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KEY ISSUES IN LCA METHODOLOGY FOR MARINE FUELS

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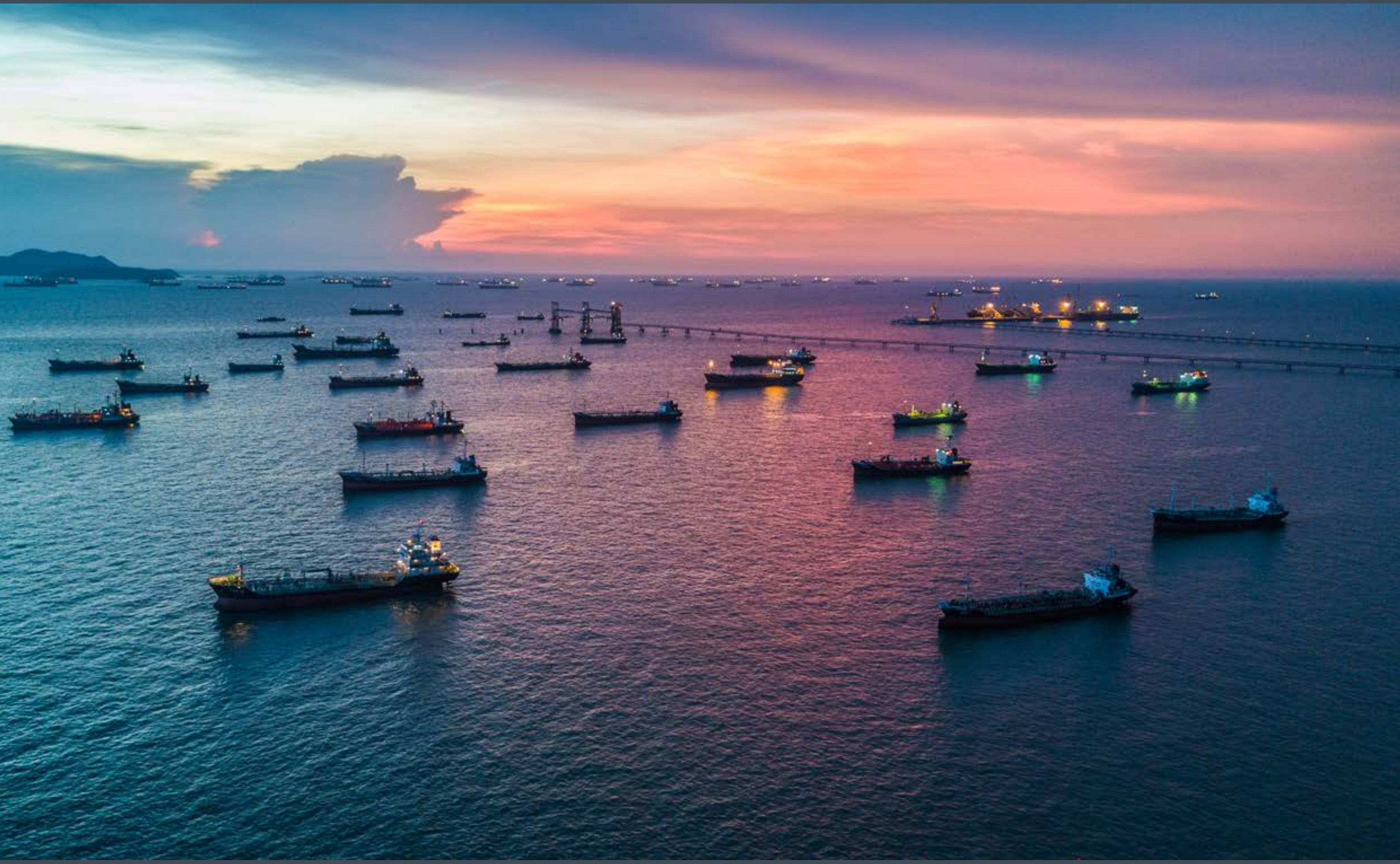

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EXECUTIVE SUMMARY

The International Maritime Organization (IMO) established a strategy under its pollution prevention treaty (MARPOL) that proposes quantitative reductions in carbon intensity and greenhouse gas (GHG) emissions from international shipping. Developing life-cycle analysis (LCA) guidelines is one of the "short-term measures" listed under the strategy and the LCA guidelines are being crafted now. This can mark an important shift for the IMO because conducting LCAs would allow regulations to be based on well-to-wake (WTW) carbon dioxide equivalents (CO_2e) instead of solely tank-to-wake (TTW) CO_2 emissions, which is the current practice.

This paper highlights the impact of key considerations and methodological decisions when doing an LCA and demonstrates how these can impact the emissions attributable to different fuels. We compare the different LCA methodologies of five existing fuel policies and then assess the life-cycle GHG emissions of four marine fuels—soybean biodiesel, used cooking oil (UCO)-based renewable diesel, e-methanol, and hydrogen—across a variety of LCA scopes and assumptions. The results of these four case studies highlight the most critical assumptions and the importance of understanding the reason for the life-cycle carbon accounting of fuels. For the IMO, it is critical that such accounting be comprehensive enough to achieve climate goals. The following key themes emerge:

- **Fuels that have zero TTW or direct emissions can have substantial upstream production emissions that are not counted when assessing only TTW emissions.** For example, hydrogen and ammonia emit zero CO_2 at their point of consumption but might be extremely energy-intensive to produce. Further, in the case of fuels made using renewable electricity, it is critical that the electricity be both renewable and additional or else renewable electricity might be diverted from other uses or double counted toward policy targets.
- **Though indirect effects are uncertain, they might be large enough to greatly affect the estimated GHG savings of some fuel pathways, and assuming a value of zero on the basis of uncertainty is not necessarily a neutral decision.** Indeed, the assumption of zero indirect emissions risks over-crediting some fuel pathways that come with climate risks. Today emissions from indirect land-use change (ILUC) are the most commonly included indirect emissions in fuels policy and there is consensus in the literature that this effect is real, even though there is substantial variation in ILUC estimates across studies and across different feedstocks. In particular, oilseeds such as palm and soy could have such high estimated ILUC emissions that they might undermine all of the GHG savings associated with these feedstocks. To address this, some policies limit the contribution of high-ILUC feedstocks or exclude them from eligibility entirely; other policies incorporate an estimated ILUC emission factor and add it to fuels' direct production emissions as part of an LCA.
- **Sustainability certification is a safeguard included in all five major LCA policies reviewed.** Sustainability certification and monitoring, reporting, and verification are important in creating the conditions where it is most likely that the assessed LCA emissions of fuels match their real-world behavior. This includes checking that (1) renewable electricity is used for e-fuels and it is additional; (2) biofuels are not grown on high-carbon-stock land; and (3) fuels made from captured carbon are not double-claiming emissions reductions for carbon capture.

When policy instruments focus only on combustion emissions, it is possible that the intended GHG savings might be undermined by not only the ILUC emissions associated with some biofuels, but also with other indirect emissions associated with synthetic and by-product or waste-derived fuel pathways. To avoid the adoption of high-emitting

fuels in an effort to decarbonize maritime transportation, we recommend that the IMO adopt full life-cycle WTW GHG accounting for policies related to fuel operational use such as the Carbon Intensity Indicator and potential future policies like the GHG Fuel Standard. Such accounting would be consistent with other major fuels policies, which assess the indirect emissions attributable to fuels even though indirect emissions are uncertain and difficult to estimate. This can and should be combined with safeguards and certification systems to ensure that alternative fuels are delivering their intended GHG savings and avoiding unintended sustainability impacts.

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INTRODUCTION

International maritime transportation remains heavily dependent on fossil fuels and was responsible for around 3% of anthropogenic carbon dioxide (CO_2) emissions in 2018 (Faber et al., 2020). Also in 2018, the International Maritime Organization (IMO) established a strategy under its pollution prevention treaty (MARPOL) that proposes pursuing efforts toward a 70% reduction in carbon intensity by 2050 and a 50% reduction in greenhouse gas (GHG) emissions by 2050, both compared to 2008 levels (Lakshmi, 2018). The aim of this initial GHG strategy is to be aligned with Paris Agreement temperature goals. Even though achieving these goals requires reducing life-cycle, well-to-wake (WTW) GHG emissions, current IMO policies focus solely on CO2, and only on a tank-to-wake (TTW) basis.

Developing life-cycle analysis (LCA) guidelines is one of the "short-term measures" listed under IMO's initial GHG strategy. Such guidelines can be incorporated into IMO policies so they can begin regulating based on WTW carbon dioxide equivalents (CO_2e). This is important because the alternative fuels currently at the forefront of IMO's strategy, namely biofuels, "green" ammonia, hydrogen, and synthetic fuels, appear promising because their direct carbon emissions during combustion are potentially zero or are offset by biomass growth. Under TTW accounting systems, these are considered carbon neutral. However, as most biofuels are currently produced from land-intensive crops, there is concern that the increased consumption of biofuels would lead to significant changes in land-use dynamics and agricultural expansion at a global scale that results in additional GHG emissions and adverse impacts on food security. Further, "green" ammonia, hydrogen, and synthetic fuels are produced from energy-intensive processes and require large amounts of materials and water resources; this might also lead to conflicts with ecosystem services. Given this, it is essential to ensure that maritime alternative fuels policies are designed to minimize the potential for unintended consequences that would undermine their climate and sustainability goals. LCAs are a key component of assessing those risks and establishing safeguards.

This paper provides an overview of the process of doing an LCA, including specific considerations in LCA for the evaluation of transport fuels. We first highlight key methodological decisions for conducting an LCA and then summarize five existing transport fuels policies and describe their life-cycle approach for assessing the GHG emissions of alternative fuels. Following that are case studies that examine the life-cycle GHG emissions attributable to four potential marine alternative fuels; these illustrate the effects of different methodological choices on their estimated GHG emissions. The paper ends with discussion and brief conclusions.

WHAT MAKES A LIFE-CYCLE ASSESSMENT OF TRANSPORT FUELS?

LCA is a methodology used to assess the potential environmental impacts of a new product, process, or system for its entire life cycle, from the extraction of raw material through to the end of its life. LCA can help to assess the relative life-cycle impacts of different types of alternative fuels and this information can help evaluate the impacts of fuels and climate policies. It can also be used to evaluate the impacts of larger policy-design decisions and indeed, policy development for alternative fuels increasingly relies on LCA to identify which technologies should be supported in the transportation sector. However, the methodological choices in a given LCA can significantly affect the results and thus affect the outcome of comparisons of alternative fuels. It is important to utilize analytical methods that align with achieving environmental goals and that the alternative fuels supported under a given policy offer genuine, quantifiable benefits.

The International Standard ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework) describes the principles and framework for LCA (ISO, 2006). It includes the definition of the LCA goal and scope, inventory analysis, impact assessment, interpretation, reporting and review phases, and the limitations, linkages between phases, and the conditions for assumptions and optional elements. However, it does not describe the LCA technique in detail or specify methodologies for estimating life-cycle environmental impacts within a given system. Because of this substantial flexibility, comparing LCA studies is not necessarily straightforward.

The life cycle of a marine fuel can be divided in two phases: well-to-tank (WTT) and tank-to-wake (TTW) and this is illustrated in Figure 1. The WTT phase comprises the upstream fuel production activities such as feedstock extraction and transport and fuel production and distribution. The TTW phase includes the fuel combustion emissions from use in a vessel. The sum of emissions from both stages is used to determine a fuel's "carbon intensity," which is its emissions per unit of delivered energy.

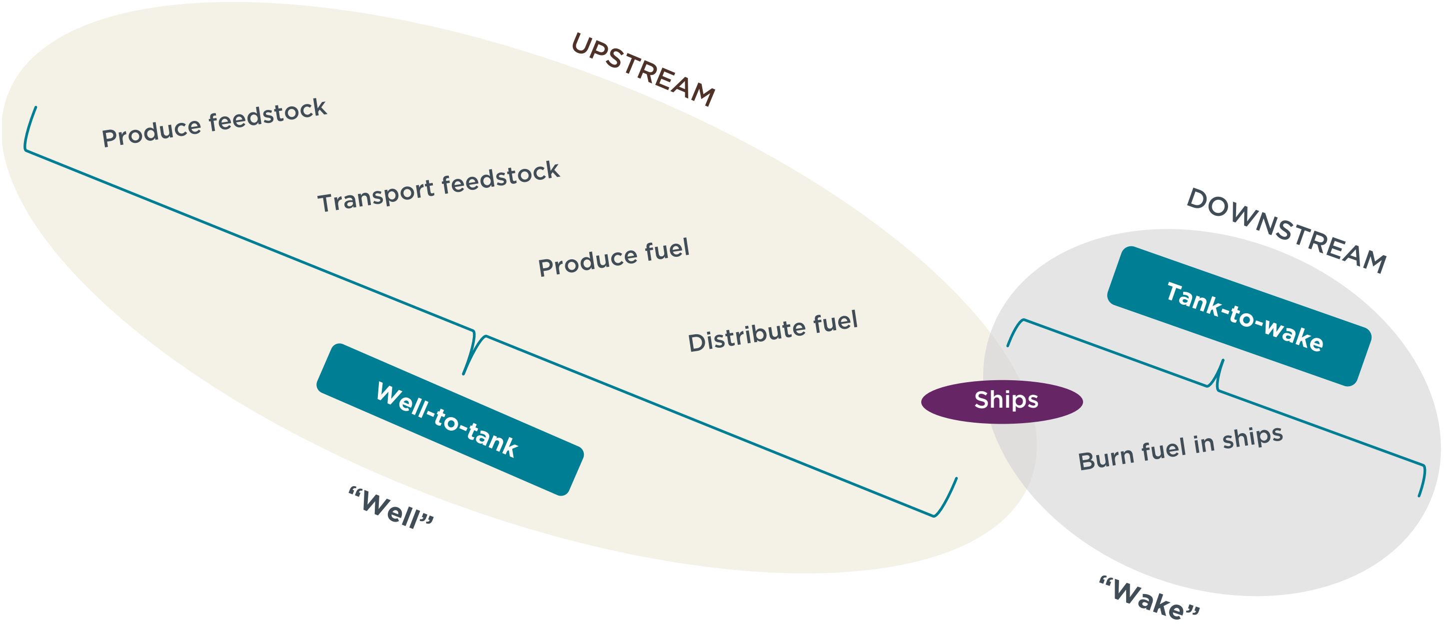

Figure 1. Overview of the life-cycle stages of a marine fuel.
Source: Adapted from Prussi (2020)

GOAL AND SCOPE

The first step of an LCA is to define its goal and scope. The goal of the LCA is its intended application, motivation, and potential audience. The goal defines the research question that the LCA is intended to answer and therefore determines the LCA methods used to assess the impacts of the product system studied. The scope should provide a clear description of the product system studied to ensure that the study's breadth, depth, and level of detail are suitable to address its goal. For example, if the goal of an LCA is to evaluate the average, per-liter GHG emissions attributable to a specific fuel producer in a given year, then the scope would be relatively narrow. In contrast, an LCA developed to inform a policy might want to compare a variety of different fuels on a consistent basis, or to assess the total sectoral climate impact of a fuel policy, and this LCA would necessarily be more expansive in scope. Given the IMO's climate strategy and the nature of international shipping, a more expansive LCA is typically going to be most aligned with regulatory goals.

The scope establishes the product system to be studied, its functions, the region and time horizon covered, and the LCA framework used, either attributional or consequential (see more below; British Standards, 2006). When defining scope, it is also necessary to define the "functional unit," which is the metric by which impacts for the LCA are calculated. Functional units can be based on different features of the product such as performance, technical quality, costs, and others (Cherubini & Strømman, 2011). For fuels, a unit of 1 L of fuel, or more commonly, 1 MJ of delivered energy, are examples of typical functional units.

