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Potential greenhouse gas savings from a 2030 greenhouse gas reduction target with indirect emissions accounting for the European Union

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1. Introduction

In November 2016, the European Commission proposed a new Renewable Energy Directive (RED II), setting a target of 27% for the share of renewable energy consumed in the European Union (EU) in 2030 (European Commission, 2016c). This proposal also includes a transport target for advanced alternative fuels that increases from 1.5% blending (by energy) in 2021 to 6.8% in 2030. There is a sub-target of 3.6% in 2030 for advanced biofuels made from feedstocks listed in Annex IX Part A of RED II, including various types of lignocellulosic biomass and wastes. A 1.7% cap in 2030 applies to feedstocks listed in Annex IX Part B of RED II, including used cooking oil, inedible animal fats, and molasses. Biofuels made from these feedstocks must meet a 70% greenhouse gas (GHG) reduction threshold, to ensure they are substantially better than conventional petroleum-based fuels. Renewable electricity used in vehicles, waste-based fossil fuels, and renewable fuels of non-biological origin are also eligible to help meet the transport target. The contribution of food-based biofuels to the overall 27% renewable energy target is capped at 7% in 2021 and declines to 3.8% in 2030; these fuels are not eligible to be used toward the transport target.

The transport target in the European Commission proposal is markedly different from 2020 EU policies for biofuels. The 10% renewable energy target for transport set in the Renewable Energy Directive for 2020 (RED; European Parliament, & Council of the European Union, 2009a) and the 6% GHG reduction target for transport set in the Fuel Quality Directive (FQD; European Parliament, & Council of the European Union, 2009b) are both expected to be met largely with food-based biofuels. These targets have been controversial due to the issue of indirect land use change (ILUC), which refers to the global market-mediated agricultural expansion in response to biofuel demand. It has been estimated by various studies and regulatory analyses in other jurisdictions that ILUC leads to substantial GHG emissions for food-based biofuels in general (CARB 2015d; EPA 2010; Laborde, 2011; Valin et al., 2015). In 2015, the ILUC Directive introduced requirements for reporting of ILUC emissions for the 2020 transport targets (European Parliament & Council of the European Union, 2015), but ILUC emissions will not be included in the regulatory accounting of the GHG impacts for the purposes of these policies.

The proposed 2030 transport target similarly does not include accounting of indirect emissions. The exclusion of food-based biofuels from the transport target effectively avoids the issue of ILUC from these fuels. However, non-food feedstocks that are eligible in the current proposal can also have land use and other indirect emissions (ICF International, 2015). Accounting for indirect emissions

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would not fundamentally change the target, because the target is for a certain amount of energy rather than GHG reduction, but it would affect the ability of Annex IX biofuels to meet the 70% GHG reduction. Were the current proposed transport target converted to a GHG reduction target, similar to the current FQD, inclusion of indirect emissions accounting would substantially change how the target is met, providing greater policy value to those pathways with greater emission reductions over the complete lifecycle.

In Section 2, we discuss indirect emissions of non-land use alternative fuel feedstocks and present an assessment of the indirect emissions of advanced fuel pathways eligible for the transport target in the current proposal. Few previous studies have attempted to assess indirect emissions for non-land based advanced fuel pathways, and few data are available for conducting this type of analysis. We thus provide the first estimates of indirect emissions for these pathways to better understand the broad impact of the current 2030 proposal and changes that could potentially be made to the target structure. Given the rising importance of non-land-based alternative fuels in EU policy and in other jurisdictions, further research is necessary to refine these estimates and to understand how the indirect emissions of these pathways may change over time.

In Section 3, we assess several questions related to the policy design of Europe's advanced fuel target by estimating the GHG emission impacts of the 2016 policy proposal compared to a GHG reduction target. We assess this impact for a GHG target with and without indirect effects accounting to provide better understanding of the climate impacts of these policy design choices.

Section 4 provides further detail on the methodological approach used in these analyses, along with data sources and assumptions. Supplementary data and assumptions are provided in the Annexes.

2. Indirect emissions of advanced fuel feedstocks

2.1 Background

The proposed Renewable Energy Directive for 2030 (RED II) states that "no emissions shall be allocated to wastes and residues [...] wastes and residues [...] shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection." This logic is entirely appropriate for waste materials with no use other than final disposal—for example, household garbage that is destined for a landfill. However, not many materials are purely "wastes" in this sense. We might consider used aluminum cans to be a waste when we discard them in a recycling bin, but those cans have a high value when it comes to recycling them into aluminum products. If everyone stopped recycling aluminum, more new raw material (in this case, bauxite ore) would need to be extracted, and more energy would be required to convert it into aluminum. The new electricity demand for refining the ore greatly exceeds the energy used to recycle used aluminum. In total, this would cost aluminum producers more money and generate greater GHG emissions from the processing of larger amounts of ore.

Similarly, most of the feedstocks listed in Annex IX of the proposal that are typically described as "wastes and residues" are not truly wastes and are not typically discarded in landfills. Molasses is used in livestock feed and is the primary input for yeast production (OECD-FAO, 2016). Inedible animal fats are used in soaps and other oleochemicals, or is burnt for power (Chudziak & Haye, 2016; Ecofys, 2012). Sawdust is used to make paper or particleboard, or is burnt for power (Mantau, 2012). If these materials are diverted from their current uses to produce biofuel, the other industries that use them will be impacted. If 100% of EU-produced molasses, for example, were used as an ethanol feedstock in 2030, there would be no molasses used in livestock or yeast. There would still be demand for bread and beer, and yeast requires a substrate for its growth—so the industry might turn to using raw juice from sugar beets instead. Then, more sugar beets would have to be grown to meet the increase in demand, and that comes with emissions from land use change and from fertilizing and harvesting the feedstock. Livestock require feed, and so farmers might add more corn and barley to livestock feed to make up the shortfall in calories. Again, producing more of these substitute feedstocks will lead to increased GHG emissions.

One might argue that if these displacement effects are small, there is no need to account for them at all. In the above example, molasses accounts for only approximately 0.5% of livestock feed in the EU. How can removing such a small component make a difference? The answer is that summing up that 0.5% over millions of cows, pigs, and sheep for all feed consumed over an entire year is in fact a large and significant quantity (approximately 1.5 million tonnes; OECD-FAO, 2016) that must be replaced with substitute feedstocks. And when we spread the emissions associated with producing those feedstocks over the quantity of ethanol that would be produced (around half a million liters), the increase in lifecycle GHG emissions per liter is not at all small: these indirect effects reduce the GHG benefits of molasses ethanol by more than 30% (see results below).

The lesson here is that very few materials are truly available emissions free. Even household waste, referred to at the beginning of this section, is often incinerated with energy recovery. If that waste is turned into biofuel, an additional source of power generation will be necessary to replace it. If there is any current productive use of a material, even if it sounds like a waste, then a displacement analysis—identifying what materials would be used to replace the feedstock and the emissions associated with it—is necessary for understanding the climate impact of using that material for alternative fuel (ICF International, 2015). On the other hand, diverting household wastes from landfills can reduce climate-forcing methane emissions. In fact, biofuels made from such feedstocks can actually have negative indirect emissions, and it is important to account for this credit as well.

We note that a displacement analysis is a different lifecycle analysis technique in place of the allocation of upstream emissions. As an example of how the latter analysis would apply, we consider the case of soybeans. Soybeans are crushed to produce both protein-rich soymeal and soy oil—both high-value products. When assessing the GHG emissions from producing the soybeans, one might assign a portion of the fertilizer and harvesting emissions to soymeal, and a portion to the soy oil, but none of the impacts are attributed to the crop residue (the dead stalks and leaves after harvesting). This makes sense since no one will grow more soybeans or otherwise change their production process to make more soy residue. When the RED II proposal states that "No emissions shall be allocated to wastes and residues," it means that, in this example, no emissions from producing soybeans shall be allocated to soy residue. Although this is a reasonable approach for allocating upstream emissions among products, it does not reflect what happens if the soy residue is diverted from its current use as livestock fodder.[1] A displacement analysis is the more appropriate tool for quantifying the emissions associated with growing more corn or hay to replace the soy residue.

Despite the strong policy relevance of understanding the indirect emissions of wastes and residues, few studies have undertaken such an analysis. Perhaps the best-known example is a report conducted by Brander et al. (2009) for the United Kingdom (UK) Renewable Fuels Agency, assessing the indirect emissions of tallow, biogas from municipal solid waste (MSW), wheat straw, and molasses. The results of this study for tallow, in particular, have drawn attention, as the central estimate for indirect emissions for this feedstock almost erases its GHG savings entirely (total GHG emissions of 74 gCO_2e/MJ for tallow compared with 86 gCO_2e/MJ for the fossil diesel comparator).

2.2 Analytical approach and results

In this study, we conduct displacement analyses for selected advanced alternative fuel pathways that are eligible to be used for compliance with the proposed transport target in the EU, and these results are presented in Table 2.1. We note that these are first estimates aimed at understanding the broad GHG impacts of the current proposal, and that our work was limited by data availability. Further research is needed into each of these pathways and any others that may be of importance to the 2030 fuel supply. These estimates may change as additional data become available or as the markets for these feedstocks change over time. The direct emissions shown in Table 2.1 are taken from the RED II proposal where available and are otherwise taken from approved pathway applications for California's Low Carbon Fuel Standard (LCFS; CARB, 2017) or from the available scientific literature. Net GHG emissions are compared to the revised fossil fuel comparator (94.1 gCO_2e/MJ) in the proposal (European Commission, 2016c). More details on estimation methodology, assumptions, and data sources are available in Section 4.

There are a few things to note in Table 2.1. The first is that for perennial grasses and short rotation woody crops—both considered types of energy crops—we did not conduct a displacement analysis, because these are primary crops grown on land. A land-use change analysis is thus more appropriate, because it captures the changes in agricultural area and land carbon stocks for new production. Here we included land-use change emissions from the recent study using the GLOBIOM[2] model (Valin et al., 2015). The estimates for these pathways are negative, indicating that land-use change from these crops actually reduces GHG emissions compared to a baseline case without these crops, primarily because these types of energy crops tend to build soil carbon where they are grown (Valin et al., 2015). The net GHG emissions profile of these crops is thus quite favorable.

