energy recovery	Substitute biomass fuel	141			444		
	Natural gas (EU)	0	0	0		3380	-2220
	Fuel oil (EU)	0	0	0		3442	-1798
Reduced use in particle board manufacture	Pulpwood	228	726	726	726	0	0
Reduced use in pulping	Pulpwood	228	726	726	726	0	0

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of sawdust and cutter shavings used as biofuel feedstock are shown in Figure M.

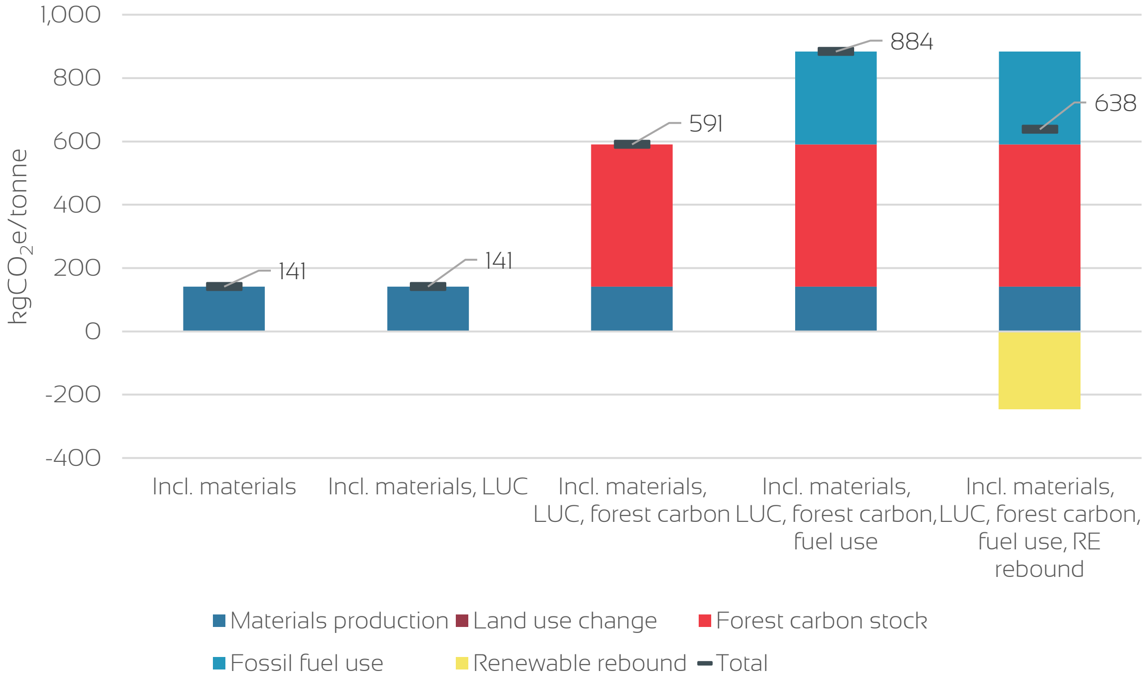

Figure M. Estimated indirect emissions associated with increased demand for sawdust and cutter shavings, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure N.

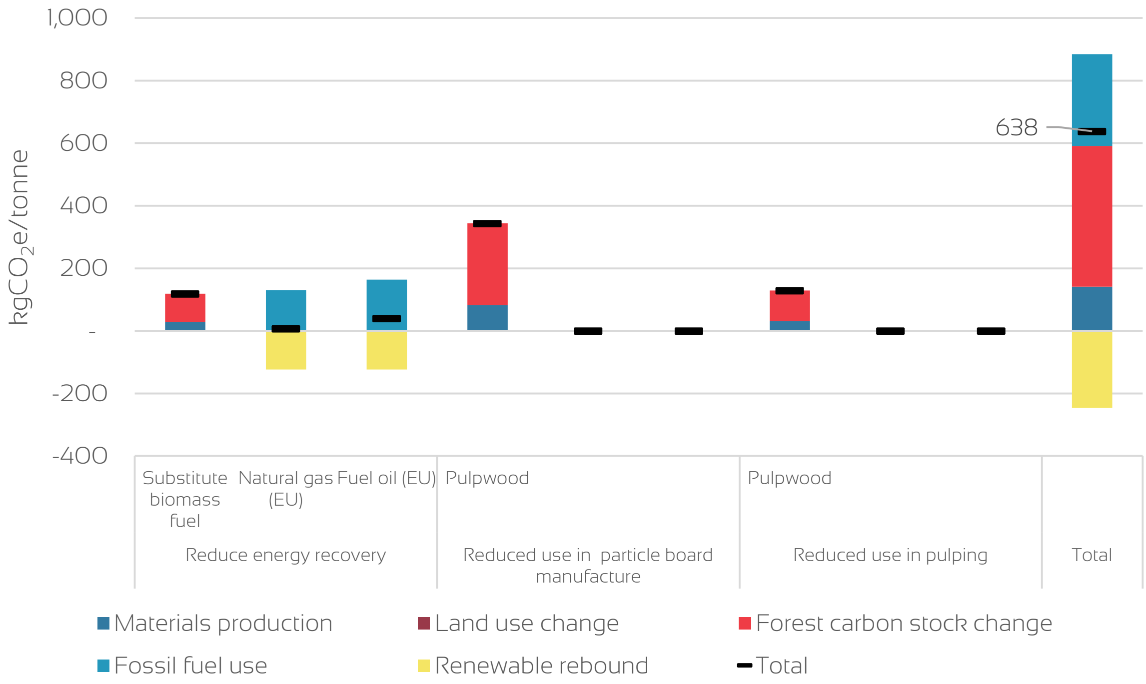

Figure N. Contribution of substitute materials to the indirect emissions profile of sawdust and cutter shavings

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for sawdust and cutter shaving derived fuels are shown in Table U. The emissions for the HVO pathway are illustrated in Figure O.

Table U. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FT diesel from Sawdust and cutter shavings	0.50	15	0 (0)	47	31	-26	67 (67)
Pyrolysis diesel from Sawdust and cutter shavings	0.74	10	0 (0)	32	21	-17	45 (45)
Cellulosic ethanol from Sawdust and cutter shavings	0.42	20	0 (0)	62	41	-34	88 (88)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

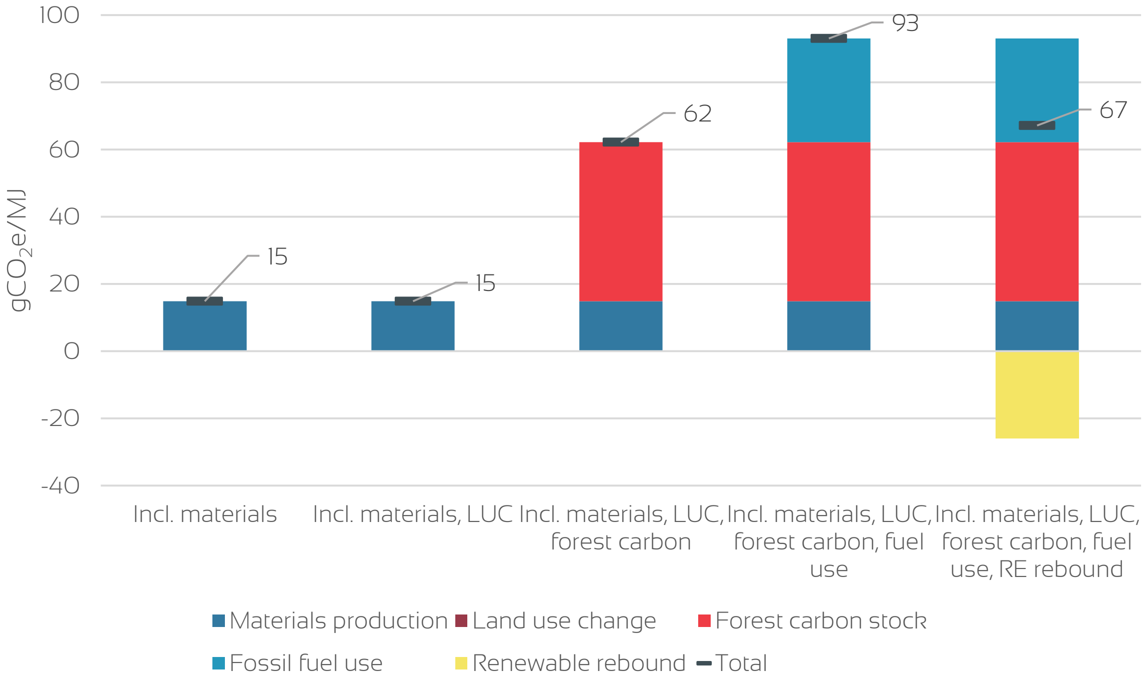

Figure O. Estimated indirect emissions from sawdust and cutter shaving-derived FT diesel