In developing the scope of an LCA there are two broad frameworks: attributional LCA or consequential. The attributional LCA is a static approach that tracks the energy and material flows along the product system. It takes a kind of accounting perspective that is established by an allocation decision and distributes the input and output flows of the system among all products based on their energy content and economic or physical properties; this is known as energy-, market-, and mass-based allocation (Ekvall, 2020). In contrast, the consequential LCA approach assesses how the flows of energy and materials to the environment are affected by potential decisions. It is a more context-specific and dynamic approach that considers the system boundary expansion, the benefits associated with the replacement of conventional technologies, and the substitution and/or use of environmental liabilities. In practice, LCAs can draw upon methods from either approach or a combination of both, depending on the goal of the analysis.

SYSTEM BOUNDARY

The system boundary describes the upstream and downstream activities within the scope of the LCA. The criteria used to define system boundaries inform the LCA results and need to align with the goal of the analysis. It is common to use a "cut-off" to exclude smaller activities that contribute less than a certain amount to the final impact; for example, a cut-off threshold of 0.5% would exclude any process that contributes less than 0.5% to a product's final impact. If system boundaries are selected arbitrarily, it can mean that upstream or downstream processes that ought to be included are excluded (Brandão et al., 2021). ISO 14044 does not establish a guideline for defining a system boundary, and while it can vary significantly across analyses, several fuels policies establish life-cycle methodologies to compare different fuels consistently within those policies.

Several activities, processes, and flows are typically considered to define the system boundaries. These include:

- Raw material acquisition and extraction
- Inputs and outputs in the principal process
- Transportation and distribution
- Production and use of energy (in the form of fuels, electricity, or heat)
- Use and maintenance of products
- Waste disposal
- Recycling and recovery of used products

We illustrate a hypothetical product system in Figure 2 and the system boundary is illustrated by the dotted line. In this example, the system boundary includes the product's upstream raw material extraction emissions, production emissions, use emissions, and final disposal. The final use of co-products is outside the system, as are the upstream emissions attributable to the energy and chemicals used to produce the system's inputs.

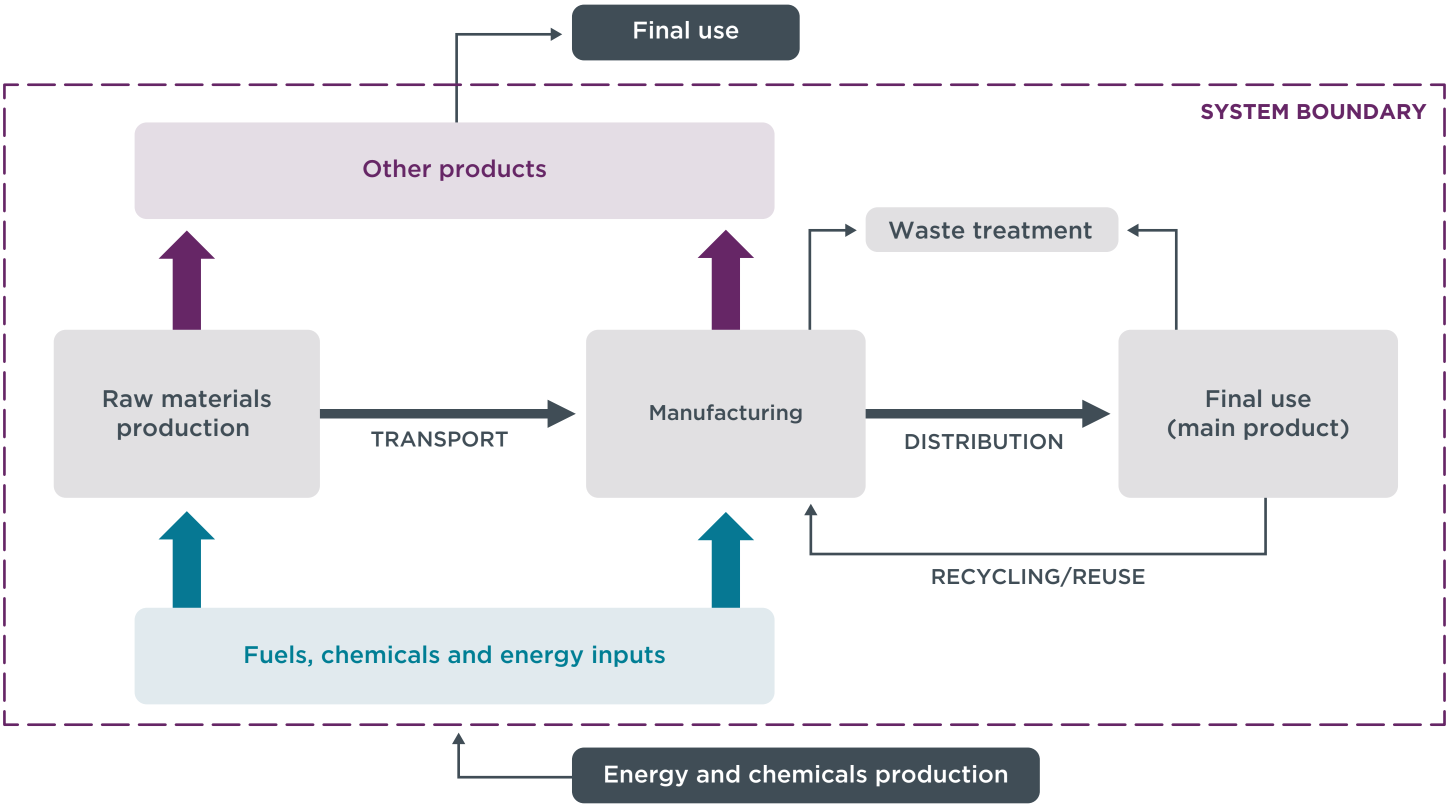

Figure 2: Example of product system and system boundaries for an LCA. Based on British Standards (2006).

Decisions about the system boundary are critical when evaluating the life-cycle climate impacts of fuels, as the emissions attributable to a fuel can change significantly based on what is included in the system. For example, a narrow scope of analysis that only includes fuel production and use stages might exclude important sources of emissions further upstream, such as the emissions from cultivating crops for biofuel production or the emissions attributable to the electricity used to power a bio-refinery.

ALLOCATION

The example system boundary in Figure 2 also shows that some product systems generate multiple products. For example, corn ethanol production generates not only ethanol but also distillers' dried grains with solubles (DDGS). Though an LCA could examine the overall product system, often the goal is to only assess the impact of one end product or service. In cases where there are multiple end products or services, it is not necessarily obvious what fraction of the environmental burden of a process should be allocated to each output and on which basis. Therefore, a common practice is to allocate emissions between multiple co-products based on their physical or economic properties (ISO, 2006). This can be done via mass, energy, or economic allocation, and in these the total impacts are split based on the proportional mass, energy content, and market value of the co-products, respectively.

Some product systems generate a mix of products with energy and non-energy uses, and in those cases, an allocation decision based on physical properties might overlook or overstate a co-product's share of emissions. While an economic allocation approach might more accurately reflect a material's share of environmental burdens, market values can fluctuate greatly over time and in different regions, and thus this approach can add uncertainty to an LCA. An alternative approach called system expansion widens the system boundary to assess the activities shared between product systems. While this approach can capture market nuances, it also introduces complexity in LCA compared to the simple partitioning of burdens used in the allocation approach. Expanding the system boundaries is usually an example of a consequential approach, even though it can be utilized within an attributional LCA.

Some materials that exist in a product system cannot be neatly defined as products or co-products. The interpretation of a material's role within the product system and how it is categorized within an LCA can have a large impact on how the environmental impacts associated with that system are attributed (ICF International, 2016). For example, some outputs from a process are materials that will be disposed of with no further use; these materials are often considered wastes with no share of the overall product system's burden. Other materials that are not the primary intended product might have some market value but might be a small share of a product system's outputs, and these are in a gray area between co-product and waste. These terms are not always defined in this way in contexts other than LCA. For example, by-products can be defined as any material that results from a process other than the primary product (European Commission, 2008); wastes can be defined as any substance or object that the holder discards or intends to or is required to discard (Council of the European Union, 2009); and residues can be defined as materials that are not intentionally produced in a process but might (or might not) be a waste (European Commission, 2008). In practice, there are a multitude of different definitions in the literature. Below we provide a brief overview, largely based on analysis conducted by ICF International (2016):

- **Primary product**: This is the singular main product of a product system and the primary value driver of that product system. The supply of this product is elastic with demand for it (i.e., an increase in demand for the product results in a price increase that stimulates more production). An example of a primary product is the corn grain from corn cultivation.
- **Co-product:** A product system with co-products generates two or more products whose supply is elastic with demand. An example of this type of system is soybean cultivation, wherein both soybean meal and soybean oil are considered value drivers for the product system.
- **By-product:** By-product definitions vary significantly across the literature. In general, by-products are considered to have lower economic value than co-products

and their production is considered inelastic with demand. Thus, while these materials can have market value, they are either produced in low quantities relative to the primary and co-products or have lower value than those products and thus do not significantly influence the value of the overall product system. As such, changes in the value of or demand for a by-product do not stimulate the additional production of primary and co-products (ICF International, 2016; Pavlenko & Searle, 2020). An example of a by-product is tallow from animal rendering.

- **Wastes and residues:** The definition of wastes and residues is also diverse in the literature. Some define wastes and residues as materials with little or no market value whose production is also inelastic to demand (ICF International, 2016; Pavlenko & Searle, 2020). Examples include flue gas emitted from a steel mill and ash left over in a boiler from biomass combustion.

Co-products are typically attributed a share of product system emissions that is proportional and calculated using either allocation or system expansion. However, LCA's of fuels made from by-products and wastes sometimes only attribute emissions from the point of their collection onward and do not include any upstream emissions from the product system; this categorization of a material can thus have a significant impact on the estimated GHG emissions, as in some cases products deemed by-products and wastes might have some market value and existing uses. The distinction between by-products and wastes and co-products is subject to interpretation and can vary considerably based on product system in question, as well as on the predominant practices in the region in which the LCA is conducted (Pavlenko & Searle, 2020). Assessing the displacement emissions associated with diverting a by-product or waste from its existing uses can be most aligned with the goals of some LCAs, rather than assuming these have no upstream emissions.

INDIRECT EFFECTS

Indirect or market-mediated effects occur outside the immediate product system or supply chain and can include market responses to policies such as increased prices or new sources of demand. A common example of an indirect effect captured by the consequential LCA approach is indirect land use change (ILUC). ILUC occurs in response to biofuel policies that increase demand for land-based biofuel feedstocks, as this in turn increases their prices and creates pressure for cropland expansion. The relationship between biofuel demand and cropland expansion is mediated through a set of complex market linkages that are often assessed using economic models (Malins, 2017). Other indirect effects include the rebound effect, where fossil fuel use recovers because its price dropped due to displacement by biofuels, and displacement effects, where diverting feedstocks to biofuel production creates the need to find replacements for those materials to continue the processes associated with their existing uses. Incorporating such indirect elements into an LCA addresses the risk of ignoring a potentially large behavioral effect that could happen at the margins of production.

CHARACTERIZATION METRICS

The inventory is the data collection process in an LCA. Inputs and outputs listed in the inventory results are classified according to different impact categories. Common impact categories considered in LCAs include resource depletion, global warming impact, ozone depletion, acidification, and eutrophication. In fuels LCA, global warming is typically the focus (Lee & Inaba, 2004). The use of characterization metrics is particularly important when assessing the life-cycle impacts of product systems. By expressing impacts using a common metric, both direct and upstream impacts can be summed across different materials, products, and services. For fuels LCA, the impact of GHG emissions is quantified based on their radiative forcing, known as global warming potential (GWP). LCAs of fuels typically utilize a 100-year time horizon for GWP values, due to considerations of long-term climate policy goals and for consistency with existing GHG inventories. Nonetheless, it is understood in the literature that using only GWP100 does not capture the full range of climate change impacts (National Academies of Sciences, Engineering, and Medicine, 2022). A 20-year time horizon (20-year GWP) could be used in a situation where short-term reductions in emissions of powerful gases with shorter atmospheric residence times are prioritized, and using more than one metric should be considered in analysis of low-carbon fuel policies. However, the carbon intensities from different LCAs can only be compared consistently if they both utilize the same set of GWP values.

COMPARISON OF LCA APPROACHES IN EXISTING FUELS POLICIES

In this section, we focus on policies in the United States, California, the European Union, and Brazil, four of the largest fuels markets in the world, and a fifth policy that is used in global commercial aviation. We provide a summary of each policy and the LCA methods and methodological choices used to evaluate fuels for that policy. (A more detailed review of these five fuel policies, including descriptions of their scope of analysis and the extent to which they consider additional sustainability safeguards to complement the LCA, is included in Appendix A.)

In the figures that help describe these policies, we use colors to illustrate the scope. As shown in the TTW-only example in Figure 3, each included stage is shaded blue and each excluded stage is shaded in red. The dark inner boxes represent the attributional, direct emissions attributable to each fuel, whereas the larger, light boxes represent the consequential, market-mediated emissions. The example in Figure 3 shows that in a TTW-only analysis, only emissions from fuel combustion are within the scope.

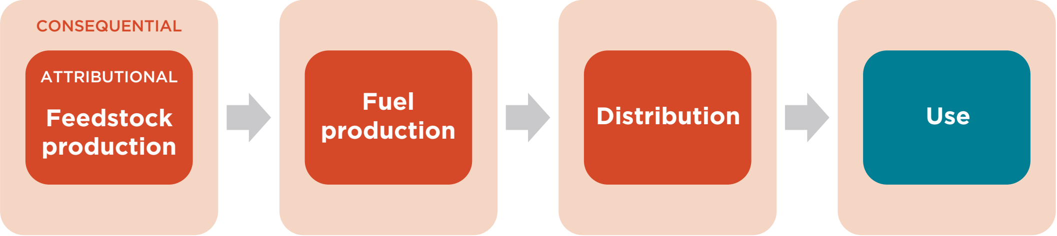

Figure 3: Overview of a scope that only considers TTW emissions.

U.S. RENEWABLE FUEL STANDARD

The Renewable Fuel Standard (RFS) is the primary federal biofuels policy in the United States. It is a volumetric mandate designed to increase the volume of renewable fuels that are produced and blended into the fuels used in the U.S. road transportation sector. Eligible fuels that meet the specified GHG reduction targets for each category are counted toward program compliance. It was first introduced in 2005 (RFS1) and was expanded in 2007 under the Energy Independence and Security Act (EISA). A revised and expanded version released in 2010 is known as the RFS2.

The RFS1 established total annual biofuel blending mandates and broad definitions for renewable fuel. The RFS2 expanded on RFS1 by introducing volumetric sub-mandates for four biofuel categories, expanding the definition for renewable fuel, and by establishing GHG reduction thresholds relative to a fossil fuel baseline. Under the RFS2, biofuel eligibility is based on both the definitions for renewable fuel set forth in EISA and each fuel pathway's life-cycle GHG emissions, as assessed by the U.S. Environmental Protection Agency (EPA). The definitions for each biofuel subcategory are based on a mix of feedstock-based requirements and thresholds for GHG savings for a given fuel relative to petroleum that range from 20% to 60%. Baseline fossil fuel emissions were also assessed by EPA and are defined as the average life-cycle emissions for either gasoline or diesel fuel sold or distributed as transportation fuel in 2005 (Energy Independence and Security Act of 2007, 2007).

Pursuant to the Clean Air Act, EPA defines life-cycle GHG emissions as "the aggregate quantity of [GHG] emissions including direct emissions and significant indirect emissions such as significant emissions from land use changes . . . related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution" (CAA

§ 211(o)(1)). Emissions for each biofuel pathway are reported in grams of CO_2e per megajoule of fuel (gCO_2e/MJ), also known as a fuel's carbon intensity (CI).