Another outlier in this analysis is whole logs from pulpwood or other

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[1] To the best of our understanding, the bulk of soy residue is not used as livestock fodder in the EU, but this may be an occasional use of the resource.

[2] Global Biosphere Management Model

Table 2.1 Direct and indirect emissions for feedstocks eligible under the proposed transport fuel target (low and high ranges in parentheses)

Pathway	Direct emissions (gCO_2e/MJ)	Indirect emissions, central estimate (and range) (gCO_2e/MJ)	Total emissions (gCO_2e/MJ)	Net GHG emission reduction	Displaced uses
Perennial grass ethanol	14	–12	2	97%	GLOBIOM LUC estimate
Short-rotation woody crop biofuel	22	–29	–8	109%	GLOBIOM LUC estimate
Power to liquids from excess renewable generation	4	0	4	96%	No displacement
Algal biodiesel	14	0	14	85%	No displacement
Straw ethanol	14	8 (4–11)	22 (18–26)	77% (73%–81%)	Livestock bedding and feed; mushroom cultivation; horticulture; heat and power. Sustainable straw removals assumed.
Forestry residues Fischer Tropsch (FT) diesel	14	6 (3–8)	20 (17–22)	79% (76%–82%)	Heat and power. Sustainable straw removals assumed.
Palm oil mill effluent (POME) renewable diesel	27	0	27	71%	Heat and power (zero carbon residues used as substitute)
MSW landfill biogas compressed natural gas (CNG)	19	–20 (–24 to –14)	–1 (–5 to 4)	101% (96%–106%)	Heat and power; avoided landfill emissions
MSW FT diesel	15	–41 (–49 to –17)	–26 (–34 to –2)	127% (118%–136%)	Heat and power; avoided landfill emissions
Molasses ethanol	22	32 (29–36)	53 (50–57)	43% (39%–46%)	Livestock feed; yeast
Black liquor FT diesel	10	29 (16–43)	39 (27–53)	58% (44%–72%)	Heat and power
Pulp logs/ fuelwood FT diesel	21	67 (55–73)	88 (76–93)	7% (1%–19%)	Paper; heat and power
Crude tall oil biodiesel	13	89 (88–90)	102 (101–103)	–8% (–9% to –7%)	Tall oil rosin applications; tall oil fatty acid applications; distilled tall oil; drilling/mining additive; heat and power
Sawdust and cutter shavings ethanol or FT diesel	14	52 (41–60)	67 (55–74)	29% (21%–41%)	Paper; wood products; heat and power
Glycerine ethanol	24	88 (84–93)	112 (108–117)	–19% (–24% to –15%)	Livestock feed; cement production
Manure biogas CNG	14	-6.0 (–12 to -3)	8 (1–10)	91% (88%– 98%)	Avoided methane emissions
Used cooking oil biodiesel	16	0	16	83%	No displacement
Animal fats biodiesel	20	22 (16–30)	42 (35–49)	55% (48%–62%)	Oleochemical applications; heat and power
Steel mill flue gas ethanol	12	13 (11–15)	26 (24–27)	73% (71%–75%)	Heat and power
Forest thinnings FT diesel	21	81 (74–84)	101 (95–104)	–7% (–10% to 0%)	Heat and power, paper

low-quality fuelwood because they can be considered a primary crop. These feedstocks are eligible in the current proposal even though they are not wastes or residues. Annex IX Part A lists "other ligno-cellulosic material […] except saw logs and veneer logs" as eligible; pulp logs and other low-quality logs are not excluded. Similar to energy crops, the most appropriate analysis to assess the indirect emissions of this pathway would be an ILUC analysis similar to Valin et al. (2015). However, we are not aware of any such analysis that has been conducted for pulp logs. A multitude of studies have assessed the direct land-use change emissions of whole trees or roundwood used for bioenergy, typically presenting results as the "payback period" necessary for tree growth to offset the original loss of biomass stocks (reviewed in JRC, 2014; Lamers & Junginger, 2013). This type of analysis inherently assumes that an additional unit of demand for roundwood is met by an additional unit of roundwood production and does not capture the market-mediated effects that would occur if pulp logs and fuelwood were displaced from their current uses in pulp production and heat and electricity generation. An increase in demand for pulpwood and fuelwood biofuel would lead to an increase in the price for these feedstocks, and this would likely result in a variety of impacts, including a degree of switching to other types of renewable heat and electricity sources, such as wind or solar, and a reduction in demand for pulpwood and in all other markets to which a pulpwood price increase is transmitted. Because we did not have the resources to conduct an ILUC analysis for pulp logs and fuelwood, we conducted a displacement analysis to capture these indirect effects to some extent. We assessed that an increase in pulpwood and fuelwood demand for biofuel results in a combination of: increased pulpwood and fuelwood production, increased generation of heat and power from other renewable sources, and demand reduction. This method results in a lower estimate of indirect emissions for the pulpwood and fuelwood biofuel pathway compared to using estimates of direct land-use change.

When interpreting these results, it is important to consider the potential environmental impacts of using agricultural and forestry residues for biofuel. The complete removal of these materials from the field or the forest floor has been shown to result in soil carbon loss through increased erosion and reduction of carbon inputs (reviewed in Searle & Malins [2016]). This body of research is reflected in the results of land-use change emissions for these pathways in Valin et al. (2015): In scenarios of 100% residue removal, this study estimates land-use change emissions of 16 gCO_2e/MJ and 17 gCO_2e/MJ for agricultural and forestry residues, respectively. Soil carbon loss may be avoided, however, with only partial residue removal and sustainable management practices, although the science on how to develop sustainable removal rates and management practices is still evolving. Valin et al. (2015) noted that "it can be concluded that the land use change (LUC) value of 16 gCO_2e/MJ biofuel consumed would become 0 gCO_2e/MJ if a sustainable straw removal rate was introduced limiting the straw removal to once every two to three years or 33–50%." In the United States, agricultural residue removal for biofuel projects has followed this guidance with conservative rates of removal (Kemp, 2015).

For the purposes of this analysis, we thus assume that agricultural and forestry residues are removed at sustainable rates and do not add GHG emissions occurring from soil carbon loss. It is important to emphasize, however, that sustainable management practices must be followed to ensure that high GHG savings are achieved for biofuel produced from straw and forestry residues. Such practices could be encouraged or required through expanded sustainability criteria for biofuel feedstocks in the 2030 RED proposal. Displacement emissions were estimated for these pathways in Table 2.1 to reflect current usage in heat and power generation (for straw and forestry residues) and livestock bedding and feed, mushroom cultivation, and horticulture (for straw). The details of these calculations and all other assumptions and data are provided in Section 4.1.

3. Advanced fuel target design

3.1 Background

The RED and FQD provide two different types of low carbon fuel policies for 2020. As described in the introduction, the RED requires 10% renewable fuel blending by energy, and the fuel used to meet this target must meet a GHG reduction threshold (of 50% or 60% depending on when the facility began operation). The policy is designed to ensure that only low-carbon fuels are used and therefore should lead to a certain total level of GHG reduction in the transport fuel mix (although it is noted that the lack of accounting for ILUC emissions puts that goal at risk). The FQD, on the other hand, directly targets GHG reductions through a requirement to reduce the GHG intensity of the road fuel mix by 6% in 2020. Both of these types of policy design are used in other jurisdictions. For example, the U.S. federal Renewable Fuel Standard

(RFS) introduces volume targets that must be met with biofuels meeting certain GHG reduction thresholds, similar to the RED. California's LCFS requires a 10% reduction in the GHG intensity of the road fuel mix in 2020, similar to the FQD.

It appears that only one policy design will be used at the EU level after 2020. According to the Commission's 2030 RED proposal, the emerging policy design would be an energy target with a GHG reduction threshold. In this section, we explore what the impacts would be if this target were transformed into a GHG reduction target that supplies a similar total amount of renewable energy, like the FQD.

A GHG reduction target is designed specifically to drive GHG reductions. In theory, it can do so more effectively than a volume or energy target for two reasons. The first is that a GHG target better incentivizes specific fuel pathways that offer better GHG savings. For example, we may consider two fuel pathways: Fuel A delivers 70% GHG savings, whereas Fuel B delivers 100% GHG savings. Both would be rewarded equally under an energy target. If Fuel A is 10% less expensive to produce, we would expect to see Fuel A deliver a greater share of the target. With a GHG reduction target, Fuel B would be valued around 40% more highly than Fuel A under the policy, because 1 liter of Fuel B gets us closer to the overall GHG reduction target than does 1 liter of Fuel A. Even though Fuel A is less expensive, the additional value of the policy incentive more than compensates for this, and we would expect to see Fuel B contribute a greater share to the target. This example highlights how the GHG reduction target appropriately evaluates fuels on a spectrum, accounting for both their relative benefits and costs, therefore identifying and promoting the most cost-effective low-carbon fuels.

The second reason a GHG target with fuels evaluated on a spectrum can be expected to drive greater emission reductions compared to an energy target is because it better incentivizes efficiency improvements within a pathway. Returning to the example of Fuel A (i.e., with a 70% GHG reduction), efficiency improvements might be possible but would be too expensive to implement based on the cost balance alone. Because Fuel A already meets the GHG reduction threshold of the energy target, the policy does not provide an incentive to further reduce GHG emissions through efficiency improvements. A GHG target, on the other hand, would provide greater value to a more efficient Fuel A, and the additional policy support may make it economical to implement those improvements. This effect can be observed in California's LCFS, where the direct carbon intensity reported in approved pathway applications for first-generation corn ethanol has declined by 2% per year from 2010 to 2015.[3]

Because GHG targets directly incentivize GHG reductions, they can more effectively drive GHG reductions per unit fuel that is supported. In theory, a switch from an energy or volume target to a GHG target should allow the EU to either (a) achieve greater GHG reductions for the same total amount of fuel delivered, or (b) achieve the same GHG reductions through a lower amount of fuel, possibly with reduced cost to obligated parties.