A.6. Black liquor

Step 1. Material definition and biofuel yields

Black liquor is a residue of the kraft pulping process, containing lignin, hemicellulose, other organic material and spent chemicals. Normally crude sulphite soap is removed from black liquor and it is then combusted in a recovery boiler, to recover the pulping chemicals and generate energy. Alternatively, black liquor could be gasified, and the syngas used either directly for heat and power (at higher efficiency than in the recovery boiler) or to produce transport fuel (IEA Bioenergy, 2007). We assume that CSS would still be extracted from black liquor prior to gasification (Berglin et al., 2003), and thus we do not consider any impact from use of this process on the CTO supply.

Following syngas production, various biofuels could be synthesised. For methanol production, we assume a yield of 0.41 tonnes per tonne feedstock. For Fischer-Tropsch diesel, we assume a yield of 0.16 tonnes fuel per tonne feedstock (Edwards et al., 2013)[67].

Step 2. Potential demand from RED II

Black liquor is listed in Annex IX of RED II, and therefore there is potential for significant demand for black liquor derived fuels. The EU supply of 60 million tonnes of black liquor per year could in principle be processed into up to 10 million tonnes of synthetic FT fuels, enough to meet the RED II mandate for supply of fuels from Annex IX part A feedstocks. Demand for alternative molecules (such as methanol or DME) could also be high in principle, but is likely to be limited by demand for these fuels in the vehicle pool.

Step 3. Existing uses

Currently, the vast majority of black liquor is combusted in recovery boilers to recover kraft pulping chemicals, and energy (Indufor, 2013). Black liquor combustion represents a significant fraction of EU biomass energy Gasifying black liquor for transport fuel would result in a reduction of energy generation at the mill, which would need to be replaced (IEA Bioenergy, 2007). We do not believe that there are any other significant scale uses of black liquor in Europe.

Step 4. Potential substitutes

Reducing energy recovery from black liquor in the recovery boiler would create demand for the use of alternative fuels, and potentially alternative infrastructure. Berglin et al. (2003) calculate additional requirements for power and fuel resulting from moving black liquor from the recovery boiler to a gasification process for fuels. Per MJ of methanol production, they find that an additional 0.27 MJ of power and an additional 0.12 MJ of fuel are required.[68] The paper assumes that these additional energy needs will be met by increasing combustion of bark or other residues in the bark boiler, and by additional biomass combustion in biomass powered condensing power plants at 35% efficiency. This gives a

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[67] We assume that the energetic efficiency of FT-diesel production from all woody materials and forestry residues is roughly the same, 50%.

[68] Author's calculation, excluding energy required to run the gasification and methanol synthesis processes, which should be included in the direct LCA.

replacement requirement of about 0.9 MJ LHV of biomass (or alternatively of fossil fuel) for every 1 MJ of methanol produced. While lime kilns specifically are generally run on fossil fuels (cf. the section on tall oil pitch), the pulping industry more generally is heavily reliant on biomass for heat and power (Miner, 2010). The pulping industry is generally power self-sufficient, and we therefore assume that any additional power needed will be generated on-site.

Step 5. Elasticity of demand

Utilisation of black liquor for biofuel production could only happen with the buy-in of the pulping industry, as the producers and users of existing black liquor supplies. Black liquor gasification and fuel synthesis is only likely to be commercialised if it improves the economics of kraft pulping, and therefore it would not seem appropriate to assume a price led reduction in energy consumption in the pulping industry as a consequence of increased black liquor gasification. We therefore assume a zero demand response in this case.

Step 6. Displacement assumptions

The displaced use is reduced energy recovery Table V. We consider the case of biofuel production in Europe using EU black liquor resources. We anticipate no other significant displacement.

Table V. Assumed fractional displacement of other dispositions by increased biofuel demand for black liquor

Displaced system	Assumed displacement fraction
Energy recovery	100%

Our assumptions for replacement fuels boiler fuels are based on the pulp and paper benchmarking study for ETS by Ecofys (Ecofys et al., 2009), from which we take biomass and natural gas as replacement fuels in the ratio 57:43.

Table W shows our assumptions about the materials that are likely to replace black liquor.

Table W. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of black liquor)	Resulting assumed change in material demand (tonne per tonne of black liquor used for biofuel)*
Energy recovery	Substitute biomass fuel	57%	0.57	0.29
	Natural gas (EU)	43%	0.15	0.06

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change.*

Step 7. Greenhouse gas intensity of replacement systems

Greenhouse gas emissions intensity of collecting and transporting forestry residues is taken from RED II, land use change emissions from Valin et al. (2015). Intensity for natural gas taken from Biograce (2017).

Table X. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stocks	Fossil fuel use	Renewable rebound
Reduce energy recovery	Substitute biomass fuel	141			444		
	Natural gas (EU)					3380	-3197

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of black liquor used as biofuel feedstock are shown in Figure P.

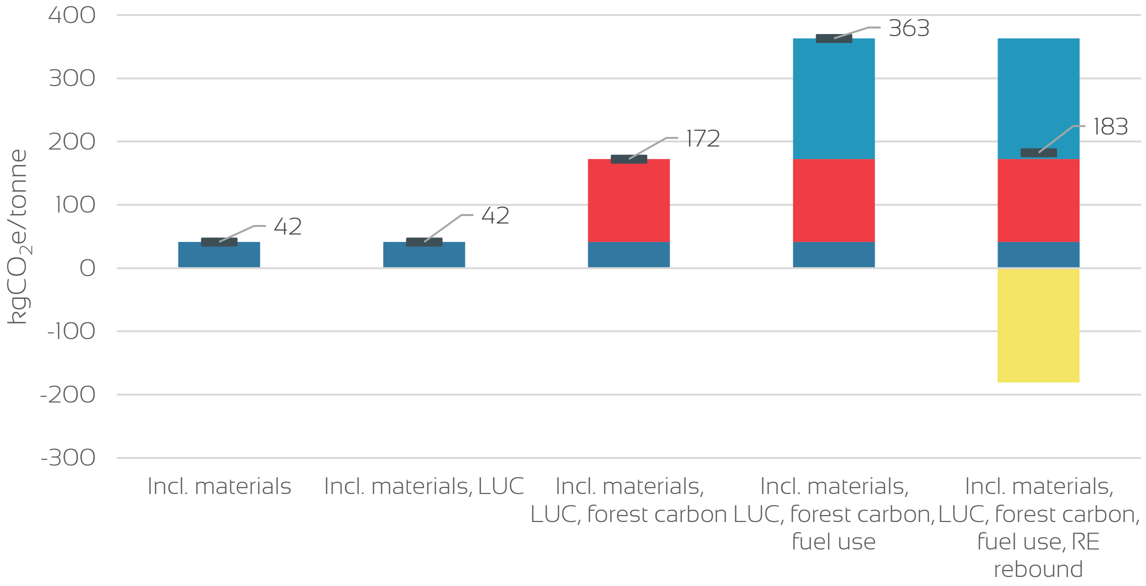

Figure P. Estimated indirect emissions associated with increased demand for black liquor, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure Q.