Scope

EPA assesses the life-cycle GHG emissions from different biofuel pathways based on feedstock production and transport, fuel production and distribution, and fuel use. For each stage, EPA assesses the aggregate impact of the change in inputs (e.g., fuel use, fertilizer use) attributed to biofuel production and converts those changes into emissions estimates. While much of the calculation methodology used for the RFS is a form of attributional LCA, the program also incorporates elements of consequential LCA. Other indirect effects such as the "international oil takeback effect" (i.e., the fossil fuel rebound effect) and the effect that increased demand for U.S. biofuels has on global oil prices were explored by EPA in draft rulemaking but were ultimately not included in the final assessment. Additionally, the indirect emissions effects related to feedstock displacement from existing end-uses has been adopted by EPA for several pathways including grain sorghum oil and landfill biogas.[1]

The graphic below illustrates the emissions sources included in the RFS' standard LCA methodology. The dark shaded inner bubbles in Figure 4 represent attributional, supply chain emissions by life-cycle stage and the lighter outer bubbles represent consequential, market mediated emissions. Although EPA applies this combination of methods to some of the primary feedstocks, including corn, soy, and lignocellulosic energy crops, other pathways are not assessed using this level of analysis.

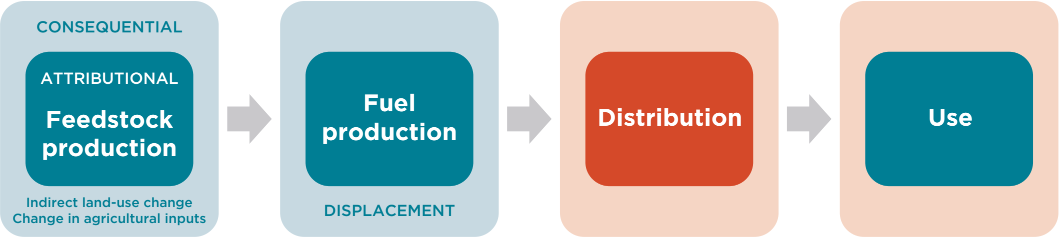

Figure 4. Scope of the standard LCA for the RFS.

Note. Blue cells are included within the scope of the LCA for this policy and red cells are out of the scope.

CALIFORNIA LOW CARBON FUEL STANDARD (LCFS)

California introduced its own biofuel policy in 2009 and it is known as the Low Carbon Fuel Standard (LCFS). The LCFS is a technology-neutral performance standard that aims to reduce the life-cycle CI of the California transportation fuel pool. Like the RFS, the program estimates emissions from each fuel type on a normalized basis of gCO_2e/MJ relative to a baseline value. Whereas the RFS utilizes a fixed GHG emissions savings threshold for biofuels to determine their eligibility and category within the program, the California LCFS utilizes a declining CI benchmark that applies to all fuels. Producers selling fuel that exceeds annual CI benchmarks generate credit deficits and fuel producers that fall below the annual CI benchmark generate surplus credits. The LCFS is implemented by the California Air Resources Board (CARB).

The original LCFS regulation established a 10% CI reduction target by 2020 based on the 2010 baseline CI of transportation fuel consumed in California. The current LCFS regulation, amended in 2018, established a 20% CI reduction goal between the 2010 baseline and 2030 (CARB, 2020). CARB implements annual CI benchmarks that

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[1] In 2018, EPA approved its first pathway (grain sorghum oil) that conducts a consequential LCA for the fuel production stage. Other pathway updates that account for indirect displacement emissions have been proposed or submitted for approval.

decline toward the long-term target, with smaller increases in the early years toward a 1.25% annual CI decrease starting in 2015. The program is a market-based mechanism wherein program deficits, measured in tonnes CO_2e, are offset through the acquisition of credits from the production and blending of lower-CI fuels. The value of a credit is flexible and has varied over time due to a variety of factors, including the cost of producing alternative fuels, the compliance target, and program uncertainty. The value of the program to a given alternative fuel is directly proportional to its GHG savings relative to the benchmark.

Petroleum extraction emissions are estimated via the Oil Production Greenhouse Gas Emission Estimator (OPGEE) model, which was designed to quantify the average emissions of crude oil supplied to California refineries (CARB, n.d.-a). The 2006 CI for crude oil was used as the reference baseline for both gasoline and diesel fuel in the original legislation (Annual Carbon Intensity Benchmarks, 2010). Upstream petroleum emissions are updated regularly based on the mix of crude oils produced and imported into California. The CI benchmark (i.e., the CI target) in the LCFS regulation declines every year toward the program's 2030 CI target.

To generate credits within the program, alternative fuel producers must also estimate a CI for their products. Unlike the RFS, non-biomass-based fuels such as battery electric and fuel cell vehicles and compressed natural gas are also eligible to generate LCFS program credits. Also different from the RFS, fuels are certified at the facility level rather than in regulatory rulemakings, as described below.

Scope

The LCFS measures life-cycle emissions using process-based attributional LCA for each stage. All inputs and emission factors for direct emissions are sourced from an adapted version of the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model. For the feedstock production stage, the LCFS considers both direct and indirect emissions from land-use change (LUC). Here, LUC emissions are quantified using a modified version of the Global Trade Analysis Projected (GTAP) model, combined with emission factors from the Agro-Ecological Zone Emissions Factor (AEZ-EF) model. Like the Forestry and Agricultural Sector Optimization Model (FASOM) model, GTAP measures the indirect emissions effects across interacting markets for the global agriculture and forestry sectors, but it differs in its input assumptions such as price elasticity of demand for different materials. Figure 5 displays the LCA scope for the LCFS. The regulation accounts for emissions from each process stage for bubbles shaded in blue.

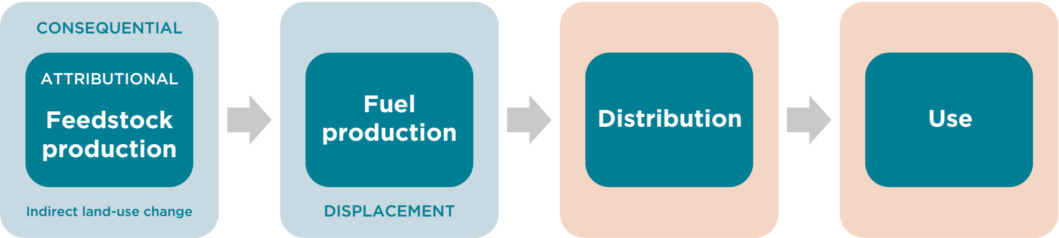

Figure 5. Scope of the LCA for the California LCFS.

Note. Blue cells are included within the scope of the LCA for this policy and red cells are out of the scope.

RENEWABLE ENERGY DIRECTIVE (RED II)

The Renewable Energy Directive (RED) is the primary policy that promotes renewable energy across all sectors in the European Union. The RED was first implemented in 2009 (RED, 2009/28/EC) and it was revised and updated in 2018 (RED II). The European Commission also proposed another revision to the RED in 2021, in response to the increased target proposed in the "Fit for 55" package of 55% EU-wide GHG emissions reduction by 2030. The 2021 revision is under evaluation by the Council and European Parliament and is expected to be adopted circa the first quarter of 2023.

Scope

The RED II is primarily a renewable energy mandate and it is applicable to all sectors. It includes a transportation-specific target of 14% renewable energy by 2030, based on the energy demand for the road and rail sectors. Though it is an energy-based target, the policy includes eligibility thresholds for alternative fuels to qualify that are estimated on an LCA basis. These include a 50%–65% GHG reduction threshold compared to fossil petroleum for biofuels, depending on the date of facility installation. Renewable fuels of non-biological origin, such as electrofuels, have a higher GHG reduction threshold of 70% to qualify. The life-cycle scope of the RED is primarily focused on the direct supply chain emissions for biofuels and does not include any indirect effects such as ILUC when assessing a fuel's eligibility, as shown below in Figure 6. There are also separate non-GHG sustainability criteria for biofuels to qualify.

The RED II establishes a transparent formula for the calculation of direct emissions attributable to alternative fuels and its Annex V defines the total fuel emissions as the sum of seven different components:

1. emissions from the extraction or cultivation of raw materials
2. annualized emissions from carbon stock changes caused by land-use change
3. emissions from processing
4. emissions from transport and distribution
5. emissions from the fuel in use
6. emissions savings from soil carbon accumulation via improved agricultural management
7. emissions savings from carbon capture and geological storage
8. emissions savings from excess electricity from cogeneration

Notably, the scope of the RED II formula includes the direct emissions from land conversion and an option to credit farms for agricultural management practices that increase onsite soil carbon stocks.

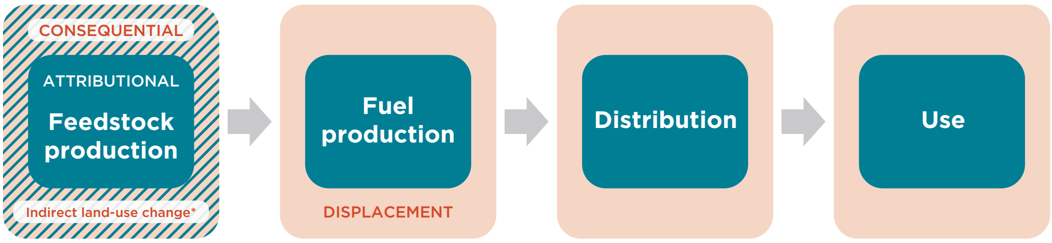

Figure 6. Scope of EU RED II LCA.

Note. Blue cells are included within the scope of the LCA for this policy and red cells are out of the scope. Feedstock production is cross-hatched because the RED considers ILUC emissions in its design and incentive structure for fuels but does not explicitly include ILUC emissions in the estimated carbon intensity of fuel pathways.

CARBON OFFSETTING AND REDUCTION SCHEME FOR INTERNATIONAL AVIATION (CORSIA)

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the International Civil Aviation Organization (ICAO)'s GHG emission reduction scheme

(ICAO, 2019b). It was introduced to implement ICAO's goal of carbon-neutral growth for international aviation emissions beyond 2020 through a mix of out-of-sector carbon offsets and in-sector GHG reductions. CORSIA standards and recommended practices include an LCA methodology developed as a system to credit the use of sustainable aviation fuels (SAF) and Lower Carbon Aviation Fuels (LCAFs).

Scope

The CORSIA scheme includes a set of default LCA values for a variety of SAFs and the guidelines to develop LCA values for individual fuel producers based on site-specific data. Direct emissions are estimated primarily using an attributional LCA approach and ILUC emissions are estimated using a consequential approach. The sum of emissions estimated using both methods are compared with the baseline emissions values for petroleum jet fuel. The baseline values are defined in the CORSIA methodology (Annex 16) and are 89 gCO_2e/MJ for jet fuel and 95 gCO_2e/MJ for aviation gasoline. Figure 7 illustrates the scope of the LCA of fuels in CORSIA. The only indirect effect included is ILUC for crop-derived fuels.

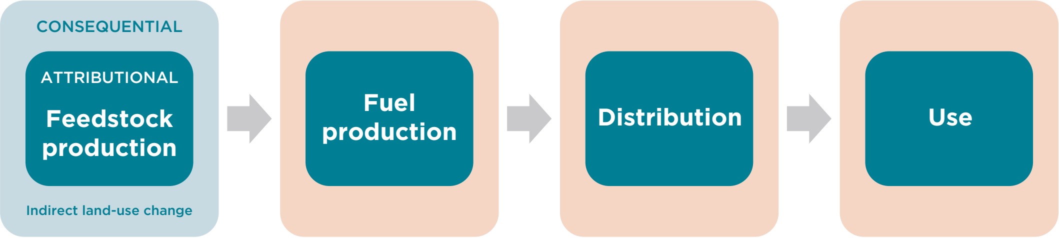

Figure 7. Scope of CORSIA's LCA.

Note. Blue cells are included within the scope of the LCA for this policy and red cells are out of the scope.

RENOVABIO

RenovaBio is the Brazilian National Biofuel Policy. It was approved in 2017 and is meant to expand biofuel production and use in the country's transport mix and improve production practices. Because the policy foresees different market treatment for biofuels with lower life-cycle GHG emissions, RenovaBio includes a methodology framework and tool, RenovaCalc, to determine the life-cycle emissions of biofuels and compare them with fossil fuels.

RenovaBio's principal instrument is the definition of national, annual decarbonization targets for the fuel sector. These goals contain individual mandatory targets for fuel distributors according to their share of the fossil fuel market and a biofuel certification scheme wherein individual scores are attributed to each biofuel producer based on the CI of their biofuels (Environmental-Energy Efficiency Note, NEEA). The scores are intended reflect the efforts of each producer to mitigate a specific amount of GHGs compared to its fossil fuel substitute in terms of equivalent tons of CO_2.

Biofuel producers and importers that join the program must hire inspection firms accredited by the National Petroleum, Natural Gas and Biofuels Agency (ANP) to carry out the certification process and validate the Energy-Environmental Efficiency Note and the eligible volume. Once certified, biofuel producers and importers can generate decarbonization credits known as CBIOs; these are financial assets negotiable via a credit market. Fuel distributors must prove compliance with mandatory individual targets through the purchase of these credits. Participation in the RenovaBio program is voluntary, but once a biofuel company joins the program, reporting of the technical parameters for the production, treatment, and conversion process steps is mandatory.

Scope

The main principle of RenovaBio's LCA methodology is to calculate the CI of biofuels on a consistent gCO_2eq/MJ basis and compare with those from the equivalent fossil fuel. The baseline CI of fossil fuels is based on literature values. The LCA methodology is based on three life-cycle guidelines currently available in Brazil: ISO 14040:2014, ISO 14044:2014, and ISO/TS 14067:2015 .

RenovaBio's LCA framework is based on an attributional LCA approach that uses energy allocation for co-products to calculate the GHG emissions for each fuel pathway. The above-mentioned RenovaCalc tool is designed to account for GHG emissions across the entire biofuel life cycle and generate a biofuel CI value that is subtracted from the fossil fuel CI and results in the Energetic-Environmental Biofuel Index (NEEA). The NEEA reflects the individual contribution of each production agent in terms of its mitigation of GHGs compared to the fossil fuel substitute in terms of tonnes of CO_2e. To convert the NEEA, given in gCO_2e/MJ, into CBIO, which are given in tonnes of CO_2e avoided, NEEA is multiplied by the eligible volume of biofuel. The figure below displays the emissions sources included in the RenovaBio LCA methodology.

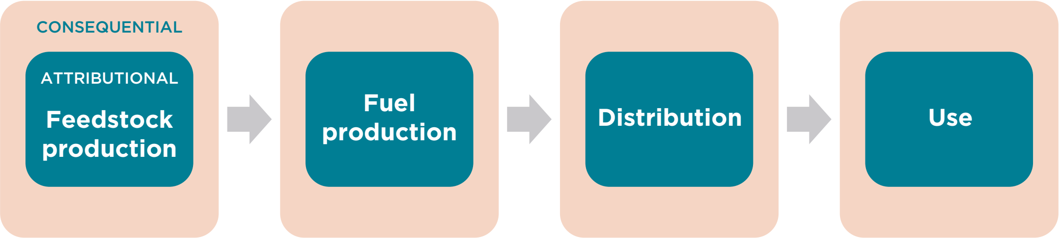

Figure 8. Scope of RenovaBio LCA.

Note. Blue cells are included within the scope of the LCA for this policy and red cells are out of the scope.

Table 1 summarizes and compares the above fuel policies according to their approach to estimating direct emissions, their allocation methods, their inclusion of indirect emissions, and other sustainability criteria.