3.2 Analytical approach and results

In this analysis, we compare the GHG savings that would be achieved with a GHG target versus the currently proposed energy target for the same total amount of energy. As a starting point, we estimate the volumes of fuel that could be delivered for each of the pathways listed in Table 2.1 at varying costs. For the energy target scenario, we assess how the required amount of fuel would be achieved at the lowest cost, and assess the full lifecycle emissions (including the indirect emissions values presented in Table 2.1) of that fuel mix. For the GHG target scenario, we assume that financial support is provided to each fuel pathway based on its lifecycle GHG intensity, and that pathways offering higher GHG reductions receive a greater level of cost reduction. We then assess how the required amount of fuel (assumed to be the same as required under the currently proposed energy target) would be achieved at the lowest net cost, and assess the full lifecycle emissions. These results are presented in Figure 3.1. The model structure, assumptions, and data sources are presented in Section 4.2.

In Figure 3.1, the columns show the amount of energy (in million tonnes oil equivalent) that is expected to be delivered by each type of feedstock and fuel in 2030 for each of the three policy scenarios. The total amount of energy is the same across the three policy scenarios. The total amount of GHG emission reductions, including direct and indirect emissions (in million tonnes CO_2e), is represented by the diamond symbols, with values displayed on the right axis.

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[3] According to a linear regression performed on the direct carbon intensity (calculated as the total carbon intensity minus land use change emissions of 30 gCO_2e/MJ) of all approved pathways for corn ethanol prior to January 1, 2016. After this point in time, the LCFS was formally readopted with changes in GHG calculation methodology. Historical pathways data were retrieved from CARB (2017).

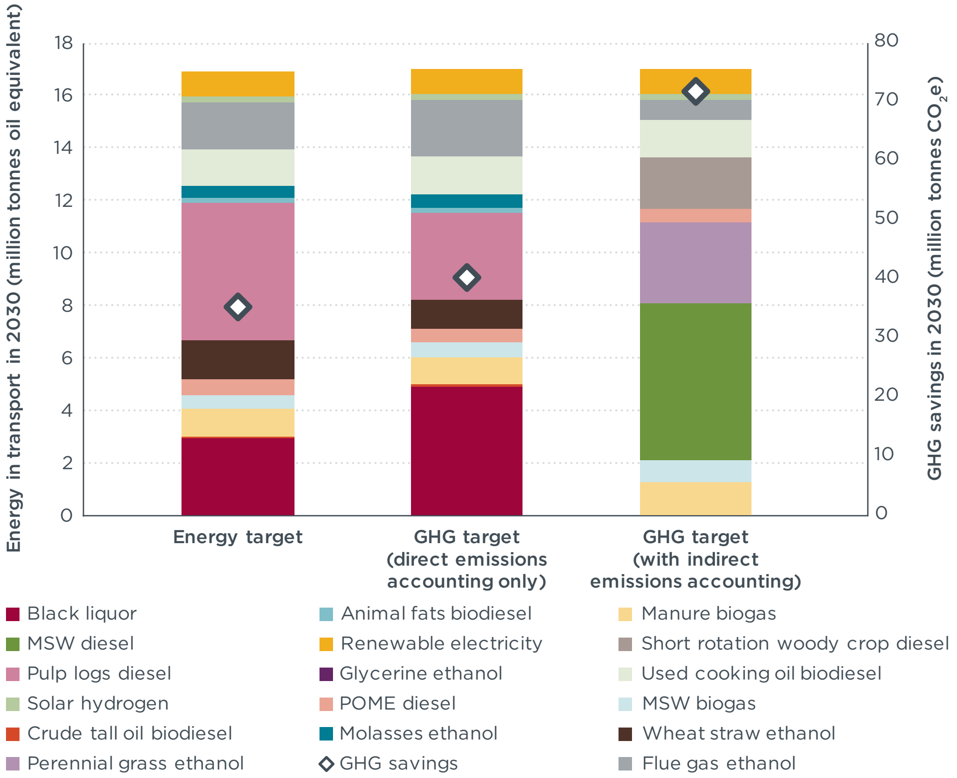

Figure 3.1 Estimated lifecycle GHG emissions savings for the proposed renewable energy transport target compared to a GHG reduction target design with and without indirect emissions accounting

In each of the three scenarios shown in Figure 3.1, the target of 6.8% of road and rail transport is met with alternative fuels, but with varying levels of GHG reduction. We estimate that the currently proposed energy target for 2030 would achieve a 3.5% reduction in the GHG intensity of the road and rail transport fuel supply, whereas a GHG target based on direct emissions accounting only would achieve a 4.0% GHG intensity reduction (an improvement of 14% over the current proposal) and a GHG target based on full lifecycle emissions accounting would produce a 7.2% GHG intensity reduction (an improvement of more than 100% over the current proposal).

The mix of alternative fuels is expected to be largely similar between the current proposed energy target and a GHG target based on direct emissions accounting only. This is largely because there is no high variation in direct emissions among the eligible pathways (Table 2.1). However, a GHG target would more strongly incentivize some pathways with lower direct emissions intensity, such as black liquor (89% direct GHG savings according to the current proposal), over those with more limited direct emissions savings, such as pulp logs and fuelwood (if we assume the rating of 79% direct GHG savings for "farmed wood" in the proposal). In addition, in this analysis, we assume a 1% annual improvement in direct emissions for all pathways by 2030 in response to the incentives with a GHG target; this represents half the rate at which direct emissions at corn ethanol facilities supplying fuel under California's LCFS have been reduced over time (see discussion above).

A GHG target with indirect emissions accounting would be expected to deliver a markedly different mix of fuels than the first two scenarios. With indirect emissions accounting, there is much greater variation in the full lifecycle GHG intensity scores among the pathways that are eligible in the current proposal (see Table 2.1). In this scenario, we assume that the 70% GHG reduction threshold in the proposal still applies, and this criterion rules out several feedstocks that contribute heavily to the targets in the first two scenarios, including pulpwood and fuelwood, black liquor, crude tall oil, and molasses. Our analysis suggests that including indirect emissions accounting in a GHG target would heavily incentivize biofuels made from energy crops, including perennial grasses and short rotation woody crops, and municipal solid waste, because each of these pathways delivers negative to near zero lifecycle emissions. Renewable electricity and hydrogen used in vehicles is assumed to be driven by policies that support electric and hydrogen fuel cell vehicles and charging infrastructure, and so the contribution of these pathways to the policy targets is the same in all three scenarios.

Although this analysis may provide a useful indication of the broad changes that could be expected under different types of policy targets, we caution the reader against interpreting the results closely. As with the analysis on indirect emissions for these pathways presented in Table 2.1, limited data are available and there is high uncertainty regarding the costs of novel alternative fuels, and this is a major driving factor in the analysis presented in Figure 3.1. These results should not be taken as precise predictions of volumes of each pathway for 2030, but rather as a general picture of what types of feedstocks would be more strongly supported. However, although there is high uncertainty in our analysis, these results support a theoretical basis for believing that (a) a GHG target would better incentivize emission reductions compared to an energy target, and (b) a policy framework that accounts for indirect emissions will drive substantially deeper GHG reductions compared to one that does not.

4. Methods

4.1 Methodology of indirect emissions analysis

4.1.1 Lifecycle assessment methodology

There is no standard or "right" way to conduct a lifecycle assessment, and, in any analysis, methodological choices must be made. In this study, we made these choices based on practicality with the goal of assessing the broad impact that alternative fuels policy will have on global climate change. Other researchers could use all the same data sources and assumptions as this study and come up with different answers based on their choice of lifecycle assessment methodology. In this section, we explain the methodological choices used in this analysis and alternative choices that could be made.

For energy crops, including perennial grasses and short rotation woody crops, we applied the land-use change emission estimates from Valin et al. (2015). For each of the remaining pathways assessed in this study, we conducted a displacement analysis. In its report on the lifecycle treatment of alternative fuel feedstocks, ICF International (2015) proposed categories for alternative fuel feedstocks, including primary products, co-products, byproducts, wastes, and residues. ICF International (2015) recommends an allocation approach to assigning upstream production emissions between primary products and co-products, which are products that are responsible for a share of the overall economic demand for a product system. For byproducts, residues, and wastes, on the other hand, ICF International recommends a displacement analysis be performed to assess the indirect emissions associated with diverting those materials from their other uses. A displacement analysis utilizes "system expansion" to expand the boundaries of the product system, wherein the upstream emissions associated with producing a material's substitute are attributed to the material diverted from its existing use. In our study, we conducted a displacement analysis for one feedstock, pulp logs and fuelwood, which should be considered a primary product. In Section 2, we argue that a land-use change analysis using an economic model would be a more appropriate way to assess indirect emissions for this feedstock, but that such an analysis is beyond the scope of the present study. We chose to conduct a displacement analysis for this feedstock to at least partially account for the market impacts of diverting it from its current uses to biofuel, because this is likely to provide a more accurate picture than simply using direct land-use change estimates.

We did not assign displacement emissions to energy crops, power-to-liquids made with excess renewable electricity, and hydrogen from solar electrolysis because these feedstocks are not yet produced in significant volumes and thus do not have existing uses that could be displaced. To the extent that energy crops could displace production of other crops on agricultural land, such emissions are accounted for in the land-use change emissions reported in Valin et al. (2015). We also did not assign displacement emissions for algae. Although algae is currently produced and consumed in other uses, these uses are generally high value (e.g., nutritional supplements), and we consider it unlikely that demand for fuel, which has a much lower value, will displace these existing high-value uses. We did assess used cooking oil (UCO) and palm oil mill effluent (POME), but concluded that the displacement emissions for these feedstocks are zero; our reasoning is explained further below.