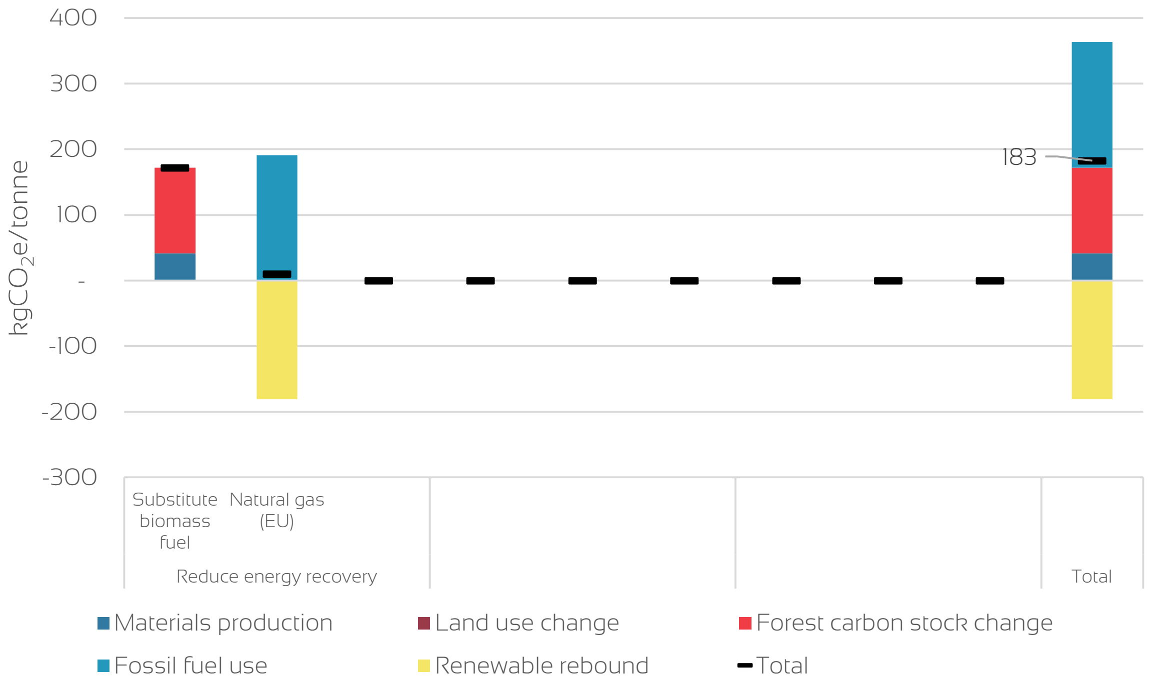

Figure Q. Contribution of substitute materials to the indirect emissions profile of black liquor

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for black liquor derived fuels are shown in Table Y. The emissions for the HVO pathway are illustrated in Figure R.

Table Y. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FT diesel from black liquor	0.50	6	0 (0)	18	26	-25	25 (25)
Methanol from black liquor	0.56	5	0 (0)	16	24	-22	22 (22)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

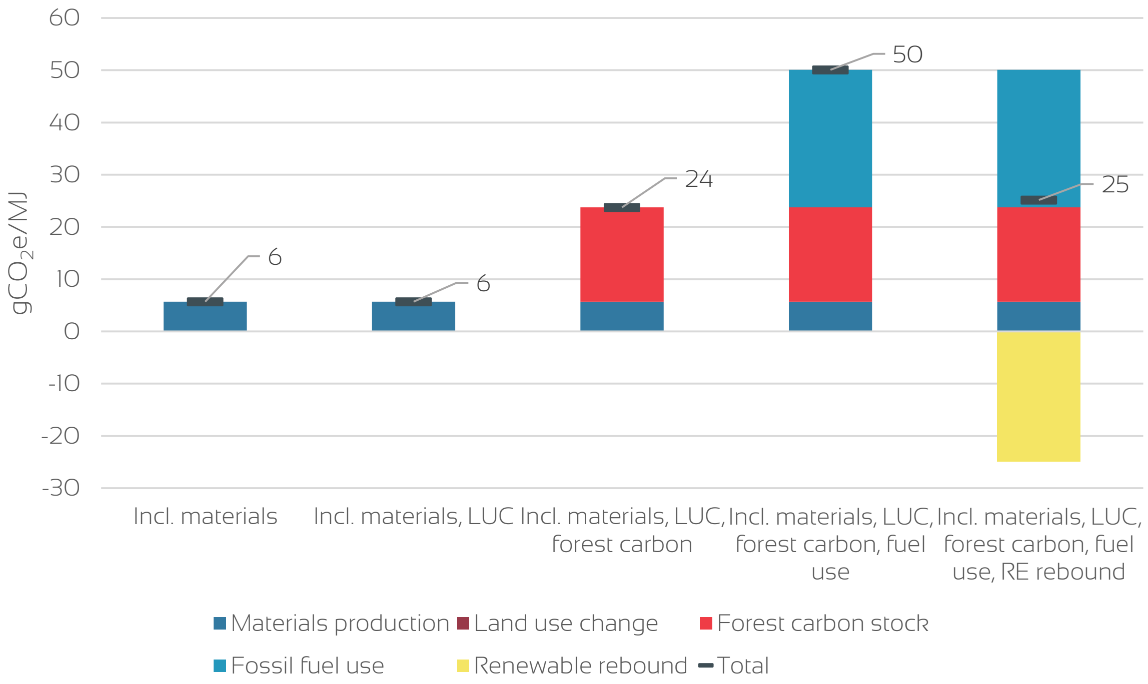

Figure R. Estimated indirect emissions from black liquor-derived FT diesel

A.7. Crude glycerine

Step 1. Material definition and biofuel yields

Glycerine is an impure form of the chemical 1,2,3-propanetriol, or glycerol, with significantly lower value than pure glycerol. It is produced in significant quantity as a by-product of biodiesel transesterification.

The only process documented at scale for producing biofuel from glycerine is gasification and methanol syntheses. We assume an energy efficiency (LHV) of conversion of 50% (IEA-ETSAP & IRENA, 2013; van Bennekom et al., 2012). It is also possible that glycerine could be used as a feedstock for gasification and FT synthesis (X. Wang, Li, Wang, Liu, & Ma, 2008), but we are not aware of companies seriously considering investing in this pathway at this time.

Step 2. Potential demand from RED II

The renewable methanol industry has achieved limited penetration as a transport fuel as compared to the ethanol or FAME production industries. The glycerine to methanol process pioneered by BioMCN was apparently unable to deliver competitive returns despite double counting under the existing RED. We therefore consider potential demand for methanol from glycerine to be relatively modest. Four commercial plants of the size reported for the BioMCN facility would require at least 2 million tonnes of glycerine feed per year, absorbing the majority of global glycerine production. We consider it unlikely that the economics of methanol production from glycerine would allow more than two commercial scale facilities globally, with a combined glycerine demand of up to one million tonnes per annum.

Step 3. Existing uses

Glycerine is essentially 100% utilised. Current markets are refining, animal feed, heat and power, chemical applications of crude glycerine, and cement manufacture.