Table 1: Summary of fuel policies

Policy	Direct emissions	Allocation	Indirect emissions	Other sustainability criteria
EPA RFS	Primarily a consequential analysis; includes direct emissions from feedstock production, material inputs, feedstock conversion, distribution, and use	System expansion, energy- and mass-based allocation	Indirect land use change and modifications in crop, livestock, fertilizer, and energy production	Certification needed (LCA assumptions) Aggregate compliance (monitor nationwide LUC)
CA LCFS	Process-based attributional, including feedstock production, material inputs, feedstock conversion, distribution, and use	System expansion, energy- and mass-based allocation	Indirect land use change quantified for relevant pathways	Certification needed (Pathway approval by an accredited body detailing emissions sources, input and output materials, co-products, wastes, and transportation modes)
EU RED	Process-based attributional, including feedstock production, material inputs, feedstock conversion, distribution, and use	Energy-based allocation	Not quantified (Indirect land use change mitigation by capping food and feed-based biofuels and phase out of biofuels with high risk of indirect land use change)	Certification required (Third-party voluntary certification to ensure consistency with the land-use criteria and verify overall LCA emissions) GHG reduction eligibility threshold Sustainability criteria (Specific criteria applicable to biofuels to maintain soil quality and biodiversity and protect against deforestation)
CORSIA	Process-based attributional, including feedstock production, material inputs, feedstock conversion, distribution, and use	Energy-based allocation	Indirect land use change quantified for relevant pathways	Certification needed GHG reduction eligibility threshold Sustainability criteria (Land carbon stock, water quality and availability, soil health, air quality, biodiversity conservation, waste and chemicals management, human labor, land use and water use rights, and food security)
RenovaBio	Process-based attributional, including feedstock production, material inputs, feedstock conversion, distribution, and use	Energy-based allocation	Not quantified (addressed by risk management mechanisms through eligibility criteria)	Certification needed Eligibility criteria (Biomass should be sourced from areas where native vegetation has not been suppressed after 2018, and from properties registered in the rural environmental system and that comply with the agroecological zoning)

CASE STUDIES OF LCAS OF ALTERNATIVE MARINE FUELS

Here we explore four LCA case studies of possible alternative fuels for the marine sector: soybean biodiesel, used cooking oil (UCO)-based renewable diesel, e-methanol, and hydrogen. These were chosen because they are fuel pathways that require different resources and processing and would be used in novel propulsion systems. Additionally, each pathway utilizes different feedstocks and conversion processes. In Figure 9, below, the feedstocks are on the left side and the renewable feedstocks are in green and the fossil-fuel-based feedstocks are in gray. The conversion steps are in blue and the finished fuels are in purple.

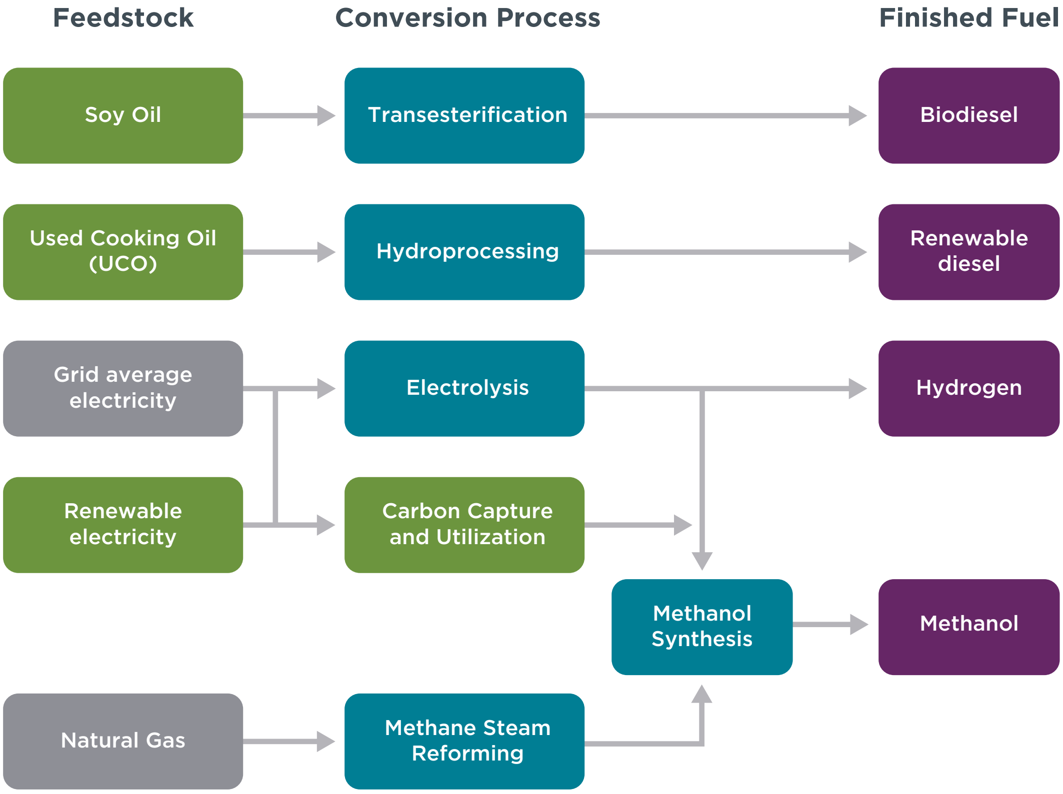

Figure 9. The alternative marine fuel production pathways assessed in our case studies.

For each case study, we primarily estimated emissions using the GREET model. We report results in CO_2e using the 100-year GWP values to convert climate impacts of methane (CH_4) and nitrous oxides (N_2O) into gCO_2e/MJ prior to fuel combustion. We use GWP values from the Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5). The GHG estimates provided in these case studies are intended to illustrate the effects of different choices for life-cycle scope and methods on the ultimate life-cycle GHG emissions estimates for fuels. For comparison purposes, we also estimated CO_2e emissions in a 20-year time horizon (GWP20), which places a greater weight on the impacts of powerful gases with shorter atmospheric residence times. We provide the results for each case study in GWP20 in Appendix B.

For each of the fuels selected, we estimated their direct GHG emissions using different methods and assumptions. This allows us to assess the impacts of different methodological choices. This also helps to identify the most critical assumptions and potential pitfalls in the application of LCA methodology, particularly regarding allocation method and scope. Regarding indirect emissions, for soy biodiesel, we assessed the land-use and deforestation impacts by including ILUC emissions and evaluated the importance of feedstock traceability and land protections. For UCO-based renewable diesel, the displacement emissions associated with UCO diversion and substitution (by cereal or soybean oil) to animal feed were considered, as was the potential impact of waste oil fraud by using virgin vegetable oil. For methanol and hydrogen, we considered how electricity-based fuels could create indirect emissions impacts on the electricity grid. Additionally, when applicable, the GHG emissions attributable to sustainability risks were quantified; this is to illustrate the impacts of these sustainability factors relative to the range WTW emissions estimated previously. Table 4 summarizes the methodologies and assumptions for each case study.

Table 4. The methodological approaches of the case studies.

Fuel pathway	LCA choices evaluated
Soy oil biodiesel	**Allocation**: energy versus market versus mass **Indirect emissions**: ILUC
UCO renewable diesel	**Allocation**: energy versus market versus mass **Indirect emissions**: displacement and waste oil fraud
E-methanol	**Life-cycle scope**: inclusion of upstream feedstock production emissions **Indirect emissions**: increased fossil fuel demand
Hydrogen	**Life-cycle scope**: inclusion of upstream feedstock production emissions **Indirect emissions**: increased fossil fuel demand

SOY OIL BIODIESEL

Soy oil-derived FAME (fatty acid methyl ester) biodiesel is a common food-based biofuel. FAME biodiesel is a biofuel generated via the transesterification of straight vegetable oil, animal fat, or grease. We selected soy-derived biodiesel because soy oil is produced in large volumes and has a substantial global market share. In marketing year 2021–2022 (October to September), 61.74 million tonnes or 29% of all vegetable oils produced globally were made from soybeans (U.S. Department of Agriculture, 2021). In addition to the large production volumes, FAME biodiesel is compatible with existing marine engines and can be blended with bunker fuel. FAME biodiesel is a safe, technically feasible, and relatively low-cost alternative fuel for the maritime sector (Zhou et al., 2020).

We used the GREET model to estimate direct emissions from upstream production based on different LCA assumptions (Argonne National Laboratory, 2020b) and assessed the contribution of indirect emissions to the overall impact of soy biodiesel production by referencing literature on the ILUC associated with this fuel.

We started with an assumption of 0 gCO_2e/MJ on a TTW-only basis, based on IMO's current emission factor used to estimate emissions from biofuels, which treats biogenic CO_2 emissions as zero. Our default case estimated direct CO_2e emissions from upstream production using mass-based allocation because this method is commonly used in LCA estimates for soy biodiesel production; it is a default option in the GREET model and in the California LCFS (ICF International, 2016). We also compared the range of CO_2e emissions based on energy-based and market-based allocations, both of which are options in GREET.

Soy biodiesel production consists of multiple steps; there is feedstock production, which includes fertilizer production, soybean farming and transportation, and soybean crushing, and also biodiesel production, which includes soy oil transesterification and transportation processes. The soybean crushing step produces a large amount of soy meal co-product, which is commonly used for animal feed. Glycerin, another co-product, is produced during the transesterification process. These co-products are handled in the GREET model at the system level and both co-products are allocated based on the assigned method, be it mass-based, energy-based, or market-value-based. The selection of an allocation method for soy meal has a strong impact on the share of produced co-product in the system and on the corresponding CO_2e emissions. While the mass-based method allocates 77% to soy-meal co-product, it is allocated 55.6% in the energy-based method and 43.1% in market-value-based method. Consequently, our first estimate of soy oil biodiesel direct emissions with mass-based allocation results in 14.8 gCO_2e/MJ; the energy-based allocation increases the emissions to 29.4 gCO_2e/MJ, and the market-value-based allocation results in an estimate of 37.7 gCO_2e/MJ for direct emissions—more than twice that of the mass-based approach.

Additionally, although most soy biodiesel LCAs, including the analysis in GREET, assume that soy is grown on existing cropland, some policies, such as the aforementioned RFS, REDII, and CORSIA, prohibit direct conversion of high-carbon-stock land for biofuel production. This is because newly converted lands, particularly high-carbon-stock ones such as forests and wetlands, can have high land-conversion emissions. For example, an average soybean yield in 2015–2019 was 3.17 tonnes (t) per hectare (Langemeier, 2021). The quantity of CO_2 released from the grassland to cropland conversion is 110 t CO_2 per hectare and for forest it can grow to 549 t CO_2 per hectare (Argonne National Laboratory, 2020b). Depending on the fuel and the land, it can therefore take years if not decades to displace sufficient petroleum to compensate for the carbon debt associated with land clearance.

Although limiting direct land conversion can ensure that biofuel crops themselves are not grown on recently deforested land, this does not mitigate the market-mediated effects of biofuel policies, namely ILUC. The impact of ILUC emissions can vary significantly depending on the crop type, region, and other aspects of scenario design in a given ILUC study or model. Soy oil has been estimated to generate significant ILUC emissions, second only to palm oil (Transport & Environment, 2019). To factor in the range of results across the literature, we included the ILUC emissions from two ILUC models, The Global Trade Analysis Project (GTAP) and Global Biosphere Management Model (GLOBIOM). We cite results from two previous ILUC analyses, the GTAP-BIO applied to estimate the impact for soy biodiesel for the California LCFS (California Air Resources Board, 2015) and the GLOBIOM model used to assess ILUC emissions from the RED II (European Commission, 2015).

Figure 10 illustrates the results. From left to right, the bars show the range of emissions generated at each possible level of analysis, from a simple combustion emission factor at the left-hand side through to a consequential LCA on the right. The leftmost bar indicates the zero TTW CO_2e emissions without a corresponding assessment of their upstream production emissions. The next three bars display the impact of expanding the analysis to upstream production emissions (teal), the range of impacts of different allocation methods (orange), and the decision to include ILUC emissions (brown).

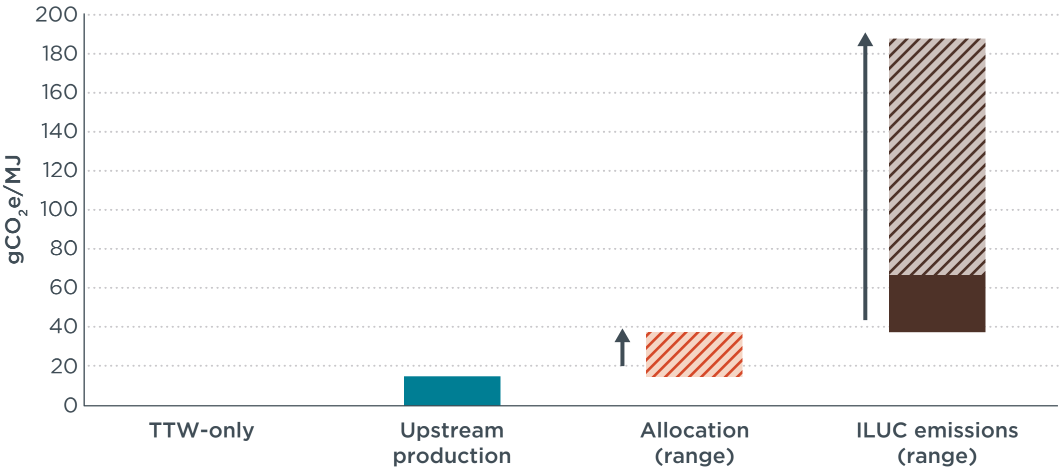

Figure 10. Range of potential life-cycle GHG emissions for soy biodiesel across different scope assumptions and calculation methods. CO_2e values were calculated using AR5 GWP100 factors.

The teal bar shows total direct upstream CO_2e emissions using the default, mass-based allocation. Using this approach, the WTW emissions are 14.8 gCO_2e/MJ in total, with 62% (9.2 gCO_2e/MJ) emitted from feedstock production and the remaining 38% (5.5 gCO_2e/MJ) emitted during fuel production. The orange bar shows the change in GHG emissions if other allocation methods were applied to the system: total direct emissions increase to 29.4 gCO_2e/MJ when using energy-based allocation and to 37.7 gCO_2e/MJ when using market value-based allocation. Finally, the brown bar shows the ILUC-related emissions range resulting from including ILUC emissions. The solid portion shows the increase when using the emission factor estimated using GTAP-BIO (29.1 gCO_2e/MJ) and the cross-hatched portion of the bar shows the emissions estimated with GLOBIOM (150 gCO_2e/MJ). The reason for the fivefold differences in ILUC emission scenarios is that the models estimate different responses to soybean oil demand, in both the extensive and intensive margins of production. The GTAP model estimates that a greater share of demand will be met through intensification of existing soybean production, with less cropland expansion. In contrast, GLOBIOM estimates higher forest and wetland conversion, particularly from palm oil substitution for soy oil in vegetable oil markets.

The emission values we calculated range from 15 to 188 gCO_2e/MJ. Changing GWP metrics from GWP100 to GWP20 leads to an increase of approximately 2 gCO_2e/MJ (see Appendix B).

UCO RENEWABLE DIESEL

Used cooking oils (UCO) are lipids that have been previously used for cooking in households, restaurants, and in the food processing industry. If not used as feedstock for biodiesel production, UCO can be used for animal feed (van Grinsven et al., 2020). However, the use of UCO in biofuel has increased dramatically in the last decade due to high incentives under policies such as California's LCFS and the RED II. These incentives might increase the UCO prices to levels that might reach the value of virgin oils. In this situation, UCO suppliers might attempt to increase their profits by selling virgin oils as UCO; they might also try to sell vegetable oil-based biofuels as UCO-biofuels or mix vegetable oil-based biofuels with UCO-based biofuels (van Grinsven et al., 2020).

This case study first estimated the direct production emissions for UCO-derived renewable diesel using the GREET model. UCO renewable diesel direct production emissions are estimated around 20 gCO_2e/MJ. Adjusting allocation methods for the UCO conversion process only has a minor impact on estimated direct production emissions, as it adds less than 1 gCO_2e/MJ to the baseline emissions.