For the remaining pathways, we used a methodology roughly similar to that presented in the report by Brander et al. (2009) for the UK Renewable Fuels Agency, which assessed the indirect emissions of tallow, biogas from MSW, wheat straw, and molasses. We determined the existing non-fuel uses of each feedstock and assumed that displacement would occur equally across all these uses. For example, if 70% of molasses that is not used for biofuel is used for livestock feed and 30% for yeast, we assume that an additional tonne of molasses used for ethanol will displace 0.7 tonnes of molasses in livestock feed and 0.3 tonnes in yeast production. An alternate strategy that could be used here would be to assess which existing uses would be displaced first; this approach is termed the "order of dispatch" by Brander et al. (2009) and would be made "based on consideration of price and technical, consumer preference, or regulatory constraints, and any other determining factors." To continue the molasses example, if we can tell that one of the substitute materials for livestock feed (corn) is cheaper than the substitute material for yeast production (raw juice from sugar beets) based on the amount of molasses displaced, then we would have reason to believe that molasses would first be displaced from livestock feed before it is displaced from yeast production. This approach could more accurately predict actual displacement effects than the weighted average approach we used, although we note that the order of dispatch method cannot be entirely accurate either. In reality, we would expect the price of the substitute material for the first use (corn) to rise as demand for it rises, and some amount of molasses would likely be displaced from the second use (yeast production) before all molasses is displaced from livestock feed. We chose to use the weighted-average approach primarily because we lacked the data necessary to determine the order of dispatch for several feedstocks.

We also note that in a perfectly complete displacement analysis, one would consider not only existing uses of a feedstock, but also what would happen to the feedstocks if there were zero demand for biofuel. This could potentially include potential future uses that do not exist yet or changes to current uses. This follows the logic of ILUC modeling in comparing the counterfactual scenario (with increased biofuel demand) to a baseline scenario (without the increased biofuel demand). In the molasses example, perhaps we would expect yeast production to drop to 2030 due to lower bread demand in response to changes in dietary patterns. We would then assign a lower share of displacement emissions to yeast. In a few select cases (described below), we did account for expected changes in uses of materials to 2030, but, in most cases, we did not have the data available to do so.

A related decision was to set the baseline at the present, considering only current non-energy uses of feedstocks. One feedstock where this methodological choice has a significant effect is used cooking oil. Currently, the EU imports large quantities of used cooking oil from the United States for use in biofuel (USDA, 2015). Historically, used cooking oil in the United States was used in livestock feed (Nelson & Searle, 2016). Used cooking oil cannot be used in livestock feed in the EU and currently has no non-biofuel uses in the EU (Hillairet, Allemandou, & Golab, 2016). However, it appears that currently all U.S. used cooking oil is either used domestically for biodiesel production or is exported to the EU for biodiesel production (Nelson & Searle, 2016); thus, there is no longer any non-fuel use of the material. If we define the baseline scenario as "zero EU biofuel demand," then we must ask: what would happen to the U.S. used cooking oil that is currently exported to the EU? It might be used in livestock feed, in which case we would assess the displacement emissions of livestock feed. However, it might be used in increased U.S. biodiesel production, and there is reason to believe that this would actually be the case: the U.S. federal RFS program tends to set annual biodiesel volumes at expected production levels, rather than any particular policy target (e.g., EPA, 2016b). If the EU had zero demand for biofuels, we might then expect to see higher US biodiesel targets. U.S. used cooking oil would thus be used entirely for biodiesel with or without EU biofuel demand. Thus, it is not clear that setting the baseline scenario as "zero EU biofuel demand" would produce a different answer on the indirect emissions of used cooking oil. In any case, we did not have sufficient data to set the baseline at "zero EU biofuel demand" for all feedstocks, and so we chose to set the baseline at current usage.

We selected substitute materials with elastic supply for all analyses, following ICF International (2015) to avoid conducting second- and third-order displacement analyses. For example, the immediate effect of increasing demand for molasses in biofuel may be that greater volumes of molasses are imported to the EU from Brazil, where molasses would otherwise be used to produce ethanol. Because Brazil would still have a high demand for ethanol, the country would produce higher quantities of sugarcane than it would in the baseline scenario. The net result would thus be increased use of sugarcane. Applying the approach recommended by ICF International to assume only substitute materials with elastic supply would, in effect, short-circuit this double displacement analysis by assuming EU molasses is replaced by sugarcane (in our analysis, detailed below, we assume increased sugar beet production, but the results would be very similar for sugarcane).

An important decision we made was to count emissions from displacement of feedstock from non-biofuel energy uses. For example, black liquor is primarily used to generate power and steam (i.e., heat) for pulp mills, and we considered the effect that biofuel demand would have on the use of heat and power in pulp mills. ICF International (2015) recommends the opposite—not accounting for displacement from other energy uses. The reasoning presented in that report is that if one conducted a displacement analysis for use of a material in biofuel (displacing use in power) and did the same for use of the same material in the power sector (displacing use in biofuel), one would be double counting displacement emissions and unfairly penalizing the feedstock for displacing uses in both the power and biofuel sectors at the same time. Another argument for not accounting for displacement of other energy uses is that there is no reason to encourage the use of a feedstock in one energy sector over another; indeed, Pavlenko, El Takriti, Malins, & Searle (2016) found that there is no clear benefit in terms of GHG reductions to using advanced biofuel feedstocks in the transport sector over heat and power, and vice versa. If black liquor is used to displace petroleum in the transport sector instead of displacing electricity, the climate benefits will be similar. Although these arguments have merit, we have decided to account for displacement from other energy uses, to differentiate between feedstocks that would displace other energy uses and those that would not. The climate benefits may be the same if one is simply choosing between black liquor use in transport vs. heat and power, but the present situation is not that simple. With an advanced alternative fuel mandate, we effectively have the choice to use black liquor, displacing it from heat and power generation, or to use perennial grasses that are not currently used for anything. The overall climate benefit is clearly higher if we continue using black liquor for heat and power and incentivize using perennial grasses for biofuel, compared to a scenario where we use black liquor for biofuel and produce heat and power from alternate feedstocks. The second reason we chose to account for displacement from non-fuel energy uses is that indirect emissions are currently not accounted for in EU incentives for heat and power, and it does not appear that such accounting is likely to occur in the near future. One could imagine a potential situation in which displacement emissions for non-fuel energy uses are accounted for in biofuel policy, and, a few years later, displacement emissions are estimated for feedstocks used in heat and power. In that case, it may be appropriate to avoid counting displacement from fuel uses in heat and power policy at that time.

A final argument that is sometimes presented for why displacement from non-fuel energy uses should not be accounted for is that the usage in heat and power is likely to be replaced with new renewable electricity generation, associated with zero emissions. We agree that displacement of biofuel feedstocks from heat and power is likely to result in increased generation of other renewables because of incentives to meet renewable energy targets in the EU. However, we disagree that new renewable electricity generation will be zero carbon. Although wind, solar, geothermal, and hydro electricity may all be very low carbon, much of the EU's current renewables mix is from biomass, and much of that is from pulp logs and other low-quality fuelwood, which, as we discuss in more detail below, is associated with significant emissions. In our analysis, we thus assume that usage of renewable feedstocks in heat and power will be replaced by a mix of renewable heat and power sources, but that this mix carries a non-zero carbon intensity. The net result is that black liquor, for instance, does have significant displacement emissions. In some cases, this treatment may not reflect the first-order effects of feedstock diversion. For example, crude tall oil used in heat and power is likely to be replaced by fuel oil, as fuel oil would be better suited to crude tall oil boilers than other feedstocks. We assume that more fuel oil used in crude tall oil boilers would result in less fuel oil used somewhere else in the EU, and greater production of other renewables due to renewable energy targets. The final result is greater production of other renewables in any case.

A final methodological choice was to assume a 10% demand reduction in all non-biofuel uses of feedstocks. The reasoning behind this is that an increase in demand for a material due to a biofuel mandate will lead to an increase in the price of that material, and as a result, other users of the material will reduce their overall consumption. To follow the molasses example, an increase in usage of molasses for biofuel will increase the molasses price. Some livestock farmers will thus stop buying molasses for feed and will instead buy more corn and barley (this is the displacement effect). Because corn and barley are more expensive than molasses, it is overall more expensive to raise livestock. The farmers would thus charge higher prices for meat. Some price-sensitive consumers would choose to buy less meat as a result. Once the system equilibrates, this would result in lower livestock production, lower livestock feed consumption, and lower emissions associated with producing livestock feed. To a lesser extent, one would also expect there to be a second-order demand reduction effect if the increased demand for corn and barley result in price increases of those commodities, leading to reduced demand for corn and barley in livestock feed but also in food consumption—this effect is accounted for in ILUC modeling. In our analysis, we apply ILUC estimates to all applicable materials, which should factor in this second-order demand reduction. For the first-order demand reduction effect that we assume in our analysis (the reduction in livestock production due to molasses price increase), we assume this effect to be 10% because this is roughly consistent with the level of food demand reduction factored into ILUC models (reviewed in Malins, Searle, & Baral [2014]) and with estimates of indirect fuel use change (reviewed in Malins, Searle, & Pavlenko [2015]). We apply this assumption of demand reduction to all first-order displaced uses of materials, including heat and power, and it reduces all our estimates of indirect emissions compared to not accounting for it.

4.1.2 Assumptions and data sources

Supplemental data is provided in Annex A.

Direct emissions: We took direct emission values from the 2030 RED proposal (Annex V) where available. This included: animal fats from rendering, wheat straw, farmed wood (applied to short rotation woody crops, forest thinnings, and pulp logs/fuelwood), waste wood (applied to sawdust and forestry residues), waste cooking oil, and black liquor. For biogas from municipal solid waste and manure, we took direct emission values from the 2020 RED (European Parliament, & Council of the European Union, 2009a), assuming the average for wet and dry manure. Perennial grasses ethanol was assumed to have the same direct emissions intensity as wheat straw ethanol. Power-to-liquids using excess renewable electricity was taken from Schmidt, Weindorf, Roth, Batteiger, & Riegel (2016). Renewable electricity used in vehicles was assumed to have zero emissions. Algal biodiesel was assumed to have the same direct carbon intensity as Joule Unlimited Technology's application for algal ethanol under the RFS program (EPA, 2016a). The direct carbon intensity for solar hydrogen was taken from AC Transit's application under California's LCFS program (CARB, 2015a). The value for MSW Fischer-Tropsch (FT) diesel was taken from Fulcrum Sierra BioFuels' application to California (CARB, 2015c). For molasses, it was taken from Copersucar's application to California (CARB, 2015b). For crude tall oil, it was taken from Sunpine (2011). Our direct carbon intensity for flue gas ethanol of 12 gCO_2e/MJ is from Hamelinck (2015). To the best of our knowledge, there are no estimates for the direct carbon intensity of POME renewable diesel. We estimated this based on direct emissions for hydrotreated palm oil (subtracting cultivation emissions) from the 2030 RED proposal, plus an assumed 10 gCO_2e/MJ for POME filtering and processing. We are also not aware of any estimate for the carbon intensity of glycerine biofuel and have assumed this to be roughly similar to direct emissions (subtracting cultivation emissions) for first-generation feedstocks (24 gCO_2e/MJ).