The largest use of crude glycerine in Europe (50-70%) is glycerine refining. About 600,000 tonnes of glycerine is refined per year in Europe. Animal feed use in Europe may be around of 300,000-400,000 tonnes of crude glycerine per annum. A further 100,000 tonnes is used for heat and power applications. As noted above, there is a degree of uncertainty in the literature about total production, and some material may be exported from Europe (Green Chemical, 2014). It is unclear how much is used crude for chemical applications and cement – this use may be included in the heat and power number from E4tech (Taylor & Bauen, 2014). There is no significant glycerine disposal (that we are aware of).

Step 4. Potential substitutes

As noted above, the value of refined glycerine is high compared to both crude glycerine and to the price of methanol. We therefore consider it unlikely that glycerine would be displaced out of the refining industry in large quantities as a response to increased use as biofuel feedstock.

The next largest use of glycerine is as an animal feed supplement (20-40%). Dietary research by Purdue University (Donkin, 2008) suggests that adding five units of glycerine to cattle diets could be compensated by removing 5.8 units of feed corn, and adding 0.8 units of corn gluten meal (the latter addition is likely in order to maintain protein content in the test diet). They found no change in cattle performance, though it should be noted that in this test they used purified kosher glycerol rather than crude glycerine.

Finally, there are a range of more niche uses, including digestion to produce biogas for heat and power, use as a cement additive and other chemical applications for unrefined glycerine. One potential alternative identified for crude glycerine in chemical and cement applications is propylene glycol (Ciriminna et al., 2015; Searle et al., 2017; Taylor & Bauen, 2014). Reported prices for propylene glycol run above $1,000 per tonne (ICIS, 2012; Oleoline, 2012) and therefore it might be expected expect that glycerine users in these applications would be resistant to glycerine price changes. For these reasons, we do not expect these uses to change significantly in response to biofuel demand.

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Step 6. Displacement assumptions

Here, we assume that in the animal feed sector reduced glycerine availability would result in increased use of cereal feeds and that substitution ratios will run with metabolisable energy content.[69] The primary feed cereals in the EU are wheat, maize and barley. Based on 2014 statistics from FAOstat (UN Food and Agriculture Organisation, 2017), we assume that substitution rates will be proportionate to production of the main cereals – 53% wheat, 26% maize and 21% barley.

We assume that reduced use in anaerobic digestion results in increased natural gas demand.[70]

We have developed expected displacement rates based on the utilisations documented by E4tech (Taylor & Bauen, 2014) and on the narrative consideration of responsiveness to price given above. We assume that animal feed use will be the primary displaced system, with a secondary response in anaerobic digestion, and no significant reduction in refining. The resulting displacement fractions are given in Table Z.

Table Z. Assumed displacement of other users by increased biofuel demand for glycerine

Displaced system	Assumed displacement fraction
Remove from feed market	86%
Reduced use in AD	14%

Table AA. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of crude glycerine)	Change in material demand (tonne per tonne of glycerine used for biofuel)
Livestock feed	Wheat	53%	1.2	0.52
	Maize	26%	1	0.18
	Barley	21%	1.3	0.21
Energy recovery (EU)	Natural gas	100%	0.37	0.05

Step 7. Greenhouse gas intensity of replacement systems

Greenhouse gas emissions intensities for cereals and natural gas are taken from Biograce (2017).

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[69] We use treat metabolisable energy values for poultry as indicative – 16 MJ/kg for glycerine and corn (Kato et al., 2011; Lammers et al., 2008), 13 MJ/kg for wheat and 12 MJ/kg for barley (Hazzledine et al., 2011). A full dietary displacement analysis using least cost feed formulation software is beyond the scope of this paper. We did not consider potential impacts of feed changes on emissions associated with enteric fermentation.

[70] Biogas yield of 0.58 tonne/tonne taken as average value given in Redman (2010), biogas energy content taken as 64% that of natural gas (ibid).

Table AB. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stocks	Fossil fuel use	Renewable rebound
Remove from feed market	Feed wheat	359	166	470			
	Feed corn	352	197	230			
	Feed barley	466	167	528			
Reduced use in AD	Natural gas (EU)					3380	-3197

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of glycerine used as biofuel feedstock are shown in Figure S.

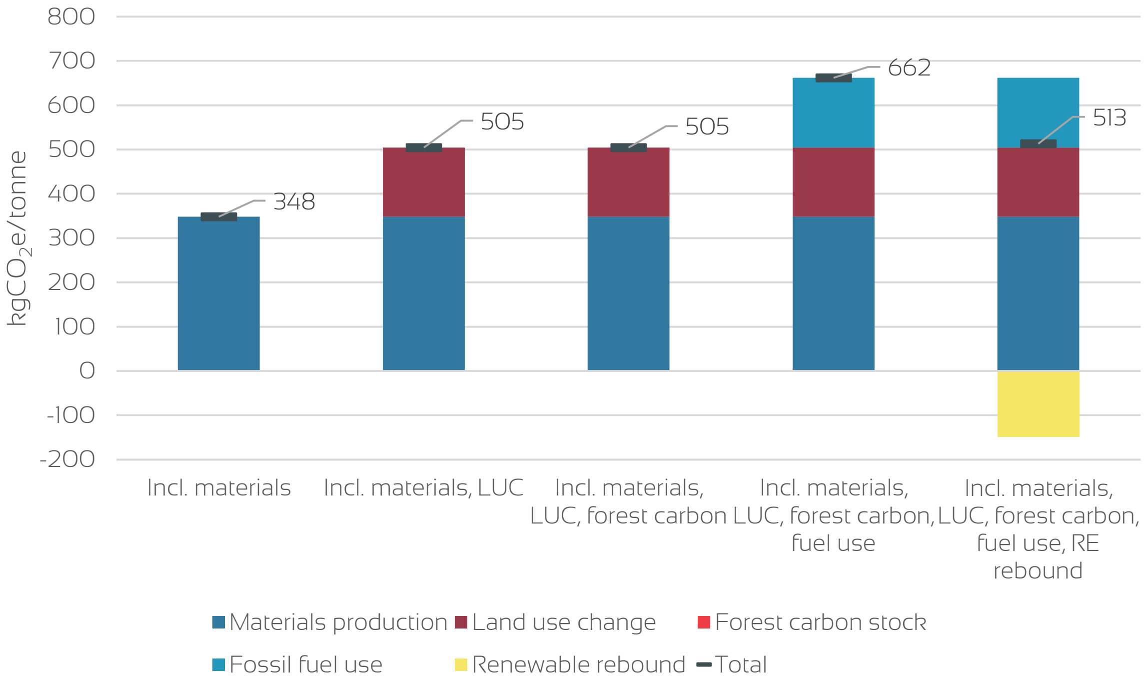

Figure S. Estimated indirect emissions associated with increased demand for glycerine, kgCO2e/tonne

A more detailed breakdown of the contribution of each substitute material is shown in Figure T.