However, there might be displacement emissions associated with diverting UCO from an existing use as animal feed as it would be substituted with either corn grain or soybean oil. Replacing UCO with such products needs to be based on nutritional content so that the dietary intake of livestock is maintained. Thus corn grain is assumed to replace UCO at a ratio of 1.2 kg of grain per 1 kg of UCO and the associated emissions are approximately 0.70 $kgCO_2e$ per kg of displaced UCO (Pavlenko & Searle, 2020); this results in possible displacement emissions of 18.9 gCO_2e/MJ. O'Malley et al. (2021) assumed that in the United States, soybean oil replaces UCO in the equivalent quantities, and after accounting for demand reduction, we estimated possible displacement emissions of 12.2 gCO_2e/MJ.

There is also the possible impact of waste oil fraud. If monitoring, reporting, and verification of biofuel supply chains is weak or non-existent, it is possible to substitute virgin vegetable oil with UCO to qualify for valuable policy incentives. To quantify this impact, we assumed that waste oil creates demand for virgin palm oil, one of the cheapest substitutes on the market. We therefore attributed palm oil ILUC emissions to the UCO and show the range of results when using ILUC emissions values established by REDII directives, 231 gCO_2e/MJ, and CORSIA based on the GLOBIOM model, 60.2 gCO_{2e}/MJ.

Figure 11 illustrates all results. The upstream production emissions for UCO renewable diesel, shown in teal, are approximately 20 gCO_2e/MJ. Factoring in different allocation approaches, shown in orange, has only a minor impact on the final estimate. On the other hand, indirect effects associated with displacing UCO from use as animal feed and with waste oil fraud might generate a significant increase in emissions, and attempting to quantify the risk of waste oil fraud could erase any benefits from the biofuel, given that emissions could reach up to 250 gCO_2e/MJ, far above than current marine fossil fuel emissions (89 gCO_2e/MJ for MGO). Changing GWP metrics from GWP100 to GWP20 leads to an increase of 2.7 gCO_2e/MJ (see Appendix B).

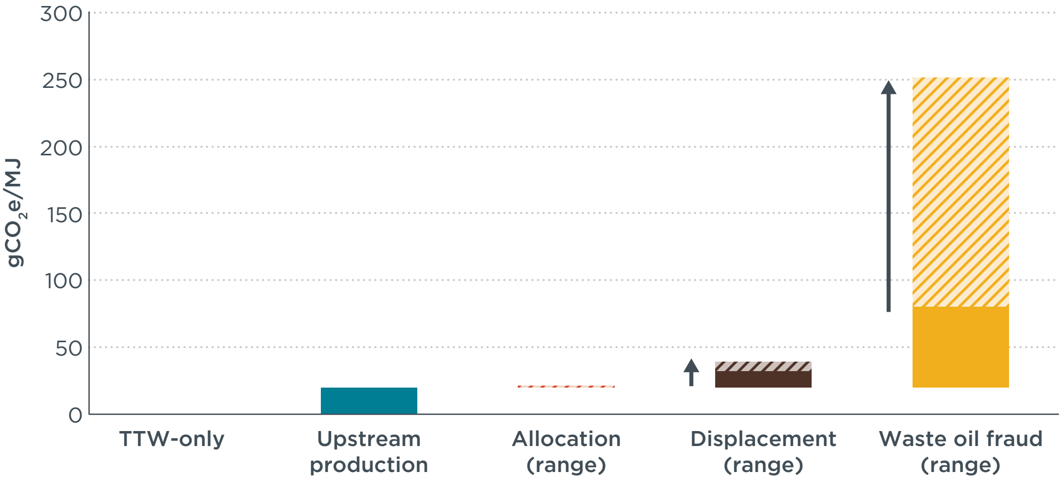

Figure 11. Range of potential life-cycle GHG emissions for UCO renewable diesel across different life-cycle scope assumptions and calculation methods. CO2e values are calculated using AR5 GWP100 factors.

HYDROGEN

The IMO has classified hydrogen as an “evolving” fuel that could be compatible with both fuel cells and internal combustion engines (Faber et al., 2020). Hydrogen has higher energy density than conventional marine gas oil (MGO) but requires a different engine and storage system. Hydrogen can be produced via a number of pathways and there is substantial variation in feedstock input, conversion process, and climate impact. We focused on the steam methane reforming and electrolysis pathways for our case study. Other pathways could be used, including coal or biomass gasification, but these appear unlikely given limited industry support, the associated environmental impacts, and the projected high costs within the 2030 time frame.

The production of “green” hydrogen consumes roughly the same amount of energy as fossil-fuel-derived hydrogen on a per-kilogram basis (Bartlett & Krupnick, 2020). However, it uses a production process known as electrolysis, wherein an electric current separates water molecules into its hydrogen and oxygen components. Because electrolysis produces zero GHG emissions, direct emissions are low and come solely from transport and distribution (T&D), compression, and precooling to deliver fuel to the end-user, which we assume here to be powered by grid-average electricity.

Figure 12 illustrates the range of possible GHG emissions for electrolysis-derived hydrogen, starting from a TTW-only analysis on the left of zero emissions; direct production emissions are in teal and the consequential impact of fossil fuel substitution is in black. Note that the life-cycle GHG emissions of electrolysis hydrogen are highly dependent on the source of the electricity used. Renewable electrolysis powered by solar, wind, and hydro power has no upstream GHG emissions, but electrolysis powered via the electricity grid can lead to sizeable fossil fuel substitution impacts. GREET incorporates grid composition data from the U.S. Energy Information Administration's (EIA) 2020 Annual Energy Outlook report to estimate the relative shares of U.S. electricity production by source and to generate emission factors for electricity (Argonne National Laboratory, 2020a). Based on an assumption of U.S. grid-average electricity, we estimate that the final CI score for hydrogen increases more than tenfold if grid average electricity is used for electrolysis, as shown in the black bar. The hatched portion of the black bar illustrates the impact of assuming an upstream methane leakage rate, which increases the estimated upstream emissions from natural gas power generation plants. In total, we estimate the final CI for green hydrogen to be 17 gCO_2e/MJ when renewable electricity is used for electrolysis and 191 gCO_2e/MJ when the U.S. grid average electricity is used.

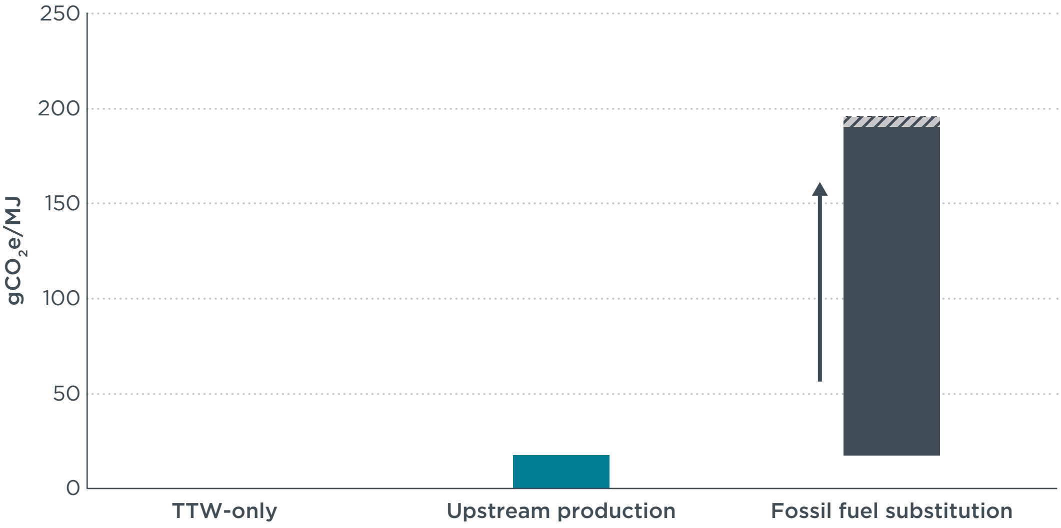

Figure 12. Life-cycle GHG emissions by production stage (electrolysis hydrogen) across different life-cycle scope assumptions and calculation methods. Hatched portion of the bar represents maximum CH_4 leakage rate. CO_2e values are calculated using AR5 GWP100 factors.

Assuming upstream grid-average electricity is used for electrolysis hydrogen production, the emissions increase from 191 to 207 gCO_2e/MJ when GWP20 values are used, using the same leakage rates and emission factor assumptions as in Figure 12.

METHANOL

Although methanol is also classified by the IMO as an "evolving" fuel, several methanol-compatible ships have been deployed in the pilot phase (Faber et al., 2020). The shipping industry has also indicated strong interest in investing in the methanol market as a low-carbon alternative to MGO and methanol ships are expected to be integral to global shipping giant Maersk's 2050 decarbonization goals.

Like hydrogen, methanol can be produced via both fossil-fuel-derived and renewable pathways. We constrained our analysis to just two pathways: synthetic methanol produced via electrolysis combined with direct air capture and conventional methanol produced via steam methane reforming (SMR). Other pathways, including thermochemical conversion of biomass, are possible. Methanol produced via conventional SMR is known as "gray" methanol and methanol produced via SMR paired with carbon capture and storage (CCS) is known as "blue" methanol.

Figure 13 illustrates the range of life-cycle emissions attributable to methanol produced from natural gas via SMR. As you can see, the largest share of emissions comes from the combustion stage (TTW), illustrated in dark gray. Although IMO has not yet published fuel-specific CI values, the organization referenced methanol emission factors developed by Brynolf et al. (2018) in a study assessing methanol's potential as a marine fuel (IMO, 2016). Based on those studies, we used 69 gCO_2e/MJ as the methanol combustion emission factor from the TTW stage. As this fuel is fossil-fuel derived rather than biogenic, combustion emissions are fully attributed. Upstream production emissions shown in teal include conversion of feedstock to fuel, steam co-production, and transportation and delivery to the end user. CCS, shown in green, can be used to reduce the emissions via CO_2 capture at the production site. Assuming a 90% capture efficiency rate, we calculate that upstream production emissions are reduced by nearly 70% when CCS is used at reforming plants. Thus, our final estimated life-cycle CI estimates for "gray" and "blue" methanol are 97 and 79 gCO_2e/MJ, respectively.

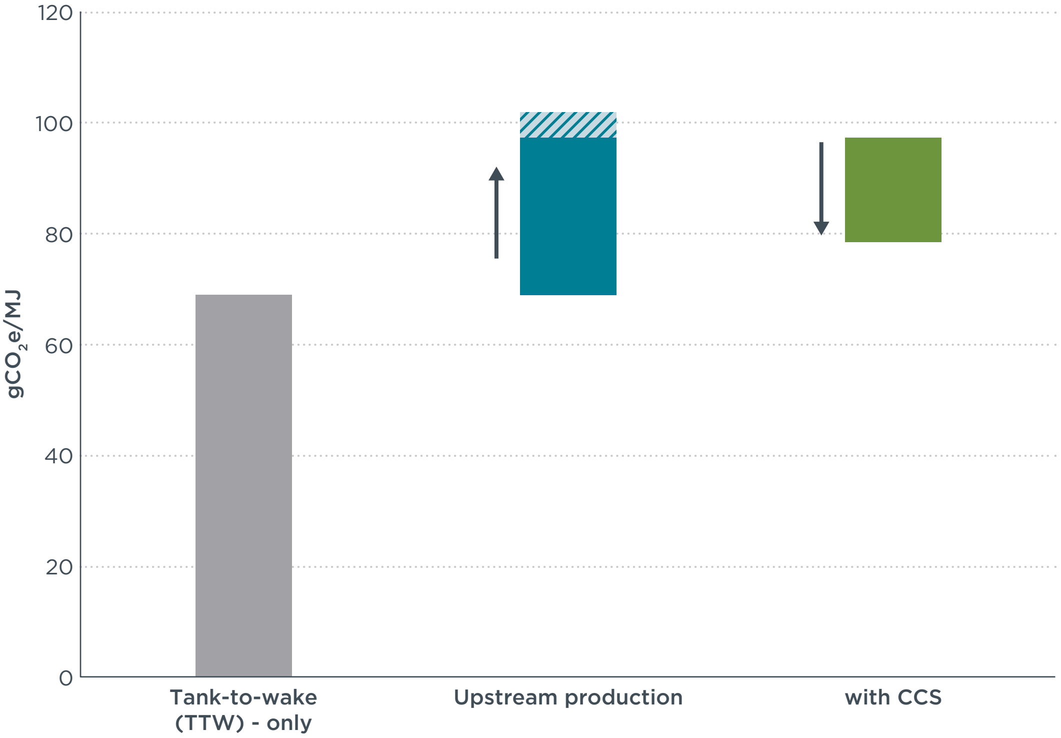

Figure 13. Range of potential life-cycle GHG emissions for methanol produced from steam methane reforming across different life-cycle scope assumptions and calculation methods. Hatched portion of the bar represents maximum CH_4 leakage rate. CO_2e values are calculated using AR5 GWP100 factors.

In Figure 13, the solid teal bar represents upstream production emissions and direct emissions, including maximum methane leakage, are represented by the hatched portion of the bar. The impact of higher upstream methane leakage was assessed by applying a minimum (0.68%) and maximum (2.3%) leakage factor along the natural gas supply chain. EPA estimates that 0.68% of methane is leaked along the natural gas supply chain, which consists of the gas recovery, processing, transmission, and distribution phases. Upstream leakage including gas recovery and transmission accounts for more than 80% of total leakage, or 0.58%. In comparison, a recent study by Alvarez et al. (2018) estimated the overall leakage rate of the oil and gas industry at 2.3%.

For green methanol production, hydrogen produced via electrolysis is combined with CO_2 and CO_2 intermediates in a synthesis reactor. Here we assume that the CO_2 input stream comes from direct air capture. The emissions associated with producing hydrogen (i.e., feedstock emissions) are considered upstream of methanol production. Methanol considered to be "green" can have sizeable upstream emissions impacts if the renewable electricity used is not additional and is instead displaced from other uses. The default calculation for green methanol in GREET assumes the hydrogen intermediate is sourced from renewable electricity. To assess the impact of using grid-average electricity, we also assess the impact using electrolysis hydrogen procured using grid-average electricity. We estimate life-cycle emissions for methanol formed from renewable electrolysis at 1.2 gCO_2e/MJ and life-cycle emissions for methanol formed from grid-average electrolysis at 177 gCO_2e/MJ. Like hydrogen, we used the EIA's 2020 U.S. grid average electricity emission factors in our estimates. Thus, in an electricity grid region dirtier than the U.S. average, upstream emissions would be higher and in a cleaner grid region, upstream emissions would be lower.

Figure 14 illustrates the potential range of green methanol production emissions across a variety of life-cycle assumptions and scopes. As "green" methanol produced from fossil-fuel-derived CO_2 emits non-biogenic emissions at the point of combustion, this fuel has positive TTW emissions (in gray). The upstream production emissions are minor when assuming the conversion process utilizes renewable electricity inputs (shown in teal) and its TTW emissions can be offset if the methanol is produced from captured CO_2 from the atmosphere (carbon capture and utilization in green). Lastly, as with hydrogen, we illustrate the impact of fossil fuel substitution if the renewable electricity is not additional, with grid-average electricity substituting for the diverted renewable electricity. The impact of assuming higher upstream methane leakage is shown in the hatched portion of the black bar.