2030 renewable electricity GHG intensity: For several pathways, we assessed the emissions from displacing feedstock usage in heat and power. We assumed that all renewable feedstocks would be replaced with additional renewable heat and power generation. We assumed that this additional generation would be comprised of: 25% pulp logs and other fuelwood; 25% wood from short-rotation woody crops; and 50% wind, solar, hydro, geothermal, and any other forms of very low carbon heat and power generation. This breakdown was roughly based on 2030 projections of renewable energy production in the EU Reference Scenario (European Commission, 2016b), which projects 59% biomass and waste in total renewables generation, with the remaining generation from wind, solar, hydro, and geothermal. We estimated that 1% of total energy production in 2030 is likely to be from MSW based on projected MSW production (Searle & Malins, 2016); the remaining 58% is thus likely to be from biomass. We assigned zero emissions to the non-biological renewables. For short-rotation woody crops, we summed cultivation emissions from the 2030 RED proposal and LUC emissions from Valin et al. (2015). For pulp logs and other fuelwood, we took direct land-use change values from the scientific literature on direct land-use change emissions for whole trees. We assumed pulp logs and other fuelwood to be sourced 77% from temperate regions and 23% from boreal regions (following the definition of boreal region by European Commission, 2017a) based on current sources of fuelwood produced in the EU (FAOSTAT, n.d.) as well as imported pellets (Pekkanen et al., 2014). For temperate regions, we derived a value of 0.72 tCO_2e per tonne biomass from Jonker et al. (2013), using the "low productivity landscape scenario" in this study. This choice was made to be consistent with the assumption in Jonker et al. (2013) that all wood removals are sourced from "low productivity" plantations. Although we agree that increased wood prices due to increased bioenergy demand should eventually result in more efficient forestry management practices, we believe that such an impact due to the volume of wood likely used for the biofuel policy in question would be very small, especially in the 2030 timeframe, and not great enough to justify assuming moderate or high productivity practices in Jonker et al. (2013) for the purposes of our analysis. For boreal regions, we derived a value of 2.27 tCO_2e per tonne biomass from Holtsmark (2012). We then added silviculture (i.e., direct production) emissions for farmed wood from the 2030 RED proposal. The assumption of 25% pulp logs and fuelwood in the 2030 renewable electricity mix had a significant impact on our results. We thus tested the impact of assuming 15% and 35% pulp logs and fuelwood in our sensitivity analysis (see Annex B). For displaced use of steel mill flue gas from heat and power generation at steel mills, we assumed the replacement energy source would be natural gas, since flue gas is not considered a renewable energy source and would thus not necessarily be replaced by renewables. For natural gas, we used a carbon intensity of 50 gCO_2e/MJ derived from EIA (2016).

Biofuel conversion yields (in mass of biofuel per mass of feedstock): Cellulosic ethanol and diesel and MSW diesel conversion efficiencies were taken from the GREET® Model (Wang, 2016). Conversion efficiencies for animal fats, used cooking oil, landfill gas, molasses, and food-based biofuels (used to estimate emissions for replacement materials, see below) are taken from the UK Renewable Fuels Agency's (n.d.) default values. The conversion efficiency of crude tall oil to biodiesel was assumed to be 80%. Glycerine ethanol was assumed to have the same conversion efficiency as glycerine methanol (van Bennekom et al., 2012). The conversion efficiency for flue gas ethanol was assumed to be 70% (personal communication with LanzaTech representative).

Substitution ratios: Unless otherwise noted, we assumed that substitution ratios (the quantity in tonnes of the substitute material per tonne of the feedstock) are based on the difference in energy content (higher heating value) between the two materials.

Emissions for replacement materials: Emissions for new heat and power production are given above. Emissions for food crops were derived from summing direct cultivation emissions from the 2030 RED proposal with LUC estimates from Valin et al. (2015), accounting for fuel-conversion efficiencies, which were taken from the UK Renewable Fuels Agency's default values.

Wheat straw: For wheat straw production, sustainable removals, and uses in other sectors, we used estimates for total agricultural residues for the top 12 produced EU crops in Searle & Malins (2016). We assumed that straw use for livestock is mostly for bedding (90%) with 10% used as feed. We assumed that the replacement for straw use in feed is wheat, because this is a major component of livestock feed (Hazzledine, Pine, Mackinson, Ratcliffe, & Salmon, 2011). We assumed that the replacements for livestock bedding are switchgrass, as well as non-biological materials including: rubber mats, sand, gypsum, and dried manure. Based on Searle & Malins (2016), a significant amount of agricultural residues is not currently used for anything and could be sustainably removed without negative impacts to soil health.

Forestry residues: We defined forestry residues as branches and tree tops. For production, sustainable removals, and use in heat and power, we used estimates from Searle & Malins (2016). To the best of our knowledge, there are no other significant uses of forestry residues. Following Searle & Malins (2016), we assumed no stump harvest, and that stumps comprise part of the fraction of forestry residues that should remain in the forest for soil health.

Palm oil mill effluent renewable diesel: We took total POME production for Indonesia from Paltseva, Searle, & Malins (2016) and assumed equal production in Malaysia for total global production. We assumed that one third of this resource could potentially be imported to the EU. Some POME is currently used to produce biogas, which is combusted for electricity to power palm oil mills in Indonesia and Malaysia. The replacement material is likely to be solid biomass residues from palm processing, including empty palm fruit bunches, palm kernel shells, and palm press fiber (Husain, Zainal, & Abdullah, 2003). These solid biomass residues currently have no other uses, and it is not necessary for soil health to return them to the plantations (Teh, 2016). Although unused POME can generate climate-forcing methane emissions, we assumed that by 2030, 100% of palm mills will be equipped with POME methane capture, consistent with IPOB (2012).

MSW landfill biogas: We took current EU landfill methane production from UNFCCC (2016) and assumed that it will be 70% lower in 2030 compared to 2014 due to policy goals to reduce landfilling waste (discussed in Searle & Malins [2016]). Currently, around 45% of landfill methane in the EU is captured, with an additional 10% flared (UNFCCC, 2016). Even with aggressive practices to cap landfills, only around 65% of landfill methane can be captured (EPA, 2017). We assumed that 85% of landfills will be capped and that landfill collection efficiency will increase to 70% in the EU in 2030. We assumed that landfill biogas used in transport will displace some landfill biogas that would otherwise be captured for heat and power production, and thus factor in replacements for renewable heat and power. We assumed that 5% of landfill biogas used in transport will displace untreated methane emissions (and thus factor in avoided methane emissions) and that 10% will displace flaring (this displacement is associated with zero emissions). We assumed a global warming potential of 25 for methane over a 100-year timescale.

MSW FT diesel: We assumed that biofuel is made from non-recycled MSW and does not affect recycling rates. We used data for MSW generation ("mixed ordinary waste") and treatment for the EU from Eurostat (n.d.) for the year 2014 (the most recent year for which complete data is available). We assumed that the amounts incinerated (both with and without energy recovery) will remain constant and that the amount of MSW that is landfilled in 2030 is 75% lower than in 2014 (note: this is consistent with the above assumption that landfill methane emissions will be 70% lower in 2030 because there can be expected to be a time lag between changes in landfill inputs and landfill gas emissions from older waste). We assumed that MSW displaced from incineration for energy and landfilled MSW producing biogas collected for use in heat and power will be replaced by additional renewable heat and power generation. We assumed that replacement renewable heat and power generation will be similarly efficient as MSW incineration for energy, based on the relatively high efficiency of MSW incineration plants in the EU estimated by Grosso, Motta, & Rigamonti (2010). We assumed that using MSW for biofuel will reduce methane emissions to the atmosphere in two ways: (a) by reducing the small amount of methane that would otherwise not be captured, and (b) by reducing the amount of methane that escapes from capped landfills. The emission factors for capped and uncapped landfill methane are taken from EPA (2017).

Molasses ethanol: Total EU production of molasses and use in livestock were taken from OECD-FAO (2016). The amount used in yeast production was provided by personal communication from a yeast industry representative. It was assumed that condensed molasses solubles (CMS) produced from molasses ethanol would be given to livestock feed to provide minerals and protein. This is consistent with current practices with CMS production in the yeast industry. Molasses composition is given in Heuzé et al. (2015) for beet molasses. The replacement material in livestock feed was assumed to be a mixture of corn and barley, because these are currently the cheapest non-molasses sources of calories in livestock feed (European Commission, 2016a; 2017b; Hilton, n.d.). The ratio of corn:barley was taken from the current ratio of these two ingredients in EU livestock feed (European Commission, 2016a). The replacement material for yeast was assumed to be raw juice from sugar beets.

Black liquor FT diesel: Projected 2030 production of black liquor was taken from Mantau et al. (2010). It was assumed that 95% of EU black liquor production is currently used to produce heat and power.

Pulp logs and fuelwood: The total resource availability of pulp logs and fuelwood is not straightforward to define because this resource has an elastic supply. The supply of pulp logs and fuelwood to the transport sector is unlikely to be limited by resource availability. For the purposes of this analysis, we have assumed the total resource availability to be equivalent to the current amount of wood used for paper production in the EU (Mantau, 2012). Our results are not sensitive to this assumption. From Mantau (2012), we assumed that roughly half of all low-quality wood produced in the EU in 2030 will be for materials and half for heat and power. We assumed that displacement of pulp logs in paper will result in greater production of pulp logs. The logic behind our analysis for pulp logs and fuelwood is discussed in Section 2.