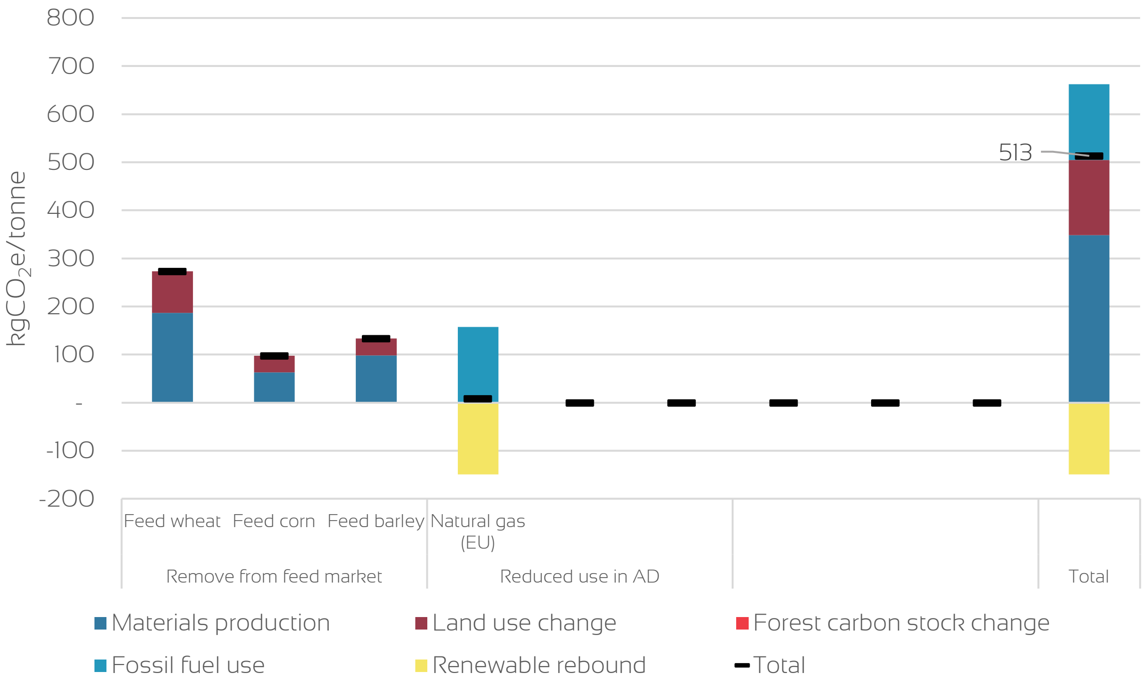

Figure T. Contribution of substitute materials to the indirect emissions profile of glycerine

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for glycerine derived fuels are shown in Table AC. The emissions for the HVO pathway are illustrated in Figure U.

Table AC. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
Methanol from glycerine	0.50	19	9 (22)	0	9	-8	28 (42)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

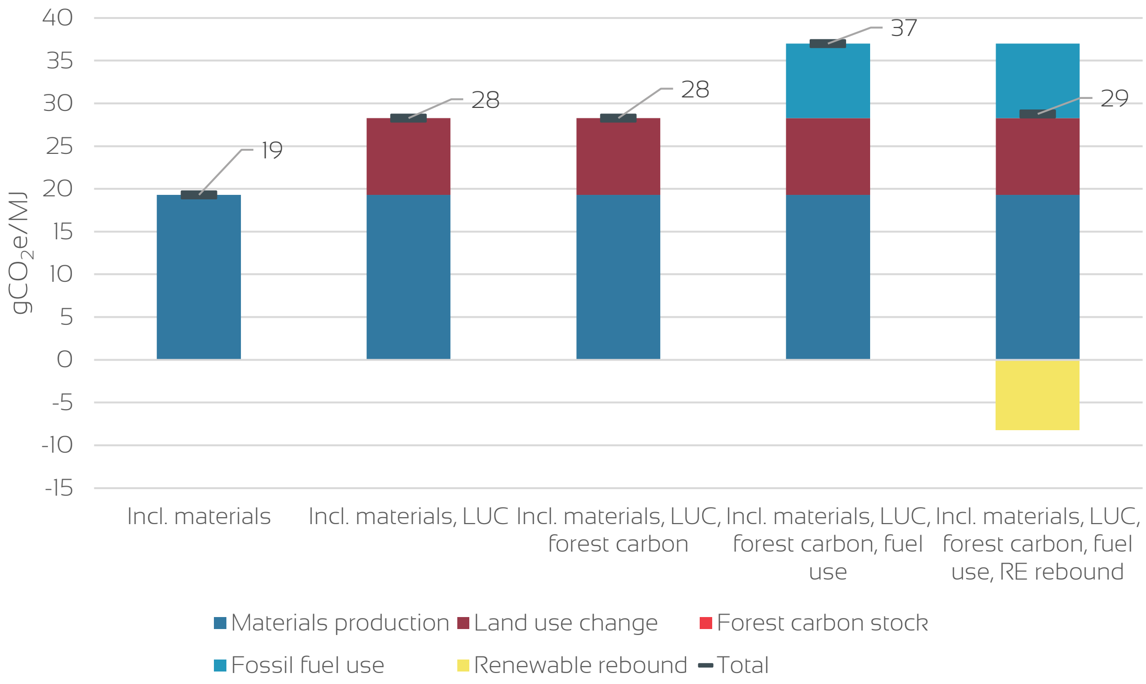

Figure U. Estimated indirect emissions from glycerine-derived methanol

A.8. Animal fats (classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009 of the European Parliament and of the Council)

Step 1. Material definition and biofuel yields

Category 1 and 2 animal fats are residual fatty materials from the meat industry that are considered potentially unsafe for human or animal consumption. FAME production from animal fats is a well-established industry, and there is also potential to hydrotreat animal fats to produce synthetic fuels. We assume yields of 0.96 tonnes FAME per tonne animal fats, and 0.82 tonnes HVO per tonne animal fats.

Step 2. Potential demand from RED II

Utilisation of fuels from feedstocks in Part B of Annex IX of the proposed RED II is capped to an estimated 4.24 million tonnes oil equivalent per year. This is still large compared to European production of category 1 and 2 animal fats (around 1 million tonnes), and thus RED II could drive significant demand.

Step 3. Existing uses

In Europe, most animal fats of grade 1 and 2 are already utilised as biodiesel feedstock. Nearly all of the rest is combusted for heat and power.

Additional category 1 and 2 material could also become available through the reduced production of higher quality category 3 material. If the price differential to category 3 was sufficiently eroded, it might for instance reduce incentives to introduce rigorous segregation of material through the supply chain. The supply of category 3 material is larger than the combined supply of categories 1 and 2, so in principle this could represent a significant source. Category 3 material has uses in food, pet food and animal feed and in oleochemicals.

Step 4. Potential substitutes

For energy recovery for heat and power, the obvious substitute for animal fats is fuel oil. There would also be potential for renderers to shift to alternate fuels such as natural gas, but this would likely require additional investment. Biofuel data reported by the UK Department for Transport (Department for Transport, 2016) shows limited use of animal fats from outside the EU, so we assume that displacement from heat and power uses would occur within the EU.

In the case of reduced categorisation of material as category 3, the likely substitute would be alternative vegetable oils. Palm oil is relatively close in properties to animal fats, and is the cheapest primary vegetable oil, and is thus likely to be the main substitute material in such uses.

Step 5. Elasticity of demand

In the absence of sector specific data, we allow for a 10% demand response (Searle, Pavlenko, El Takriti, & Bitnere, 2017).

Step 6. Displacement assumptions

It is difficult to get a clear sense of the likely balance in response to biofuel demand between displacement of animal fats from existing heat and power uses, and reduction of supply of animal fats for category 3 uses. Category 3 uses will generally return a higher value than heat and power uses, and thus we assume that heat and power uses will be the most strongly impacted (Table AD).

Table AD. Assumed fractional displacement of other dispositions by increased biofuel demand for animal fats

Displaced system	Assumed displacement fraction
Reduced energy recovery	80%
Reduced categorisation as category 3	20%

Table AE shows our assumptions about the materials that are likely to replace animal fats in these uses.

Table AE. Substitution ratios for displaced materials

Displaced system	Replacement materials	Fractional replacement in given displaced system	Substitution ratio (tonnes to replace a tonne of animal fats	Resulting assumed change in material demand (tonne per tonne of animal fats used for biofuel)*
Energy recovery	Fuel oil	75%	0.92	0.49
	Natural gas	25%	0.74	0.13
Reduced categorisation as category	Palm oil	75%	1.0	0.14
	Rapeseed oil	25%	1.0	0.05

**This is the assumed increase in demand for this material due to one tonne of increased demand for the biofuel feedstock, taking into account the fractional importance of each use and substitute material, the substitution ratio and the assumed demand change.*

Step 7. Greenhouse gas intensity of replacement systems

Greenhouse gas intensities for palm oil and fossil fuels based on Biograce (2017).