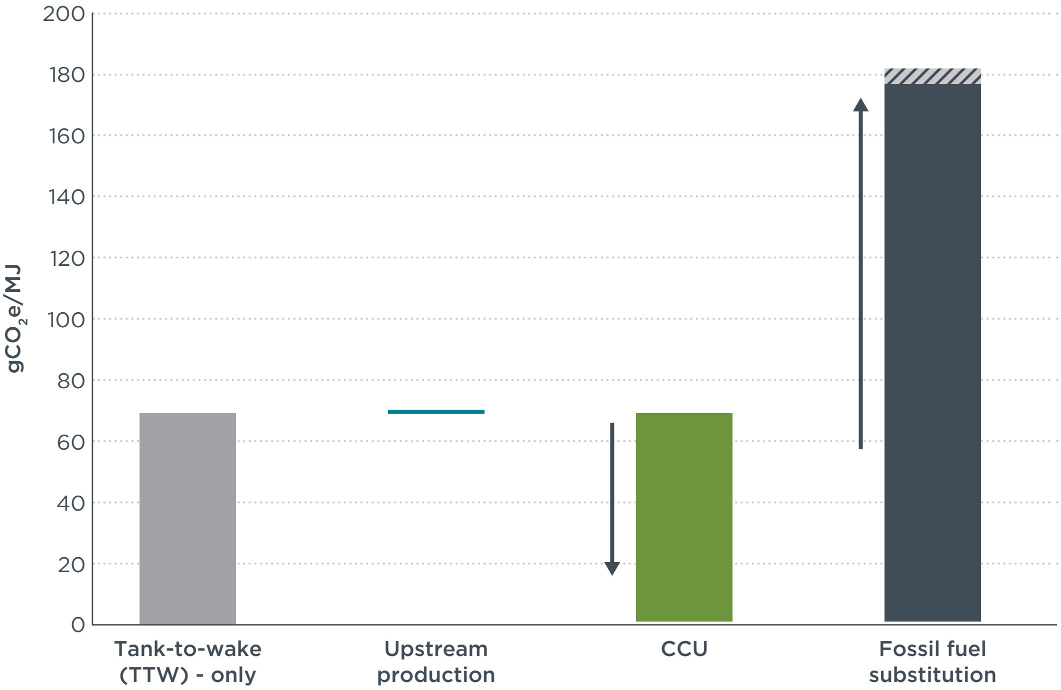

Figure 14. Range of potential life-cycle GHG emissions for green methanol across different life-cycle scope assumptions and calculation methods. Hatched portion of bar represents maximum CH_4 leakage rate. CO_2e values were calculated using AR5 GWP100 factors.

The black bar in Figure 14 underscores how important it is that electricity used in alternative fuel production is sourced from strictly *additional* resources. Even for electricity used to power electrolysis that is labeled as renewable, without proper policy safeguards, that electricity might instead be diverted from generation capacity serving the power sector and that could lead to significant indirect emissions. Renewable electricity diversion could result in additional energy production from the marginal grid mix to make up for the grid energy deficit and in many cases, we expect that the cheapest marginal unit of electricity will come from natural gas (Malins, 2019).

Additionally, the life-cycle impacts attributable to upstream carbon capture and utilization could vary considerably based on the source and additionality of the captured carbon used to produce the fuel. For example, if fossil fuels were combusted solely to produce CO_2 as an input for methanol production, the emissions reduction from carbon capture and utilization would be erased entirely. Similarly, if the CO_2 capture is double-claimed or counted toward a separate policy, such as an emission standard for power plants or industrial facilities, any upstream GHG reductions in the green methanol life cycle would be non-additional. For example, even with the use of renewable and additional electricity to produce green methanol, we estimate that if the captured CO_2 is being claimed by other sectors (in other words, if it is non-additional), the emissions savings from the methanol decline from 99% to only 24%. Certifications could be used to help verify the source and additionality of CO_2 used as an input for fuel production to reduce the risk of these outcomes.

The WTW CI estimates for blue methanol increase from 79 to 89 gCO_2e/MJ when GWP20 factors are used and CI estimates for grid-average electrolysis also increase considerably. This is because natural gas, a significant source of methane emissions, makes up nearly 40% of grid-powered electricity generation in the assumed U.S. electricity grid mix.

DISCUSSION

In comparing the five fuels policies, we found different frameworks and methodological choices but also several common themes. As is required for any LCA, all five policies accounted for the full life-cycle production and use emissions of fuels. Still, we found that they have varying product definitions. Additionally, in some cases they do not establish a clear standard for allocation and attribution of emissions; this is instead often performed on a pathway-by-pathway basis, with some variation even based on production stage.

The RFS is the only policy reviewed that incorporates elements of a consequential LCA across both the feedstock and fuel production stages. RenovaBio, meanwhile, only assesses direct emissions across the fuel supply chain using an attributional LCA. The California LCFS and CORSIA both adopt a mixed approach, wherein a consequential analysis is used only to evaluate ILUC and those ILUC emissions are added to the primarily attributional direct production emissions for fuels. While other indirect effects are not included in most of the evaluated policies, the RFS and CORSIA do include some impacts of avoided emissions and product displacement. Eligibility criteria are set in all policies except for the LCFS. Three of the policies include a GHG reduction threshold, assessed on a life-cycle basis, to be eligible. A consistent approach is to limit the use of fuels sourced from directly converted, high-carbon-stock land.

Importantly, our four case studies uniformly showed that assessing only TTW emissions of alternative fuels can provide a distorted view of the climate impacts of those fuels. This is particularly true for biofuels and hydrogen, which are counted as zero emissions in IMO's current GHG accounting practices only because they do not generate emissions at the point of combustion. As illustrated above, however, both of these fuels can have sizeable upstream production emissions before they are consumed on a ship. We estimated that soy biodiesel production emissions can range from approximately 14.8 to 37.7 gCO_2e/MJ depending on the allocation method chosen. In particular, note that choosing energy or economic allocation for soy resulted in a 100% to 250% increase in estimated direct production emissions. Hydrogen emissions can vary even more based on the choice of feedstock. For example, natural gas-derived or electricity grid-derived hydrogen can have emissions of 96 to 191 gCO_2e/MJ, respectively, and that is even higher than the emissions of conventional marine fuels (89 gCO_2e/MJ for MGO). It is therefore typical in fuels policies to assess the full supply chain of fuels in order to compare them on a consistent basis.

Moreover, expanding the scope of an LCA to include indirect effects can provide important information on the consequential impacts of fuels policies and the potential size of market-mediated emissions associated with some fuel pathways. For example, in our analysis of soy biodiesel emissions, we found that including ILUC emissions changes the estimated impact of the pathway substantially and considerations can lead to a more than tenfold increase in emissions. ILUC emissions are difficult to estimate and bring additional uncertainties to LCA results; for example, the soy ILUC emissions we reviewed ranged from 29 gCO_2e/MJ to 150 gCO_2e/MJ due to models' different estimates of natural land to cropland conversion. There can be substantial differences in ILUC estimates even within one study or model based on feedstock, with some crops estimated to have much higher ILUC impacts than others. Because of this, ICAO (2019) uses GLOBIOM to estimate a range of ILUC emission default values from -35.5 gCO2e/MJ for Miscanthus to 117.9 gCO_2e/MJ for Brazilian soy oil. The inclusion of ILUC, how it is estimated, and the use of emission factors are all critical questions for fuels policies.

Different policies utilize different approaches for addressing direct land-use change. Some policies, such as the California LCFS, attempt to address it solely through emissions accounting, by including ILUC emissions alongside direct production emissions to adjust the policy incentive for those fuels. The RFS and CORSIA complement the ILUC emission factors with additional sustainability criteria to mitigate the impacts of direct land-use change. The RFS prohibits the conversion of high-carbon-stock land for biofuel production and utilizes aggregate compliance to monitor total domestic land conversion, and CORSIA incorporates a certification system to prohibit the production of biofuels on biodiverse and high-carbon-stock land. The European Union's RED II, in contrast, caps or excludes the contribution of biofuels with high ILUC emissions and incorporates sustainability certifications to protect against deforestation and biodiversity loss on land used to produce biofuels. RenovaBio does not explicitly address ILUC or land-use change within the LCA and instead adopts eligibility criteria and certification to exclude crop production on lands out of compliance with separate agricultural zoning laws. The use of sustainability certifications can ensure biofuel production occurs on cropland or marginal land and reduce the risk of direct deforestation and emissions from direct land-use change for the land where biomass for biofuels is produced; however, these protections often fail to mitigate the impacts of ILUC. Furthermore, proposed low-ILUC certification practices intended to promote the use of crops grown with yield improvements and on unused land can fail to ensure the additionality of certified biofuel (Searle & Giuntoli, 2018).

Assessment of non-ILUC sources of indirect emissions can further change our understanding of the climate impacts of some alternative fuel pathways. For example, UCO renewable diesel typically offers low direct production emissions because it is generally considered a waste product and thus comes without the burden of upstream emissions attributable to vegetable oil production. However, in some cases UCO biofuel production diverts UCO from its existing uses and can require the use of a substitute material for those other uses. We evaluated the indirect emissions for UCO displacement for animal feed and found that UCO diversion generates indirect displacement emissions ranging from 12.2 to 18.9 gCO_2e/MJ, potentially doubling emissions for that pathway. Similarly, we found that displacement is an important issue when estimating emissions for green hydrogen and green methanol. If renewable electricity is diverted from existing uses or counted toward more than one existing policy commitment and fuel simultaneously, its effective substitute is marginal, grid-average electricity production. We estimate that for hydrogen and methanol, the substitution effect of marginal, grid-average electricity in the United States increases emissions by approximately 180 gCO_2e/MJ for both pathways.

For several of the case studies, an LCA might reveal several sources of GHG impacts that might be difficult to address by developing a GHG emission factor. For example, the UCO renewable diesel case study illustrates that waste oil fraud, particularly with palm oil, might counteract all of the benefits of substituting fossil fuels with UCO. For these pathways, some combination of certification and monitoring, reporting, and verification would be necessary to mitigate these GHG impacts. For UCO, this potential impact could be mitigated by implementing certifications and protections within the policy framework, to attempt to ensure the chain of custody of UCO supplied in a program and reduce the potential for fraud. Alternatively, it might be preferable to establish a policy safeguard by capping the contribution of these types of fuels; this reduces the contribution of pathways perceived as risky and was done in the European Union, where waste oils are capped at 1.7% of the fuels consumed in transportation.

The use of renewable electricity for fuel production poses a separate problem: Although it might greatly reduce the emissions for some fuel pathways, it is easy to attribute to multiple policies at once. At the same time, the use of grid-average electricity contributes significantly to electrofuels' direct production emissions. Here, doing an LCA would highlight the need for a separate certification process to ensure that electricity used for fuel production for these pathways is both renewable and additional. Policymakers have begun to recognize this risk, and it is best addressed by the proposed additionality requirements under the Delegated Regulation of the

European RED II regulation, which apply to any electricity used in the production of "renewable liquid and gaseous transport fuels of non-biological origin" (Oyarzabal & Falco, 2021). Policymakers can include additionality requirements contracts such as power purchase agreements (PPAs) or guarantees of origin (GOs) between a renewable power facility and hydrogen producer. An example of a flexible mechanism would be a financial additionality test, as outlined under the Clean Development Mechanism under the Kyoto Protocol. This test collects financial information from a renewable electricity supplier and seeks to demonstrate whether a facility would be financially viable in the absence of an offtake agreement between the electricity generator and hydrogen producer. In line with this form of assessment, Article 19 of the RED II states that Member States maintain authority to withhold GO certification if a facility already "receives financial support from a support scheme." Other methods to ensure additionality under the RED II include restricting eligibility to facilities that come online after or simultaneous with the installation of a hydrogen facility and restricting eligibility to facilities that are not grid-connected or those where representatives can provide evidence that the facility does not divert electricity from the central grid.

In addition to helping to ensure additionality for renewable electricity, certification can help ensure that CO_2 capture in fuels' upstream production is credited in line with the spirit of the policy. For example, upstream CCS as part of fossil-fuel-based hydrogen or methanol production can reduce those fuels' life-cycle GHG emissions, but only if that CCS is truly additional and not counted toward separate policies. If the absence of transport fuel production would result in CO_2 emissions to the atmosphere, the transport fuel would be considered an upstream CO_2 sink. However, if, in the absence of transport fuel production that CO_2 would have been permanently sequestered, then the CO_2 capture would not be attributable to fuel production. To address this issue, the European Union's proposed Delegated Act suggests an eligibility framework for recycled carbon fuels that requires fuels using captured fossil CO_2 to demonstrate that the CO_2 was priced into any applicable carbon pricing schemes and it can only be utilized for fuel production through 2035 (European Commission, 2022). This helps to ensure that the CO_2 reductions from carbon capture are not counted toward other policies and that they are not incentivized after 2035, when large, stationary CO_2 sources are expected to be phased out.

CONCLUSION

Although alternative fuels that produce low or zero emissions when combusted on ships are at the forefront of efforts to support IMO's GHG mitigation strategy, combustion emissions are not the only emissions associated with fuels. LCA is an important tool because it can guide climate policies for fuels by assessing the relative emissions of different alternative fuels through their entire life cycle from the extraction of raw material through to the end of life. This study reviewed the emissions scope and GHG accounting methods of the LCAs in five existing fuels policies and found that all of them assess all attributional emissions across the WTT and TTW life-cycle stages, to be able to compare different fuels on a consistent basis. Still, these fuel policies incorporate different methods of accounting for indirect emissions and different sustainability safeguards.

In evaluating four potentially low-GHG alternative fuels for the maritime sector, we found that indirect effects such as displacement might pose sustainability risks, even for some by-product and waste-derived fuel pathways. This was illustrated for UCO-derived renewable diesel, where the emissions attributable to producing its substitute might range from 12.2 to 18.9 gCO_2e/MJ, depending on if it is replaced by vegetable oil or grains. Similarly, we estimated that diverting renewable electricity to green hydrogen or green methanol production can lead to indirect emissions from grid-average electricity that propel these pathways' emissions to over 180 gCO_2e/MJ, approximately twice the emissions of conventional marine fuel (89 gCO_2e/MJ for MGO). Therefore, potential ILUC and indirect emissions might be significant enough to change some alternatives' ability to reduce GHG emissions, and IMO's LCA guidelines should include at least some kind of safeguard to minimize these effects if they are not explicitly included in the LCA emissions estimates.

IMO's current approach of assessing only TTW emissions does not reflect the full GHG impacts of fuel switching. Crediting GHG reductions achieved at the point of combustion risks not only over-crediting GHG reductions achieved in the sector, but potentially incentivizing high-emitting alternative fuels in the long run. To avoid this, we recommend that IMO adopt full, life-cycle WTW GHG accounting in policies that relate to fuel operational use such as the Carbon Intensity Indicator (CII) and potential future policies like the GHG Fuel Standard (GFS). It is critical that LCA guidelines for the maritime sector are based on a well-structured methodology. Any incentives promoting the use of alternative fuels should be combined with safeguards and certification systems to ensure that the fuels delivered to the marine sector are delivering their estimated GHG savings and avoiding unintended, indirect effects.

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APPENDIX A. DETAILED REVIEW OF POLICIES

This section provides a detailed review of five existing fuels policies and assesses the scope of their life-cycle analysis (LCA) and methodology as applied to alternative fuels. In addition to a summary of the policy and the LCA methods and methodological choices used to evaluate fuels for that policy, we discuss whether indirect effects are included and consider the degree to which additional sustainability safeguards or criteria complement the LCA.

U.S RENEWABLE FUEL STANDARD

How direct emissions are assessed

The U.S. Environmental Protection Agency (EPA) uses different models to estimate direct emissions associated with the biofuel production supply chain. Direct emissions begin with feedstock extraction and extend through to delivery to the final consumer. Supporting analysis for the RFS estimated direct emissions for a future production year at that time, 2022, rather than estimating emissions at the time of regulatory implementation. Future year estimates were adopted to reflect market and technology conditions for the final year that statutory volumes were set under the RFS program, and they combine attributional greenhouse gas (GHG) accounting with a projection of future technology changes in response to the program.

EPA uses the Forestry and Agricultural Sector Optimization Model (FASOM) model to estimate the aggregate changes in domestic energy and agricultural inputs from increased biofuel demand (EPA, 2022). FASOM is a partial-equilibrium model that quantifies agricultural and land-use change impacts across the U.S. agriculture and forestry sectors. These include impacts from the production and transport of agricultural inputs such as fertilizer, pesticides, and herbicides (EPA, 2010). FASOM is also used to calculate the changes in quantity and type of U.S. livestock and the change in soil carbon and above- and below-ground biomass due to changes in domestic biofuel demand.