Crude tall oil biodiesel: The components of crude tall oil have many applications. These include applications for tall oil rosins, tall oil fatty acids, other distilled tall oil products, drilling/mining additives, and heat and power production (Peters & van Steen, 2013; Rajendran, Breitkreuz, Kraft, Maga, & Brucart, 2016). The amounts used in each of these applications were taken from these sources. The replacement materials were assumed to be gum rosins and petroleum rosins for tall oil rosins applications, from Cashman, Moran, and Gaglione (2013). Cashman et al. (2013) assumed that soy oil replaces the other non-energy uses, but here we assumed that rapeseed oil is the replacement because rapeseed oil is produced in much higher quantities in the EU.

Sawdust: Sawdust is used in heat and power generation and in material uses, including in particle board and as pulp for paper production. These quantities were taken from Mantau (2012). We assumed that all material uses are replaced by additional pulp log production.

Glycerine ethanol: Crude glycerine is a byproduct of biodiesel production, and is also produced from propene. There is an existing market for refined glycerine (also called "glycerol"), which has a much higher value than crude glycerine (Quispe, Coronado, & Carvalho, 2013). Glycerine production for 2030 was estimated from expected biodiesel production (assuming the 3.8% food-based cap applies equally to biodiesel and ethanol, and using the European Commission's 2030 reference scenario [European Commission, 2016b]), plus an additional 600 thousand tonnes that was produced from other sources in 2014 (inferred from Global Market Insights [2016]). We assumed that glycerine ethanol cannot displace refined glycerine because of the large difference in price. We thus assumed that displacement only occurs for other users of unrefined glycerine. We assumed these uses to be split equally between livestock feed and as an additive to cement production (Ciriminna, Pina, Della, Rossi, & Pagliaro, 2014). We assumed that the replacement for livestock feed is a mix of corn and barley (similar to molasses, above) and that propylene glycol is the replacement for cement production (Ciriminna et al., 2014). The emissions intensity of propylene glycol production is from Pavlenko et al. (2016).

Manure biogas: The total potential production of livestock biogas in the EU is from Meyer et al. (2016). We assumed no other uses of manure biogas. Although some manure may be used as a fertilizer, there is also the possibility that the nutrient-rich digestate after anaerobic digestion could be returned to farms for use as fertilizer. We assumed avoided methane emissions for manure used for biogas, and, to estimate the emissions that would occur in the absence of collection for biofuel, we assumed average methane emission factors for “composting-extensive” and “poultry manure” for temperate climates from Jun, Gibbs, & Gaffney (n.d.).

Used cooking oil biodiesel: We estimated total UCO consumption in the EU from USDA (2015) and assumed that an additional 200 thousand tonnes could be collected from households by 2030 (Hillairet et al., 2016). We did not account for any other uses of UCO; this reasoning is explained above.

Animal fats biodiesel: Only Categories 1 and 2 animal fats (i.e., inedible) are eligible under the 2030 RED proposal. Total production of these categories of animal fats was taken from Taylor & Bauen (2014). The other uses of these categories of animal fats are for heat and power generation at the rendering plants, and for some oleochemical uses. We took these amounts from Chudziak & Haye (2016) and Ecofys (2012). We assumed that the replacement material in oleochemical production is palm oil, because this is typically the lowest cost alternative oil/fat.

Flue gas ethanol: We assumed that the main alternative use of flue gas is for heat and power, and that 70% of flue gas produced in EU steel mills is used for heat and power (Wörtler et al., 2013). We assumed that the replacement heat and power source is natural gas, using a 40% efficiency of conversion to electricity (Wang, 2016), compared to a 28% electrical conversion efficiency for flue gas (personal communication). Total flue gas potential in the EU was assumed to be 10.3 million tonnes (personal communication).

Forest thinnings FT diesel: Forest thinnings are produced when small trees in plantations are thinned out to allow more space for the remaining trees to grow larger. Some thinnings are collected and used for heat and power production; for pulp for paper production; or in small material uses, such as in fence posts. The remainder is typically left in the forest to decay over time. We estimated total thinnings production by applying a ratio of thinning volume to roundwood volume from the 75% highest yielding practice scenario from Kerr & Haufe (2011) to total roundwood harvest data in the EU from Eurostat (n.d.), assuming that 50% of thinnings are counted in the roundwood totals. In the absence of other data, we assumed that 50% of thinnings production is collected, and that 50% of this amount is used for material uses and the remainder for heat and power generation. We assumed that the replacement material for material uses is additional pulp logs and other low-quality wood.

Sensitivity analysis: The values of indirect and total emissions, and of percentage of GHG reduction given in parentheses in Table 2.1 are the results of a sensitivity analysis. The details of the parameters tested in the sensitivity analysis are given in Annex B.

4.2 Methodology of advanced fuel target design

4.2.1 Cost analysis

We used a simple cost optimization model to assess the lowest cost options to comply with each policy scenario. For each pathway, we identified a low-end cost estimate (representing the likely cost of the first batch of feedstock to be used for biofuel) and a high-end cost estimate (representing the likely cost of using the last remaining batch of feedstock to be used for biofuel). To illustrate, the low-end cost of wheat straw ethanol was based on a relatively optimistic projection for Nth-of-a-kind cellulosic ethanol facilities, factoring in a fairly low market price for straw ($65/tonne; Peters, Alberici, & Passmore, 2015). The high-end cost was estimated by assessing the additional feedstock cost for harvesting and transporting the most expensive straw and adding this to the low-end cost estimate. We estimated the high-end feedstock cost for straw by applying straw harvesting costs per hectare (Esteban, Ciria, Maletta, Garcia, & Carrasco, 2010) to a straw yield of 0.5 tonnes per hectare (assuming the field produces barely enough straw for harvesting) and transport costs from JRC (2007) for 400 km (our estimate for the longest distance one could possibly transport straw from a farm to a biorefinery); the high-end cost for straw using this method was $237/tonne.

For other pathways, we estimated the high-end cost based on the most expensive replacement material that would be used in the current uses of the feedstock. For example, the high-end cost for animal fats was assumed to be the same as for virgin palm oil.

We compared all alternative fuel cost estimates to the cost of the fuel type being replaced. For example, compressed natural gas is less expensive per unit energy than diesel or petrol, so manure biogas would have to be cheaper than straw ethanol per unit energy to have the same market penetration ability. For the GHG target scenarios, we applied a carbon price to all fuel pathways, assuming a carbon price of \$200/tCO_2e. For the scenario with a GHG target based on direct carbon intensities, we applied the direct carbon intensities only. For the scenario with a GHG target based on indirect emissions accounting, we applied the full lifecycle carbon intensities. To illustrate, short-rotation woody crop diesel was more expensive than wheat straw without a carbon price (\$627 and \$399 per tonne oil equivalent respectively, compared to fossil diesel and petrol) for the low-end costs, but short-rotation woody crop diesel was less expensive than wheat straw when the carbon price was applied based on full lifecycle emissions (-\$230 and -\$207 per tonne oil equivalent, respectively, compared to fossil diesel and petrol). For the scenario with a GHG target based on indirect emissions accounting, all pathways that did not meet the 70% GHG reduction target in the 2030 RED proposal were excluded.

We then created a linear supply curve from the lowest cost estimate to the highest cost estimate. We created 20 "bins" of equal feedstock supply (assumptions for total potential feedstock and fuel supply are given above in Section 4.1.2) and assigned to each a cost, ranging linearly from the lowest to the highest cost estimate. The exceptions to this rule were used cooking oil and animal fats, which are already used in high volume for biodiesel. We thus estimated 2030 production costs based on 1G biodiesel from the UK's Transport Energy Task Force report (n.d.) adjusted for the lower cost of UCO and animal fats compared to virgin vegetable oils, and applied this price to 85% of the potential volume of UCO and animal fats biodiesel.

We then "stacked" the bins into the same dataset and performed the cost optimization analysis through sorting. First, we applied a constraint for ethanol blending. We assumed that the maximum amount of ethanol that would be consumed in 2030 would be 10% of total gasoline consumption (European Commission, 2016c) and that this would be met with the lowest cost eligible ethanol bins. We then applied a constraint for the sub-target for Annex IX list A feedstocks (3.6% of total road and rail transport energy in 2030) and assumed that this volume would be met by the lowest cost Annex IX list A bins. The remainder of the 6.8% target was then met with the lowest cost bins from any pathway. Because the bins for each pathway vary by price, it is possible that, for example, the three lowest cost options would be met by the cheapest fuel, Fuel A, but that the first bin for Fuel B would be less expensive than the fourth bin for Fuel A. There is a cap of 1.7% on the contribution of Annex IX list B feedstocks to the 6.8% target, but in no case was this cap binding in our analysis (i.e. the contribution of Annex IX list B was always lower than 1.7%).

We assumed that the amount of renewable electricity and hydrogen used in vehicles would be driven by policies promoting the purchase of electric and fuel cell vehicles as well as charging infrastructure installation and that these volumes would not be significantly influenced by renewable fuel policy. In previous research, we have found that the potential economic benefits of credit generated in renewable fuel programs to consumers are likely to be small compared to existing vehicle purchase subsidies (ICCT, 2017). We thus first subtracted these projected volumes from the amount of fuel needed to meet the 6.8% target before proceeding with the cost optimization analysis above.

Estimated total GHG savings for each scenario were calculated based on the full lifecycle GHG intensities of each pathway, including indirect emissions. This amount was divided by the total amount of road and rail energy in 2030 (European Commission, 2016b) multiplied by the updated fossil fuel comparator (94.1 gCO_2e/MJ; European Commission, 2016c).