Table AF. Greenhouse gas intensity of increased use of replacement materials, kgCO2e/tonne

Displaced system	Replacement materials	Materials production	Land use change (RED)	Land use Change (GLOBIOM)	Forest carbon stocks	Fossil fuel use	Renewable rebound
Reduce energy recovery	Fuel oil (EU)					3442	-2589
	Natural gas (EU)					3380	-3197
Reduced classification as cat 3	Palm oil	1781	2022	8492			
	Rapeseed oil	1297	2022	2390			

Step 8. Greenhouse gas emissions per unit of material used as biofuel feedstock

The estimated indirect emissions per tonne of animal fat used as biofuel feedstock are shown in Figure V.

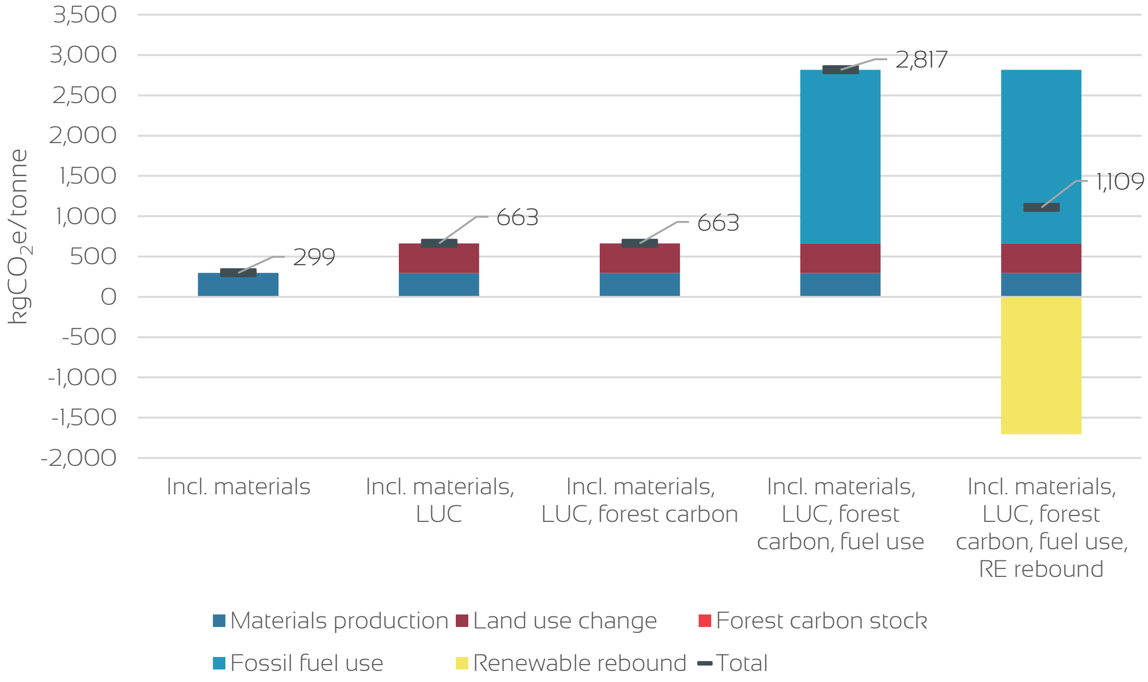

Figure V. **Estimated indirect emissions associated with increased demand for animal fat, kgCO2e/tonne**

A more detailed breakdown of the contribution of each substitute material is shown in Figure W.

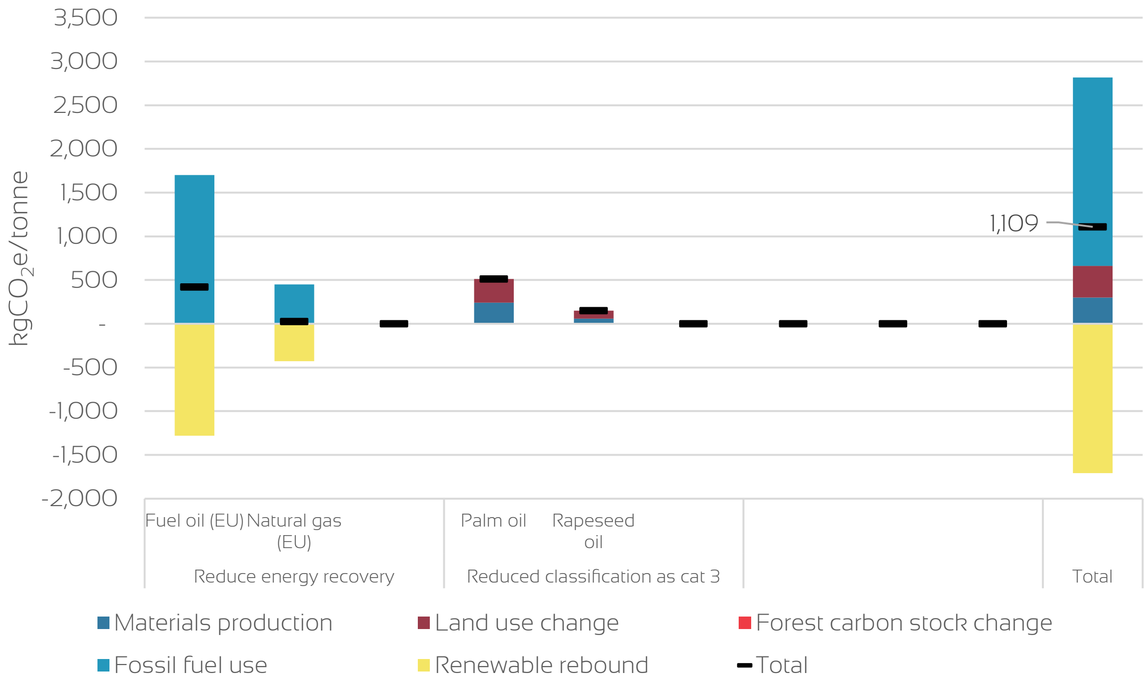

Figure W. Contribution of substitute materials to the indirect emissions profile of animal fat

Step 9. Greenhouse gas emissions per MJ of biofuel produced

The estimated indirect emissions for animal fat derived fuels are shown in Table AG. The emissions for the HVO pathway are illustrated in Figure X.