The quantified change in energy and agricultural inputs are then combined with per-unit fuel and fertilizer emission factors from the Greenhouse gases Regulated Emissions, and Energy use in Transportation (GREET) model to estimate GHG emissions associated with feedstock production. EPA also applies emission factors from the CENTURY and DAYCENT models developed at Colorado State University to estimate nitrous oxide (N_2O) emissions from fertilizer application. Livestock emission factors based on Intergovernmental Panel on Climate Change (IPCC) guidance are applied for final emissions estimates (IPCC, 2006d). While the FASOM model can be used to estimate direct emissions at the site level (e.g., clearing an acre of land for planting soybeans), it can also be applied to simulate systemwide effects of the U.S. agriculture and forestry industries. These are secondary, or indirect, effects and the method of assessing these is described below.

EPA also uses GREET to quantify emissions associated with feedstock and fuel transportation and distribution (T&D). T&D emissions are published by GREET for common biofuel pathways and have remained largely consistent since the model was first released in 1996. Version 1.8c of the model was referenced in EPA's Regulatory Impact Analysis (RIA) to calculate T&D emissions for common biofuel pathways. The GREET model incorporates parameters regarding transport distances, distribution mode (e.g., truck, pipeline), and the rate of fuel leakage.

For the fuel production stage, EPA uses models developed by the U.S. Department of Agriculture and the literature to simulate energy and material balances when feedstock is converted to fuel. EPA also consulted industry technology providers to inform process calculations and throughputs following a public comment period on the 2010 RFS2 rulemaking. Modeled energy requirements for processes such as transesterification of vegetable oils to biodiesel and fermentation of starch products to ethanol are then multiplied by emission factors from GREET to estimate the fuel production emissions published in the 2010 RIA. EPA allocates a portion of fuel production emissions according to Table A1 for co-products formed during feedstock-to-fuel conversion.

Allocation methodology

Biofuel production often involves numerous intermediate materials that form during the conversion of feedstock to fuel. For example, dried distillers grains and solubles (DDGS) is a protein-rich product used in animal feed that is left over after the corn ethanol fermentation process. Because DDGS has market value, it is often considered a co-product rather than a by-product or waste material.

The RFS does not utilize any formalized definitions to categorize different feedstocks as co-products, by-products, or wastes, but it does follow general guidelines. Under its standard LCA methodology, EPA assesses whether final and intermediate materials have a market price, if those materials are the primary driver for cultivating a product system, and if the material's primary alternative/destination is disposal or dumping into a stationary combustion source (ICF International, 2016). If it is determined to be a driver for cultivating a product system, a material would be classified as a co-product and if it goes for disposal, a material would be classified as a waste product.

In most cases, EPA uses the system expansion allocation approach when co-products are sold or consumed in external markets. This methodology quantifies the share of emissions offset or added to an end-product (i.e., fuel) as a result of intermediate, co-product formation. For example, bagasse formed during sugarcane extraction can be used to generate electricity, and that reduces the quantity of grid electricity that needs to be purchased at sugarcane ethanol plants. Similarly, DDGS can be used in animal feed and that reduces the amount of corn that farmers need to purchase.

When using the system expansion approach, emissions are allocated based on the mass or energy content of the co-products. For biofuel pathways that produce more than one type of fuel (e.g., naphtha and renewable diesel), EPA allocates a portion of the GHG emissions associated with final fuel production to all output materials on an energy-equivalent basis. Consistent with GREET, mass allocation is used for assessing edible co-products. An overview of the co-product allocation methodology adopted by EPA in the 2010 RIA and subsequent rulemakings is provided below:

Table A1. Allocation methodology for common biofuel intermediates and end products in the U.S. RFS. *Source*: Adapted from ICF International (2015).

Process	Applicable feedstock(s)	Co-products	Allocation methodology
Vegetable oil extraction (edible)	Soybean oil, canola oil	Oil Meal	Mass allocation
Biodiesel production	Soybean oil, canola oil, UCO, tallow	Biodiesel Glycerin	Energy allocation
Renewable diesel production	Soybean oil, canola oil, UCO, tallow	Biodiesel Light fuel gas Naphtha	Energy allocation
Ethanol production	Corn	Corn oil DDGS	System expansion (DDGS displaces animal feed)
Ethanol production	Grain sorghum	Oil DGS	Displacement (diverted sorghum oil necessitates additional corn)
Ethanol production	Sugarcane	Sugarcane juice Bagasse	System expansion (bagasse displaces grid electricity)

How indirect emissions are assessed

Indirect emissions modeling is used to measure the significant indirect effects related to a fuel's life cycle (Clean Air Act Section 211(o)(1)). For the feedstock production stage, EPA uses a consequential analysis that is assembled using attributional elements. EPA combines outputs from FASOM with the FAPRI-CARD model to simulate the effects of U.S. biofuel demand on international agriculture and forestry sectors within a 2022 time frame, which was a future demand estimate at that time. FAPRI-CARD is a partial-equilibrium agricultural trade model designed to measure the effects trade, economic policy, and market developments on international agricultural inputs. The model was developed at the Food and Agricultural Policy and Research Institute and is maintained by the Center for Agricultural and Rural Development at Iowa State University (Devadoss et al., 1989). Results from FAPRI-CARD including "changes in crop acres and livestock production by type and country globally" (RIA, p. 302) are combined with fertilizer, energy, and shifting land-use assumptions from FASOM to calculate total GHG emissions from the agricultural sector.

Beyond the feedstock production stage, the RFS does not quantify indirect emissions for most fuel pathways.

While EPA uses system expansion methodology for co-product allocation, to date it only uses full displacement emissions accounting for the grain sorghum oil pathway. In a 2018 rulemaking, EPA quantified the indirect effects associated with substitute material production when sorghum oil is extracted from DDGS. EPA assumed that corn replaces the reduced-oil DDGS in livestock feed on a mass basis for its final CI calculations. Mass-based substitution represents a conservative approach, however, and the rulemaking noted that other methods could be used. EPA also uses displacement methodology for the landfill biogas pathway by calculating avoided methane emissions when biomethane is diverted from its existing uses and converted to fuel. Flaring is considered to be the baseline use of landfill gas in all cases (Regulation of Fuels and Fuel Additives, 2014).

EPA also considered conducting a consequential LCA for the fuel use stage in its 2010 rulemaking. This would involve modeling the effects of the RFS on global oil demand, known as the "oil takeback" or global fossil fuel rebound effect. This type of analysis would project volumes of renewable and petroleum fuel in the market in 2022 compared to a counterfactual scenario representing future-year projections if the RFS program had never been implemented. In addition to the high complexity and uncertainty associated with it, EPA determined it would be inconsistent with statutory directive (EPA, 2015). Instead of comparing fuel life-cycle GHG emissions relative to a 2005 petroleum baseline, a scenario analysis would compare the emissions associated with replacing a marginal unit of petroleum with biofuel in 2022. In summary, the RFS accounts for the indirect effects from feedstock production for all pathways and the indirect effects from fuel production for the grain sorghum oil pathway.

Certification and non-GHG sustainability criteria

EPA includes additional sustainability protections under the RFS program to better ensure GHG reductions. In the Energy Independence and Security Act statute, the definition of renewable biomass is limited and only includes planted crops, trees, and associated residues grown on land cleared prior to 2007. The provision does not apply to animal waste, separated yard and food waste, biogas formed during the decomposition of renewable biomass, and algae. The intent of this provision was to minimize the effects of future land-use change.

Because tracking land-use change can require gathering large amounts of data, EPA introduced the concept of "aggregate compliance" to streamline the statutory enforcement process. Rather than assess land-use change at the farm level, EPA "only requires individual recordkeeping and reporting if the baseline level of agricultural land is found through an annual EPA determination to have been exceeded" (EPA, 2015). The baseline level of agricultural demand in the United States is set at the 2007 acreage for cropland, pastureland, and Conservation Reserve Program land. EPA reviews publicly available land data from the U.S. Department of Agriculture annually to determine whether the program is at risk of triggering more detailed enforcement mechanisms; this occurs when total agricultural land use comes within 5 million acres of the 2007 baseline.

To date, aggregate compliance has been the only enforcement method used for demonstrating compliance with the statutory definition of renewable biomass. EPA has argued that historical agricultural land contraction trends and economic factors that encourage farmers to use existing land such as crop insurance and price support have disincentivized conversion of existing land to grow crops for biofuel (EPA, 2015).

To qualify for RFS credits, parties must register their fuel through an online portal (EPA, 2020). Parties must also agree to an on-site engineering review of their production records conducted by an independent third-party. Under the RFS, fuel credits are known as Renewable Identification Numbers (RINs) and are traded between renewable fuel producers and obligated parties. Facilities both generating their own RINs or exporting fuel to producers with the intent to generate RINs must agree to the third-party review. Applicants must submit reviews to receive certification and provide incremental 3-year updates by January 31 of the subsequent calendar years. EPA reviews facility-level pathway petitions on a rolling basis and once a facility is approved, it is categorized and assigned a RIN-code.

EPA released evaluation criteria and LCA calculation examples for common biofuel pathways in its 2010 RIA. These include corn ethanol, corn butanol, soy and waste grease biodiesel, sugarcane ethanol, and cellulosic biofuels produced from feedstocks such as switchgrass and corn stover. The life-cycle GHG emissions and calculation methodology for other eligible pathways such as landfill biogas were published in subsequent rulemakings. When new fuel producers apply for pathway approval, EPA assesses their submission materials relative to published pathways and conducts supplementary analysis where relevant. This certification process determines whether new biofuel facilities qualify under the program's four biofuel sub-categories.

CALIFORNIA LOW CARBON FUEL STANDARD

How direct emissions are assessed

CARB developed its own model for measuring emissions associated with each stage of fuel production. CARB uses a modified form of the GREET (CA-GREET 3.0) and it has undergone two major updates over the past 10 years. CA-GREET uses California-specific emission factors for criteria pollutants, regional-specific input parameters such as electricity grid makeup, and additional fuel pathways beyond those included in the standard GREET model.

GREET was developed by researchers at the U.S Argonne National Laboratory and is one of the most comprehensive models for estimating fuel life-cycle GHG emissions. The model works by calculating the energy and fossil fuel requirements for common fuel production pathways and then applying emission factors to calculate final emissions in grams per MMBTU of fuel. In the CA-GREET model, users can alter input parameters for a chosen fuel production pathway such as feedstock source, use of carbon capture and storage, and use of intermediate product recycling. Fuel producers can also input their own LCA data for new pathways to calculate their own, facility-specific direct emissions.

CA-GREET is also used to estimate direct emissions from T&D, fuel production, and fuel use. These estimates are separated by life-cycle stage and updated based on user inputs in the model, such as petroleum refinery efficiency, rate of methane leakage, and co-product allocation methodology (e.g., steam displacement on an energy basis).

Allocation methodology

The LCFS follows GREET methodology for allocating upstream emissions to wastes, residues, and by-products for conventional ethanol and biodiesel (ICF International, 2016). In GREET, by-products are defined as secondary products with little economic value and thus, few associated production emissions. Co-products, meanwhile, have significant economic value that drive decision-making and financial reporting, and these make up a larger share of a fuel's emissions footprint. Wastes and residues are not separately defined in GREET and are treated like by-products.

The GREET model uses energy allocation for inedible co-products like jatropha oil and when a co-product can be used for electricity production, and it uses mass-based allocation for edible non-energy co-products like soymeal. CARB uses process-based allocation for several pathways where one allocation method is more appropriate at one process stage and a separate allocation method is better suited for a subsequent stage. For example, emissions from soy crushing are allocated on a mass basis, whereas the transesterification of soy oil is treated with energy allocation to attribute emissions to the finished glycerine and biodiesel. However, since CARB approves pathways at the facility-level, there are no strict rules for applying allocation methodology within LCFS regulation.

CARB has provided some guidance for allocation of less conventional feedstocks. For "low-value by-products" or feedstocks that can be sold outside the fuel sector but with little economic value, CARB recommends a displacement allocation approach. Using this methodology, materials receive "the CI of the product that replaces it" (ICF International, 2016) when diverted from an existing end-use toward the biofuels sector. For example, manure biogas is assumed to be left untreated in covered lagoons, so it receives an emissions credit to account for avoided methane release when it is instead converted to biofuel. While this practice was suggested in a 2014 concept paper, it has not been fully adopted for all pathways (ICF International, 2016). For example, while inedible tallow is assumed to be a by-product without upstream emissions attributable to the beef industry, the rendering process is assumed to be in the scope of tallow collection and energy allocation is used to attribute emissions between tallow and other inedible animal products.

Like EPA, CARB also uses system expansion or displacement methodology at the attributional stage. For example, when corn oil is pressed out of DDGS during the ethanol dry milling process, the dryer heating requirements for reduced-oil DDGS decrease, along with its associated emissions. These avoided emissions are allocated to corn oil in final CI calculations. Additionally, wet DDGS is typically given a co-product credit when it is used as an ingredient in animal feed. However, this co-product credit is reduced when corn oil is pressed out of DDGS, so CARB adds these emissions back into the final CI for corn oil. We summarize the allocation methodology used by CARB for a selection of biofuel feedstocks and co-products in Table A2 below.

Table A2. Allocation methodology for common biofuel intermediates and end-products in the California LCFS. Adapted from ICF International (2015).

Process	Applicable feedstock(s)	Co-products	Allocation methodology
Biodiesel production	All biodiesel feedstocks	Biodiesel Glycerin	Energy allocation
Vegetable oil extraction	Soybean, canola	Oil Meal	Mass allocation
Rendering	Tallow	Animal waste (e.g., meat, bone meal) Tallow	Energy allocation
Ethanol production	Corn, sorghum	Corn ethanol Wet or dry distillers' grains and solubles	System expansion (displacement)
Ethanol production	Corn oil	Corn oil Wet or dry distillers' grains and solubles	System expansion (displacement)

How indirect emissions are assessed

The LCFS includes consequential emissions for crop-based biofuel pathways from ILUC. To estimate ILUC emissions, a version of the GTAP model is used and supplemented with the Agro-Ecological Zone Emission Factor (AEZ-EF) model. Indirect LUC emissions are not calculated for waste feedstocks identified by CARB staff, such as used cooking oil (UCO) and municipal solid waste. GTAP was developed by researchers at Purdue University and it models international economic effects associated with an increase in demand for crop-based biofuels. Per feedback from CARB, GTAP was updated to quantify the market displacement effects of co-products, expand the number of agro-ecological zones modeled, and include a carbon emissions factor table. This version of the model is known as GTAP-BIO and was adopted by CARB in 2009 legislation.

GTAP is a general equilibrium model that measures land-use change in response to a single input: a volumetric increase in biofuel production. In 2015, GTAP was updated with the AEZ-EF model to bolster GHG emissions estimates for various types of land-use conversions (CARB, 2014). AEZ-EF closely follows the IPCC's GHG accounting guidance on biomass and forestry data.

CARB does not explicitly account for the indirect emissions associated with other stages of biofuel production, including T&D, fuel production, and fuel use. However, several pathways associated with avoided methane emissions, such as manure and landfill biogas, include market displacement effects when feedstock is converted to biofuel. Methane venting from covered lagoons is considered the default baseline for manure biogas while methane flaring is considered the baseline for landfill gas (CARB, n.d.-b).

Certification and non-GHG sustainability criteria

CARB has an extensive certification process for new biofuel pathways that is conducted at the facility level to ensure that claimed CI's under the LCFS match facility specifications and operating conditions. Fuel pathways under review are separated into two categories: Tier 1 and Tier 2. Tier 1 includes common biofuel pathways such as corn ethanol and soybean biodiesel while Tier 2 applies to "fuel pathways that the Board's staff has limited experience evaluating and certifying, including fuel pathways that are not currently in widespread commercial production" such as corn stover ethanol and other second-generation biofuels (CARB, 2019, p. 149). For the Tier 1 application process, users must complete a spreadsheet detailing process inputs and outputs (e.g., electricity and fuel consumption). This data is then submitted to an accredited verification body that determines whether the applicant has met all necessary requirements for certification. Upon certification, the pathway applicant becomes a "Fuel Pathway Holder" and is eligible to begin reporting and trading credits in the current quarter.