4.2.2 Assumptions and data sources

Feedstock availability: The total production and availability of feedstocks for alternative fuel production is given for most pathways above, in Section 4.1.2. For energy crops, total potential feedstock production (20 million tonnes) was assumed to be roughly double that identified in Allen et al. (2014; about 10 million tonnes using a central estimate for crop yields), because that study emphasized that its estimate of land availability was conservative due to the poor availability of data classifying land as "marginal" for agriculture. We assumed this was split evenly among perennial grasses and short rotation woody crops. For context, the amount of energy crops assumed in the biofuel shock in Valin et al. (2015) was around 9 million tonnes. We note that the amount of perennial grass ethanol and short-rotation woody crops diesel projected in our scenario with indirect emissions accounting implies the usage of 12.4 million tonnes of energy crops in total. For power-to-liquids using excess renewable electricity, the potential volume was estimated to be 20% of total projected renewable electricity production in 2030 (European Commission, 2016b). We are not aware of any reliable estimates of potential algae production in the EU, and so we assumed potential production to be 10 million tonnes. We note that no power-to-liquids or algal biofuel was found to be cost competitive in any of our scenarios. The total quantity of electricity was taken from Lutsey (2015), and the renewable fraction for 2030 was taken from European Commission (2016b). No multiple counting of renewable electricity was assumed. The quantity of hydrogen from solar hydrolysis was estimated to be three times the amount of renewable hydrogen projected for France, Italy, Germany, and the United Kingdom in the "2DS High H_2" scenario in 2030 from OECD/IEA (2015).

Wheat straw ethanol: The lowest cost estimate was taken from Peters et al. (2015), which assume a feedstock cost of around $65/tonne. The most expensive feedstock estimate is explained above in Section 4.2.1.

MSW biogas: The lowest cost estimate was taken from the UK's Transport Energy Task Force report (n.d.), and the highest is the most expensive cost estimated for small facilities in IRENA (2017).

MSW FT diesel: The lowest cost estimate was taken from Peters et al. (2015) for FT diesel from cellulosic feedstocks, subtracting the feedstock cost of around $65/tonne. The most expensive feedstock cost was the highest reported MSW collection cost (for Denmark) in Hogg (2001).

Perennial grass ethanol: The lowest cost estimate was taken from Peters et al. (2015), which assume a feedstock cost of around $65/tonne. The most expensive feedstock cost was estimated by adding transport emissions, using the same source and formula as for wheat straw above.

Short rotation woody crop FT diesel: The lowest cost estimate was taken from Peters et al. (2015), which assume a feedstock cost of around $65/tonne. The most expensive feedstock cost was estimated by adding transport emissions, using the same source and formula as for wheat straw above.

Pulp logs and fuelwood FT diesel: The lowest cost estimate was taken from Peters et al. (2015) for FT diesel from cellulosic feedstocks, subtracting the difference in feedstock cost ($26/tonne, based on a low range cost estimate of 12 Euros per cubic meter from Asikainen & Laitila [2006] and assuming a wood density of 0.5 tonnes per cubic meter.) The high-end cost was derived from the highest pulp wood price in Austria (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2015), which assumes a transport distance of 100 km, and adding cost for an additional 300 km transport from Anttila, Tahvanainen, Parikka, Laitila, & Ala-Fossi (2007).

Forest residues FT diesel: The lowest cost estimate was taken from Peters et al. (2015) for FT diesel from cellulosic feedstocks, subtracting the difference in feedstock cost. The low-range feedstock cost was estimated from the lowest costs for harvest, bundling, etc., from Asikainen & Laitila (2006), and assuming zero transport cost. The high-end feedstock cost is the same, but assuming 400 km transport, using transport cost from Asikainen & Laitila (2006).

Black liquor FT diesel: The lowest cost estimate was taken from Peters et al. (2015) for FT diesel from cellulosic feedstocks, subtracting the feedstock cost. The high-end feedstock cost was estimated to be the levelized cost of new natural gas heat and power (IDEA, 2013), plus an additional assumed $20/tonne feedstock to account for the cost of purchasing new green liquor chemicals.

Crude tall oil biodiesel: The lowest cost estimate was taken from the UK's Transport Energy Task Force report (n.d.) for 1G biodiesel, but adding in the difference in feedstock cost (the lowest cost for crude tall oil is around $400/tonne, from Peters & van Steen [2013]). The high-end feedstock cost was assumed to be the price of gum rosin, the most expensive replacement material, taken from Summit PineChem (2017).

Sawdust FT diesel: The lowest cost estimate was taken from Peters et al. (2015) for FT diesel from cellulosic feedstocks, subtracting the difference in feedstock cost ($50 per dry tonne for sawdust from Burden [2015]). The high-end price was estimated by adding transport cost for 400 km, following the formula for forestry residues above and assuming the same cost per kilometer because sawdust, like forestry residues, is bulky.

Glycerine ethanol: We are not aware of any reliable cost estimates for biofuel made from glycerine. We assumed the cost from the UK's Transport Energy Task Force report (n.d.) for 1G ethanol for the low-end cost. For the high-end cost, we assumed the highest price for refined glycerine over the past 10 years (Quispe et al., 2013).

Manure biogas: The lowest cost estimate was taken from the UK's Transport Energy Task Force report (n.d.), and the highest was assumed to be the same as for the most expensive MSW biogas from IRENA (2017).

Used cooking oil biodiesel: The lowest cost estimate was taken from the UK's Transport Energy Task Force report (n.d.) for 1G biodiesel, but reducing the feedstock costs by one third. This is consistent with the typical proportional difference in price between yellow grease and virgin vegetable oils from USDA (2017). The high-end cost was estimated based on the advertising costs of the Belgian campaign for household UCO collection (Greenea, 2017), scaled to the projected increase in EU-wide UCO collection and doubled to account for the direct costs of UCO household collection.

Animal fats biodiesel: The lowest cost estimate was assumed to be the same as for UCO biodiesel. The high-end feedstock cost was assumed to be the same as for palm oil (Indexmundi, n.d.).

POME renewable diesel: We are not aware of any cost estimates for POME renewable diesel. The lowest cost estimate was assumed to be the same as for used cooking oil biodiesel. POME can be expected to be available at very low cost, but the collection and processing costs may be similar to yellow grease (processed used cooking oil); thus, we assumed the overall cost would be similar to UCO biodiesel. The most expensive cost was the lowest cost plus the cost of natural gas, on an energy equivalent basis, to replace POME biogas combustion in any facilities where combustion of solid biomass is not possible.

Molasses ethanol: The lowest cost estimate was taken from the UK's Transport Energy Task Force report (n.d.) for 1G ethanol. The high-end cost estimate was assumed to be the same as the minimum price for raw sugar (European Commission, 2017c). We note that, on a per-gram sugar basis, raw sugar is only slightly more expensive than molasses ($335 per tonne for raw sugar and $313 per tonne for the sugar component of molasses).

Flue gas ethanol: The lowest cost estimate was taken from the UK's Transport Energy Task Force report (n.d.) for 1G ethanol. It has been reported that LanzaTech's process for producing flue gas ethanol should eventually be as cheap as first-generation ethanol (ARPA-E, n.d.). The highest cost estimate included the levelized cost of new natural gas heat and power (same as for black liquor above).

Algal biodiesel: The low- and high-end costs for algal biodiesel are from Kovacevic & Wesseler (2010).

Forest thinnings FT diesel: The lowest cost estimate was taken from Peters et al. (2015) for FT diesel from cellulosic feedstocks, adding the difference in feedstock cost. The low-end feedstock cost was taken as the lowest harvesting and bundling cost from Asikainen & Laitila (2006), assuming zero transport cost, and the highest cost was the same plus the transport cost for 400 km.

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Annex A. Supporting data

Table A. Supporting data used in displacement analyses to estimate indirect emissions

Pathway	Total production (million tonnes)	Other uses (million tonnes)	Alternate materials	Emissions of alternate materials (tCO$_2$e/t material)	Substitution ratio
Straw ethanol	148 (sustainable removals)	Livestock feed (2.5)	Wheat	0.42	0.99
		Livestock bedding (22.2)	Switchgrass (25%)	–0.08	1
			Rubber, sand, gypsum, and dried manure (75%)	0	N/A
		Mushroom production (1.8)	Switchgrass	–0.08	1
		Horticulture (1.8)	Switchgrass	–0.08	1
		Heat and power (37.6)	Pulp logs (25%)	1.06	0.89
			Short-rotation woody crops (25%)	–0.14	0.89
			Wind, solar, geothermal (50%)	0	N/A
		Unused (82)	N/A	0	N/A
Forestry residues FT diesel	21.5 (sustainable removals)	Heat and power (5.1)	Pulp logs (25%)	1.06	1
			Short-rotation woody crops (25%)	–0.14	1
			Wind, solar, geothermal (50%)	0	N/A
		Unused (16.4)	N/A	0	N/A
POME renewable diesel	3	Heat and power (1.5)	Palm solid biomass processing residues	0	N/A
		Unused (1.5)	N/A	0	N/A
MSW landfill biogas	2.1 million tonnes oil equivalent (Mtoe)	Heat and power (1.8 Mtoe)	Pulp logs (25%)	1.06	2.2
			Short-rotation woody crops (25%)	–0.14	2.2
			Wind, solar, geothermal (50%)	0	N/A
		Unused (0.3 Mtoe)	N/A	0	N/A
MSW FT diesel	119.7	Incinerated with energy recovery (68.0)	Pulp logs (25%)	1.06	0.23
			Short-rotation woody crops (25%)	–0.14	0.23
			Wind, solar, geothermal (50%)	0	N/A
		Incinerated without energy recovery (26.6)	N/A	0	N/A
		Landfilled with 85% methane capture used for heat and power (21.3)	Pulp logs (25%)	1.06	0.23
			Short-rotation woody crops (25%)	–0.14	0.23
			Wind, solar, geothermal (50%)	0	N/A
			Avoided methane emissions	0.61 tonnes methane per tonne feedstock for capped landfills; 1.61 tonnes methane per tonne feedstock for uncapped landfills	1
Molasses ethanol	2.2	Livestock (1.5)	Barley (26%)	0.41	1
			Corn (37%)	0.31	1
			Condensed molasses solubles (37%)	0	1
		Yeast (0.7)	Sugar beet	0.05	2.875