Table AG. Summary of indirect emissions for relevant fuel pathways

	Biofuel yield (MJ/MJ feedstock)	Materials production	Land use change	Forest carbon stock	Fossil fuel use	Renewable rebound	Total
FAME from Animal fats	0.96	8	10 (34)	0	58	-46	30 (54)
HVO from Animal fats	0.97	8	10 (35)	0	60	-48	31 (56)

Land use emissions based on RED II, with results using values from GLOBIOM in brackets

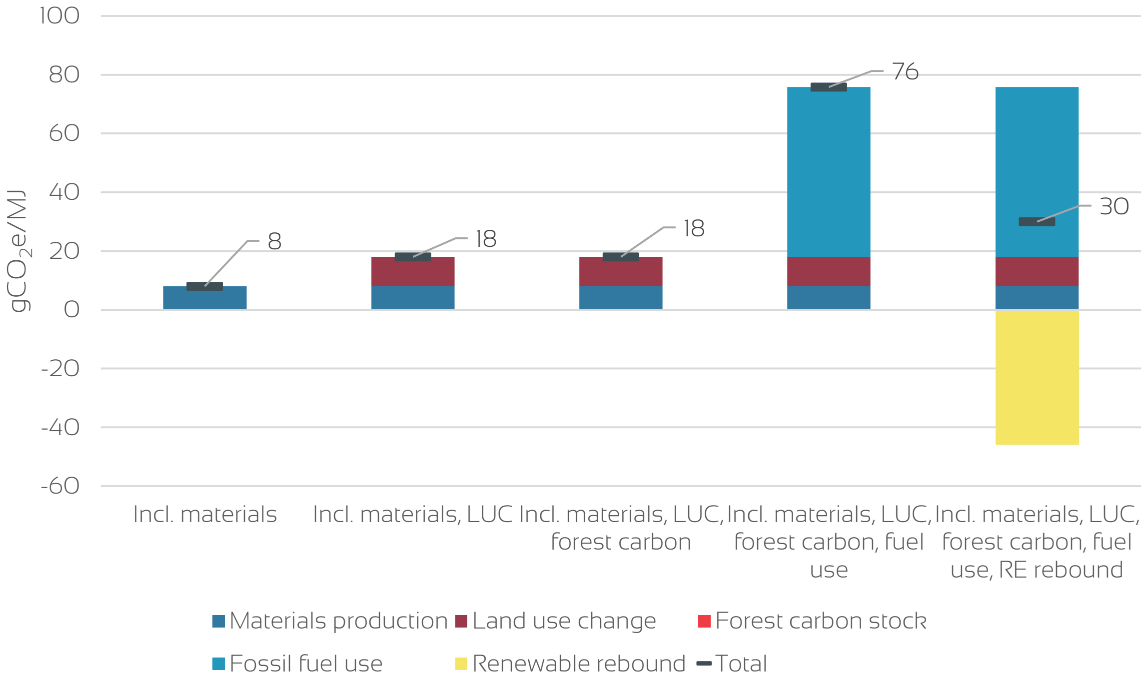

Figure X. Estimated indirect emissions from animal fat-derived FAME

A.9. Summary chart

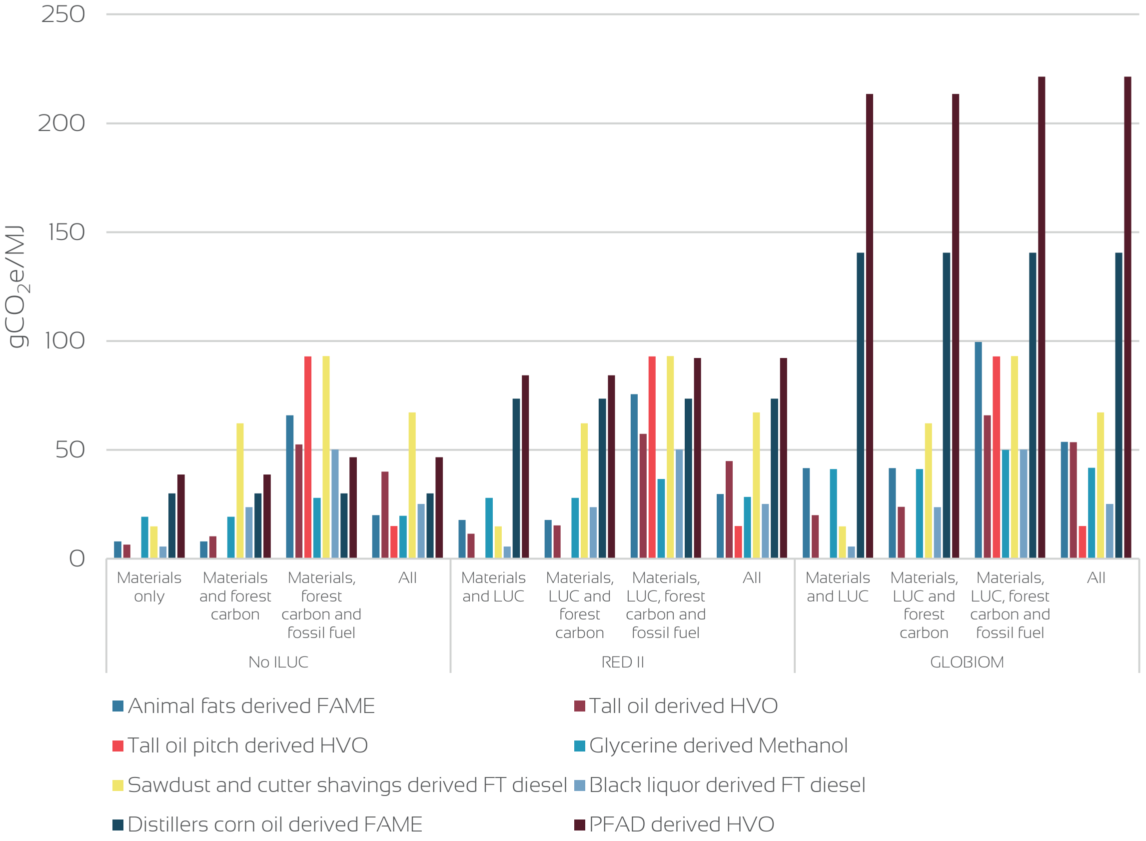

Figure Y. Comparison of indirect emissions results for various fuel pathways and system boundary choices

Annex B. Additional details on lifecycle assumptions

B.1. Biofuel yields

Table AH. Yields for considered biofuel pathways from each feedstock

Material	Material LHV	Pathway	Yield		Co-product*	Reference
	MJ/ kg		MJ/ MJ	tonnes fuel/ tonne material	%energy	
Animal fats	37.1	HVO	0.97	0.82		Biograce (assume same as virgin oils)
		FAME	0.96	0.96	4%	Biograce
Tall oil	36.42	HVO	0.98	0.81		Cashman et al. (2016)
		FT diesel	0.50	0.41		Assume same energetic efficiency as sawdust
Tall oil pitch	16	HVO	0.79	0.29		Assume 80% energy efficiency of tall oil conversion as given in Cashman et al. (2016)
Glycerine	36.1	Methanol	0.50	0.91		Assuming 50% energy conversion efficiency (van Bennekom et al., 2012; IEA-ETSAP & IRENA, 2013)
Sawdust and cutter shavings	19	FT diesel	0.50	0.22		JEC WTT 4 v4a give efficiency for wood to syndiesel of 46-51%.
		Pyrolysis diesel	0.74	0.32		GREET, via Malins and Baral (2014)
		Cellulosic ethanol	0.42	0.30		GREET, via Malins and Baral (2014).
Black liquor	14.5	FT diesel	0.50	0.16		Assume same energetic efficiency as sawdust
		Methanol	0.56	0.41		Berglin (2013)
Distillers corn oil	**37.1**	**HVO**	0.97	0.82		**Biograce (assume same as virgin oils)**
		FAME	0.99	1.00	4%	**Biograce**
PFAD	**37.1**	**HVO**	0.97	1.97		**Biograce (assume same as virgin oils)**
		FAME	0.94	0.95	4%	**Biograce (assume 5% less efficient than virgin oils)**

It is assumed that co-products such as lignin are utilised for on-site energy generation and dealt with in the direct LCA for the fuel pathway.

B.2. Substitution ratios for replacement materials

Table AI. Substitution ratios (tonne material to replace one tonne of biofuel feedstock)

	Animal fats	Tall oil	Glycerine	Tall oil pitch	Sawdust and cutter shavings	Black liquor	Distillers corn oil	PFAD
Fuel oil (EU)	0.92	0.90	0.89	0.40	0.47	0.36	0.92	0.92
Natural gas (EU)	0.74	0.73	0.37	0.32	0.38	0.15	0.74	0.74
Fuel oil (for CSS) (EU)		0.84						
Natural gas (for CSS) (EU)		0.69						
Fuel oil (RoW)	0.92	0.90	0.89	0.40	0.47	0.36	0.92	0.92
Natural gas (RoW)	0.74	0.73	0.72	0.32	0.38	0.15	0.74	0.74
Fuel oil (for CSS) (RoW)		0.84						
Natural gas (for CSS) (RoW)		0.69						
Soy oil		1.00					1.00	1.00
Palm oil	1.00	1.00					1.00	1.00
Feed corn	2.00		1.00				2.00	2.00
Pulpwood	1.95	1.92	1.90	0.84	1.00	0.76	1.95	1.95
Feed wheat	1.84		1.20				2.50	1.84
Coconut oil	1.00						1.00	1.00
Rapeseed oil	1.00						1.00	1.00
C5 hydrocarbon resins		1.00						
Forestry residues	1.95	1.92	1.90	0.84	1.00	0.38	1.95	1.95
Aggregate CTO substitutes*		1.00						
Feed barley			1.30					
Sunflower oil							1.00	
Coal (RoW)		1.37						
Coal (EU)		1.37						
Substitute biomass fuel	2.0	1.9	1.9	0.8	1.0	0.6	2.0	2.0
Substitute biomass fuel (for CSS)	1.82	1.79	1.77	0.79	0.93	0.54	1.82	1.82
Coal (for CSS) (RoW)		1.28						
Coal (for CSS) (EU)		1.28						

**See Table AI*

Substitution ratios not assessed where that substitution was not relevant to the modelling in this study.

B.3. Calculation of the 'renewable rebound'

In the European Union, renewable energy use is subject to targets. In the proposed RED II, there is a binding target of 27% for the contribution of renewable energy to overall EU energy supply. Assuming that targets for use of renewable energy in transport will be met, the remainder of the 27% target must be met through renewable energy in the heat and power sector.
This means that if biomass resources are displaced from existing use in the EU heat and power sector into biofuel production, the energy currently recovered from those resources would need to be replaced by new renewable energy generation elsewhere in the economy in order for targets to still be met. This is predicated on the assumption that renewables deployment is primarily policy driven, and that 2030 renewables targets will only just be met. If one expected the EU to achieve several percentage points above the required targets, then replacement would no longer be necessary. Recognising that it may not be necessary to fully replace lost renewable energy generation capacity due to slight over-compliance across the system, we assume that only 90% of displaced renewable energy generation will be replaced.

As it stands, somewhat more than half of renewable energy in the EU comes from biomass[71]. On the other hand, wind and solar energy generation has grown impressively in the past five years, and so it seems reasonable to assume that by 2030 biomass energy will have a reduced share. Predicting the marginal renewable energy generation likely to be brought into the mix to meet additional 2030 demand could be the subject of a whole report (indeed, whole research program). We do not attempt any sort of sophisticated modelling or calculation of cost hierarchies, and instead simply assume that half of replacement renewable energy would come from biomass, and half would come from zero-carbon electricity generation (presumably primarily wind and solar). For biomass renewables, we assume an average carbon saving of 66.5 gCO2e/MJ of energy consumed across heat and power applications, taken from research for the European Commission on the *Carbon impacts of biomass consumed in the EU* (Matthews et al., 2015). For additional zero carbon electricity generation, we assume that the displaced power generation would be from natural gas, on the basis that the contribution of coal and oil to power generation in the EU is already expected to decline substantially by 2030 (European Commission, 2016a). We take the carbon intensity of efficient natural gas electricity production to be 111 gCO2e/MJ (Hussy, Klaasen, Koornneef, & Wigand, 2014). This gives us an expected carbon saving through the renewable rebound of 88.8 gCO2e per megajoule of renewable energy replaced. We assume that existing combustion of biomass resources will be either for heat only or for heat and power with an average thermal efficiency of 80%. This gives a final renewable rebound displacement credit of 63.9 gCO2e per megajoule (lower heating value) of material displaced.

B.4. Sensitivity

As in any study of this nature, the results show considerable sensitivity to parameter choices. For indirect land use change, we have given an indication of sensitivity by presenting results for three cases (no ILUC, ILUC factors based on work with GLOBIOM, ILUC factors based on work with MIRAGE). For forest carbon stocks, we have similarly considered three cases (see below). We have not attempted systematic sensitivity or uncertainty analysis (for instance using Monte Carlo analysis), for one because it is beyond the scope agreed for the study, but more importantly because given the significant data challenges associated with an exercise of this sort, it is not clear how meaningful such an analysis would be (as there would generally be no clear basis to assess appropriate ranges or distributions

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[71] http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Primary_production_of_energy_from_renewable_sources,_EU-28,_1990-2015_F2.png

for the parameters to be varied). The model used for this study is fundamentally linear, and given the level of disaggregation provided in the results it should be possible for the reader to investigate the implications of changed assumptions on the mix of displaced materials or of changed assumptions on the greenhouse gas intensities of those materials.

B.4.1. Sensitivity to forest carbon stock assumptions

As noted above, the presumed environmental performance of fuels from feedstocks that may be replaced by harvested forest materials (fuelwood, pulpwood, forest residues) is highly dependent on assumptions regarding carbon stock change due to increased harvest. In this study, we consider three cases for the greenhouse gas intensity of additional wood harvest for fuel or materials use. In the central case, we assume a carbon debt value for pulpwood of 726 kgCO_2e/tonne (Searle et al., 2017). For the low emissions case, we also consider a best case scenario in which active management of forest carbon stocks and of harvest sustainability, along with expansion of forest area, allows additional removals for bioenergy to be delivered with no carbon stock change. For the high emissions case, we take the carbon debt value for pulpwood of 2,270 kgCO_2e/tonne for increased boreal wood harvest from Holtsmark (2012). The resulting ranges of calculated indirect emissions for affected feedstocks and for example derived fuels are shown in

Table AJ. Range of forest carbon stock change and total emissions for forest carbon stock affected feedstocks

	Materials production	Land use change (RED)	Forest carbon stock			Fossil fuel use	Renewable rebound	Total
kgCO2e/tonne			low	mid	high			
Tall oil derived HVO	234.1	177.1	25.0	137.2	375.9	1506.0	-445.9	**1608.5 (1496.3-1847.2)**
Sawdust and cutter shavings derived FT diesel	141.4	0.0	16.4	449.3	1369.5	293.5	-246.0	**638.2 (205.3-1558.5)**
Black liquor derived FT diesel	41.5	0.0	23.8	130.7	357.9	191.2	-180.8	182.5 (75.6-409.7)

Table AK. Range of forest carbon stock change and total emissions for example forest carbon stock affected fuels

gCO2e/MJ	Materials production	Land use change (RED)	Forest carbon stock			Fossil fuel use	Renewable rebound	Total
			low	mid	high			
Tall oil derived HVO	6.5	5.0	0.7	3.8	10.5	42.1	-12.5	45 (41.8-51.6)
Sawdust and cutter shavings derived FT diesel	14.9	0.0	1.7	47.3	144.2	30.9	-25.9	67.2 (21.6-164)
Black liquor derived FT diesel	5.7	0.0	3.3	18.0	49.4	26.4	-24.9	25.2 (10.4-56.5)

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Suggested reference

Malins, C. (2017). Waste not want not - Understanding the greenhouse gas implications of diverting waste and residual materials to biofuel production. Cerulogy and the International Council on Clean Transportation.

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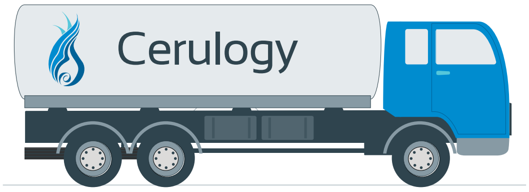
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