Pathway	Total production (million tonnes)	Other uses (million tonnes)	Alternate materials	Emissions of alternate materials (tCO_2e/t material)	Substitution ratio
Black liquor diesel	84.9	Heat and power (80.7)	Pulp logs (25%)	1.06	0.76
			Short-rotation woody crops (25%)	−0.14	0.76
			Wind, solar, geothermal (50%)	0	N/A
		Unused (4.2)	N/A	0	N/A
Pulp logs and fuel wood diesel	107.8	Paper (53.9)	Pulp logs	1.06	1
		Heat and power (53.9)	Pulp logs (25%)	1.06	1
			Short-rotation woody crops (25%)	−0.14	1
			Wind, solar, geothermal (50%)	0	N/A
Crude tall oil biodiesel	0.7	Tall oil rosin applications (0.3)	Gum rosins	2.41	1
			Petroleum rosins	2.94	1
		Tall oil fatty acids applications (0.2)	Rapeseed oil	3.1	1
		Other distillation (0.1)	Rapeseed oil	3.1	1
		Drilling/mining additives (0.1)	Rapeseed oil	3.1	1
		Heat and power (0.1)	Pulp logs (25%)	1.06	2.2
			Short-rotation woody crops (25%)	−0.14	2.2
			Wind, solar, geothermal (50%)	0	N/A
Sawdust diesel	58.3	Heat and power (38.9)	Pulp logs (25%)	1.06	1
			Short-rotation woody crops (25%)	−0.14	1
			Wind, solar, geothermal (50%)	0	N/A
		Pulp and other materials (19.4)	Pulp logs	1.06	1
Crude glycerine ethanol	0.3	Livestock feed (0.1)	Barley (41%)	0.41	0.93
			Corn (59%)	0.31	0.93
		Cement (0.1)	Propylene glycol	0.6	1
Manure biogas	4.2	Unused	Avoided methane emissions (4.2)	−0.3	1
Animal fats biodiesel (categories 1 and 2)	0.2	Heat and power (0.2)	Pulp logs (25%)	1.06	2.0
			Short-rotation woody crops (25%)	−0.14	2.0
			Wind, solar, geothermal (50%)	0	N/A
		Oleochemical uses (0.01)	Palm oil	8.1	1.03
Flue gas ethanol	10.3	Heat and power (7.2)	Natural gas	0.4	0.7
		Unused (3.1)	N/A	0	N/A
Forest thinnings diesel	48.3	Heat and power (12.1)	Pulp logs (25%)	1.06	1
			Short-rotation woody crops (25%)	−0.14	1
			Wind, solar, geothermal (50%)	0	N/A
		Paper and other materials (12.1)	Pulp logs	1.06	1
		Left in forest (24.1)	Carbon storage	1.8	1

Annex B. Sensitivity analysis

We changed the following parameters to determine low- and high-end estimates for indirect emissions for the pathways assessed in this study.

B.1 Low-range estimates

- For the 2030 renewable heat and power mix, we changed the assumption from 25% pulp logs and other fuelwood to 15%. The contribution of wind, solar, and other very low carbon renewables increased from 50% to 60%. This affected indirect emissions estimates for straw ethanol, forestry residues diesel, MSW landfill biogas, black liquor diesel, pulp logs and fuelwood diesel, crude tall oil biodiesel, sawdust diesel, animal fats biodiesel, and forest thinnings diesel.
- For wheat straw, we changed the assumption of 10% wheat replacing straw use in livestock to 0%.
- For molasses, we assumed 100% corn used as the replacement in livestock feed.
- We changed the assumption of the proportion of black liquor that is used for heat and power generation from 95% to 90%.
- We assumed that 10% of the replacement material for pulp logs and fuelwood used for pulp would come from short-rotation woody crops.
- We assumed that 10% of the replacement material for sawdust used for pulp and materials would come from short-rotation woody crops.
- For glycerine, we assumed 100% corn used as the replacement in livestock feed.
- For manure biogas, we doubled our estimate of methane production in the baseline scenario (doubling avoided methane emissions).
- For flue gas ethanol, we changed the assumption about the proportion of steel mills that current utilize flue gas from 70% to 60%.
- We assumed that 10% of the replacement material for forest thinnings used for pulp and materials would come from short-rotation woody crops.

B.2 HIGH-RANGE ESTIMATES

- For the 2030 renewable heat and power mix, we changed the assumption from 25% pulp logs and other fuelwood to 35%. The contribution of wind, solar, and other very low carbon renewables decreased from 50% to 40%. This affected indirect emissions estimates for straw ethanol, forestry residues diesel, MSW landfill biogas, black liquor diesel, pulp logs and fuelwood diesel, crude tall oil biodiesel, sawdust diesel, animal fats biodiesel, and forest thinnings diesel.
- For wheat straw, we changed the assumption of 10% wheat replacing straw use in livestock to 20%.
- For molasses, we assumed 100% barley used as the replacement in livestock feed.
- We changed the assumption of the proportion of black liquor that is used from 95% to 100%.
- For glycerine, we assumed 100% barley used as the replacement in livestock feed.
- For manure biogas, we halved our estimate of methane production in the baseline scenario (halving avoided methane emissions).
- For flue gas ethanol, we changed the assumption about the proportion of steel mills that current utilize flue gas from 70% to 80%.

Annex C. Alternate assumptions on heat and power

In our main analysis of indirect emissions presented in Table 2.1, we assumed that pulp logs and fuel wood would be eligible feedstocks to contribute towards the 27% renewable energy target in the RED II and would thus be a major contributor to the renewable heat and power mix in 2030. If all stem wood were made ineligible to be used towards the renewable energy target, including for the heat and power sectors, the GHG intensity of grid-average heat and power generation would be significantly different. In this scenario, there would be no direct increase in pulp logs and fuel wood used for heat and power as a result of diverting renewable feedstocks to advanced biofuel production; diverting these feedstocks would only drive increased production of eligible renewable energy sources such as wind and power. However, there would likely be an indirect increase in stem wood in non-energy uses. As an illustrative example, we may consider a pulp mill collocated with a saw mill. The joint facility currently uses all black liquor and half of the sawdust it generates for energy production and uses the remaining sawdust for pulp and other materials (reflecting typical usage of these materials in the EU). If all black liquor were diverted for biofuel production, this facility may begin using 100% of its sawdust for energy production, and may increase purchases of pulp logs to use for pulp and other materials. In this example, diversion of black liquor from heat and power production would result in an increase in pulp log production, even though the pulp logs are not directly used for heat and power.

To estimate the maximum effect that advanced biofuel demand could have on pulp log and fuel wood production in a scenario where these feedstocks are not eligible for the renewable energy target, we sum the estimated amounts of feedstocks currently used for materials that could potentially be diverted to heat and power production. This includes straw (use in livestock bedding and horticulture but not mushroom cultivation or feed), sawdust, animal fats, and forest thinnings. We assume that crude tall oil is not likely to be diverted from material uses to heat and power production due to the difference in value between those applications. We divide this total amount of feedstock by the expected total amount of non-transport renewable energy needed to meet the 27% renewable energy target in 2030; this calculation yields 7%. In our central estimates, we assume half this share (3.5%) of all feedstock diverted from heat and power would be replaced by pulp logs and fuel wood. In the sensitivity analysis, we assume 1.75% and 7% replacement by pulp logs and fuel wood for the low and high estimates, respectively. We also apply the same assumptions listed in Annex B for the sensitivity analysis. We assume that the remainder of heat and power demand is met with wind, solar, geothermal, and other renewable energy technologies with zero carbon intensity. For this scenario, we assume no energy crops are used for additional heat and power production. The indirect emissions estimate for pulp logs and fuel wood is the same as in Table 2.1.

Table B presents the central, low, and high indirect emissions estimates for this scenario.

Table B. Direct and indirect emissions for feedstocks in a scenario where stem wood is not eligible for the renewable energy target (low and high ranges in parentheses)

Pathway	Direct emissions (gCO_2e/MJ)	Indirect emissions, central estimate (and range) (gCO_2e/MJ)	Total emissions (gCO_2e/MJ)	NET GHG emission reduction
Perennial grass ethanol	14	−12	2	97%
Short-rotation woody crop biofuel	22	−29	−8	109%
Power to liquids from excess renewable generation	4	0	4	96%
Algal biodiesel	14	0	14	85%
Straw ethanol	14	1 (0–3)	15 (14–17)	84% (82%–85%)
Forestry residues Fischer Tropsch (FT) diesel	14	1 (0–2)	15 (14–16)	84% (83%–85%)
Palm oil mill effluent (POME) renewable diesel	27	0	27	71%
MSW landfill biogas compressed natural gas (CNG)	19	−28 (−29 to −27)	−9 (−10 to −8)	110% (108%–111%)
MSW FT diesel	15	−55 (−57 to −53)	−40 (−42 to −38)	143% (140%–144%)
Molasses ethanol	22	32 (29–36)	53 (50–57)	43% (39%–46%)
Black liquor FT diesel	10	4 (3–8)	14 (12–19)	85% (80%–87%)
Pulp logs/ fuelwood FT diesel	21	67 (55–73)	88 (76–93)	7% (1%–19%)
Crude tall oil biodiesel	13	87 (87–87)	100 (100–100)	−6% (−7% to −6%)
Sawdust and cutter shavings ethanol or FT diesel	14	39 (34–42)	53 (48–56)	43% (41%–49%)
Glycerine ethanol	24	88 (84–93)	112 (108–117)	−19% (−24% to −15%)
Manure biogas CNG	14	-6.0 (−12 to −3)	8 (1–10)	91% (88%– 98%)
Used cooking oil biodiesel	16	0	16	83%
Animal fats biodiesel	20	11 (10–13)	31 (30–33)	67% (65%–68%)
Steel mill flue gas ethanol	12	13 (11–15)	26 (24–27)	73% (71%–75%)
Forest thinnings FT diesel	21	76 (72–76)	96 (93–97)	−2% (−3% to 0%)