Under the Tier 2 certification process, applicants must complete facility-level CI calculations using the California GREET model by inputting the most recent 24 months of operational data. Applicants must also complete documentation that requires them to provide a full overview of well-to-wheel emissions sources, to identify all input and output materials used during the production process, and to describe all transportation modes used. Additional information such as the combustion efficiency of power equipment and a list of all wastes and co- and by-products should also be included. Consistent with the federal RFS pathway certification process, applicants should also submit a copy of the Third-Party Engineering Review Report (40 CFR Part 80.1450) and the RFS Fuel Producer Co-Products Report (40 CFR Part 80.1451). Upon submission of all these materials and approval by an accredited verification body, applicants must then report site-specific inputs for full pathway validation. If that is approved, the third-party verifier passes along this information to CARB and it is posted for public comment. Following a 10-day comment period and satisfactory completion of any necessary adjustments by the applicant that result, the fuel pathway is deemed eligible and credits become available in the current LCFS reporting quarter.

RENEWABLE ENERGY DIRECTIVE (RED II)

How direct emissions are assessed

The direct emissions of biofuels in RED II are calculated as a sum of the direct emissions from fuel use, emissions from the extraction, cultivation, and processing of the feedstocks, and emissions from carbon stock changes. The eligibility criteria for the RED II also includes a GHG reduction eligibility threshold of 50%–65% based on the facility's completion date, which is estimated based on direct supply chain emissions for each fuel.

The RED II also includes a set of default life-cycle factors, separated by life-cycle stage for a variety of commercialized and emerging biofuel pathways. These estimates were developed by the JEC. Each of the included pathways has a "default" value that reflects conservative assumptions on production parameters and a "typical" value that reflects production that is representative of EU consumption. To minimize regulatory burdens, biofuel producers are entitled to claim the default value for their pathway under the RED II as long as that pathway meets the GHG reduction threshold for the Directive. Producers are also able to develop their own, facility-specific LCA values for their biofuels using the methodology in Annex V. Producers can use the BioGrace LCA model to estimate their own, facility-specific values for the RED II. The model includes standard values and input parameters developed by the EU's Joint Research Centre to estimate the default values in the RED II Annex V (European Commission. Joint Research Centre, 2017).

Direct land-use change is calculated as annualized emissions from carbon stock changes caused by land-use change by dividing emissions equally over 20 years. When a feedstock is produced from degraded and heavily contaminated lands, a saving bonus of 29 g CO_2eq/MJ is applied.

How indirect emissions are assessed

While the RED II does not include indirect emissions in its life-cycle accounting, it recognizes the potential impact of ILUC to fuels' total emissions and uses this as a justification to limit the contribution of fuels made from food and feed crops. The policy includes a cap on the contribution of food and feed crops up to a maximum share of 7% of road and rail energy demand for each Member State.[2] Intermediate crops, defined as catch and cover crops whose use does not trigger additional demand for land, are excluded from this cap. Additionally, the recast RED II sets limits on high ILUC-risk biofuels by freezing their use at the 2019 level and including a gradual decline to zero by 2030. Biomass certified as having low ILUC risk is exempted. To distinguish fuels with high and low ILUC risk, the European Commission adopted a Delegated Act with criteria to identify high-ILUC-risk fuels; the Act established a formula to estimate the ILUC risk for a feedstock wherein crops with an annual average expansion of global production area higher than 1% that affect more than 100,000 hectares and for which the share of that land expansion onto high-carbon-stock land has a history of being higher than 10% are considered high risk (European Commission, 2019).

Allocation methodology

The RED II utilizes only one allocation method and it requires the use of energy allocation to attribute emissions for processes with co-products. Co-products in RED II are defined as "the primary aim of the production process" (L328/99 para 117 RED II), and where co-products are produced, GHG emissions are to be divided between the produced fuel and the co-products in proportion to their energy content. Residue is defined in the RED II as a substance that is not the primary aim of the production process and the process was not deliberately modified to produce it. Waste is defined as a "substance or object which the holder discards or intends or is required to discard" (P.1, Article 3 of the Directive 2008/98/EC) and it excludes substances that have been intentionally modified or contaminated from meeting this definition. Wastes include tree tops and branches, straw, husks, cobs, and nut shells, and residues from processing include crude glycerine and bagasse. For residues and wastes, the RED II considers these materials to have zero life-cycle GHG emissions up to the process of collection. By-products are not specifically defined in the RED II and are only mentioned in relation to animal by-products under the EC Regulation No 1069/2009 of the European Parliament and of the Council; these materials are treated in a similar manner as wastes and residues.

Certification and non-GHG sustainability criteria

The RED II includes several sustainability criteria applicable to all biofuels used for generating compliance. It establishes specific criteria for biofuels made from feedstocks derived from agricultural and forestland. For agricultural biomass, producers are required to have monitoring or management plans in place in order to address the impacts on soil quality and soil carbon. Furthermore, the agricultural land cannot be converted after 2008 from primary forest, forestland classified as highly biodiverse, legally protected land, or highly biodiverse grassland. Additionally, agricultural biomass cannot be derived from high carbon-stock land converted after 2008, including forestland, wetland, peatland or shrublands.[3] For forest biomass, there are additional requirements to ensure the legality of forestry operations, and management plans to ensure forest regeneration and long-term productivity, and to preserve soil quality and biodiversity.

To demonstrate compliance, the RED II allows fuel producers to use third-party, voluntary certification schemes to evaluate the source of their feedstock to ensure consistency with the land-use criteria and verify their overall LCA emissions. These

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[2] The cap is also set to Member States' 2020 food- and feed-based biofuel consumption levels plus 1%, if that sum is lower than 7%

[3] Specifically, this last category includes "land spanning more than one hectare with trees higher than five metres and a canopy cover of between 10 % and 30 %, or trees able to reach those thresholds in situ."

verification schemes are approved by the European Commission, with 13 different voluntary and national certification schemes approved as of 2022 (EU Commission, 2022). In addition to the mandatory sustainability criteria for biofuels, there are additional optional criteria for fuels to qualify under specific sub-categories within the policy, such as low-ILUC risk feedstocks.

CARBON OFFSETTING AND REDUCTION SCHEME FOR INTERNATIONAL AVIATION (CORSIA)

Allocation methodology

In CORSIA, co-products of the supply chain, including fuels, chemicals, electricity, steam, hydrogen and/or animal feed, are allocated on the basis of energy content in proportion to their contribution to the total energy content. To estimate ILUC emissions for Sustainable Aviation Fuels (SAF), CORSIA allocated coproduced road biofuels and SAF on an energy basis for seven fuel production pathways: Hydrotreated Esters and Fatty Acids (HEFA), grain Alcohol-to-Jet (ATJ) and Ethanol-to-Jet (ETJ), sugarcane ATJ and ETJ, Fischer-Tropsch (FT), and Synthesized Iso-paraffins (SIP). Each pathway share is based on the values estimated in the core LCA for CORSIA except for the HEFA, pathway which increased SAF co-product to 25% energy share instead of the 15% recommended in the core LCA analysis. For non-cellulosic pathways, the feedstock volume must be fixed at the current level and the regional shares of the global SAF production were projected to 2035.

CORSIA defines by-products as secondary products with inelastic supply and economic value, and waste and residues are defined as secondary materials with inelastic supply and no (waste) or little (residues) economic values. CORSIA Methodology (ICAO, 2019a) provides an open “positive list” of by-product and waste feedstocks aggregated using publicly available regulatory and voluntary sources. Additional materials can be included in the positive list after additional evaluation using ICAO Council’s approved guidance published in the CORSIA Methodology. For wastes, residues, and by-products, the emissions from feedstock production are treated as zero and only the emissions from the collection onward are included.

How direct emissions are assessed

The core LCA for CORSIA includes the attributional GHG emissions from the feedstock production, collection, recovery, processing, extraction, transportation, and conversion to a fuel. GHG emissions from the fuel transportation, distribution, and combustion in an engine are also included. All emissions from co-products generated at any stage of the core LCA processes are allocated based on their energy content. Feedstocks made from wastes, residues, and by-products are set to zero at the production step and emissions are only attributed from the point of collection onward.

How indirect emissions are assessed

The impact of ILUC emissions is assessed using two global economic models: GLOBIOM and GTAP-BIO. Both models evaluate the effect of the SAF expansion (or “shocks”) by 2035 and compare the predicted values with the fuel production of the base year (2011 for the GTAP-BIO and 2010 for the GLOBIOM). The ILUC emissions intensity is calculated by summing the emissions from the land converted for feedstock production and incorporating energy-based co-product allocation.

In CORSIA, the SAFs produced from wastes and residues generate avoided landfill emission credits (LECs) and recycling emission credits (RECs). For calculating LEC, the waste category and landfill conditions first need to be identified in correspondence with the CORSIA LCA Methodology (ICAO, 2019a). Based on the category, the weighted average of degradable organic content, and the dissimilated carbon fraction (corrected for methane slip) can be calculated. REC, on the other hand, is generated as avoided emissions from additional recyclable material (plastic and metals) recovered and sorted during feedstock preparation. For both REC and LEC credits, they can be subtracted from the direct LCA emissions value only if they are selected according to the CORSIA approved sustainability certification scheme (ICAO, 2020).

Other sustainability protections

CORSIA's eligible fuels should follow two sustainability principles: they should produce lower carbon emissions in LCA when compared to the baseline values, and they cannot be produced from the high-carbon-content feedstocks. The first criterion is met when the LCA emissions are at least 10% lower than baseline values (89 gCO_2e/MJ for jet fuel and 95 gCO_2e/MJ for AvGas). Compliance with the second criterion can be achieved by either using only feedstocks from the land converted to biofuel production after January 2008 or by submitting direct land-use change emissions values. These values should be calculated based on the IPCC land categories and compared with the default ILUC emission values. If the direct land-use change GHG emissions exceed the default value, they should be used for biofuel evaluation (ICAO, 2019b).

The certification process in CORSIA is based on the eligible sustainability certification schemes for aviation fuels approved by the ICAO Council and listed in the ICAO document titled CORSIA Approved Sustainability Certification Schemes (ICAO, 2020). An airplane operator can apply an actual core LCA value as a part of the certification process if the pathway has lower LCA emissions than the default values or if the pathway does not have a default value. The certification schemes ensure that methodology from the CORSIA Methodology for Calculating Actual Life Cycle Emissions Values was applied correctly and that the fuel is compliant with the sustainability criteria from CORSIA Sustainability Criteria for CORSIA Eligible Fuels (ICAO, 2019a, 2019b).

RENOVABIO

How direct emissions are assessed

RenovaBio utilizes facility-specific GHG estimates developed by fuel producers in the RenovaCalc model developed specifically for the program. For both producers and suppliers, it is mandatory to provide primary data for the fields associated with the eligibility criteria and "total area," "total production," and "recovered residues." For the remaining parameters, it is possible to include specific production data (primary data) or standard production data (for which penalties are attributed).The main methodological references for estimating agricultural emissions in RenovaBio are the IPCC Guides (IPCC, 2006a, 2006b, 2006d) in particular v.4 Agriculture, Forestry and Other Land Use (IPCC, 2006d). When available, specific emission factors for the region and crop under analysis are preferred over the IPCC default emission factors.

For the processing stage, RenovaCalc does not utilize standardized production data and users are obligated to input their own production data for the biofuel conversion process. The contribution of the processing stage to the life-cycle environmental performance of biofuels is mostly associated with product(s) and co-product yield and the on-site consumption of fuels and electricity. Emissions associated with the upstream production of chemicals that are used in industrial processes and with waste treatment are generally not the primary driver of emissions for biofuels; however, they are included in the model and contribute to the biofuel's carbon intensity calculations. In RenovaCalc, their emissions are based on typical profile of each chemical input.

The main methodological references for estimating for industrial processes GHG refer to the IPCC Guidelines (IPCC, 2006a, 2006b, 2006c), in particular v.3 Industrial Processes and Product Use (IPCC, 2006c). When available, specific emission factors for the processes under analysis are preferred over the IPCC default emission factors.

For the distribution phase, RenovaCalc requires the same type of information for all fuel pathways regarding the distribution system for all commercialized biofuels. For each biofuel, an average distribution distance from the producing facilities to the final consumers was determined and it is the same for all transportation modes. Transportation modes available at RenovaCalc are road, pipelines, rail, and maritime, which is only for imported corn-based ethanol. If the fuel producer does not have information regarding the distribution stage, road transport is assumed as the standard option except in the case of imported corn-based ethanol.

Allocation methodology

RenovaBio's LCA methodology is based on an attributional LCA approach that uses energy allocation to attribute emissions between different co-products. Here the total emissions in the production chain of biofuels are distributed among the co-products of the process based on their energy content. For example, when producing biodiesel from soybeans, the emissions generated in the process are not entirely allocated to biodiesel, but distributed among all process products such as glycerin, soybean meal, filter cake, and others, based on their relative energy densities. Additionally, some feedstocks are considered residues (Table A3) and these are only attributed GHG emissions from the collection stage onward; they do not bear the upstream emissions of feedstock production.

Table A3. Feedstocks considered as residues in the RenovaBio program.

Residues category	Type
Agricultural and forest residues	• Straws from sugarcane, corn, sorghum, and wheat • Husks from rice, nuts, coffee and similar • Corn cob • Bark, stumps, branches, leaves, needles, tree tops, forest chips, and sawdust from planted forests
Agro-industrial residues/ Process residues	• Vinasse and other agro-industrial effluents • Bagasse from sugarcane and sorghum • Filtercake, ash and soot • Animal fat • Other animal-based residues • Glycerine (raw) • Used cooking oil (UCO)
Other	• Animal waste • Sludge from waste treatment facilities • Biogas from landfills

How indirect emissions are assessed

The RenovaBio LCA methodology does not account for indirect emissions from biofuel production that could be linked to changes in land use dynamics and deforestation, for example, and also does not account for the avoided emissions from use of residues. Its approach to dealing with potential land use emissions relies on the establishment of eligibility criteria based on the separate agro-ecological legislation outside of RenovaBio itself.

Other sustainability protections

In the RenovaBio program, direct and indirect land use change associated with biomass production for biofuels is handled outside of the LCA accounting through eligibility criteria. Eligible biomass should be sourced from production areas whose native vegetation has not been suppressed since November 2018. Also, it should be sourced from rural properties with active (or pending) CAR (Rural Environmental

Registry), according to the National System of Rural Environmental Registration. CAR is a national electronic public registry that is mandatory for all rural properties; its purpose is to integrate environmental information about rural properties and their ownership, and it is a database for controlling, monitoring, planning, and combating deforestation (BRASIL, 2020).

Finally, for biomass produced within the national territory, the producer must meet the following requirements: for sugarcane, compliance with the Sugarcane Agro-ecological Zoning (ZAE Cana); for oil palm, compliance with the Agroecological Zoning for Oil Palm Culture (ZAE Oil Palm); for other cultures, compliance with Agroecological Zoning if applicable. The Agroecological Zoning (ZAE) is a technical-scientific instrument based on the environmental potential and vulnerabilities of a specific region, especially the climate, soil, vegetation, and the geomorphology characteristics that focus on land suitability for agricultural use; it also considers the social and economic characteristics. It delimits agroecological zones, which are homogeneous areas, environmental units, or even small portions of land suitable for agricultural activities, and for each delimited zone, a set of general and specific guidelines are determined to guide public policies and land use practices (Embrapa, n.d.).

APPENDIX B. CASE STUDIES USING GWP20

Here we present results for the case studies when the life-cycle GHG emissions are determined based on GWP20 factors. Table B1 compares the direct emissions for the case studies using GWP100, as presented in the main text, and with the GWP20 values. Below that are the charts with results in GWP20 for the four case studies.

Table B1. Case studies life-cycle GHG results using GWP100 and GWP20 factors.

Fuel	Direct GWP100 emissions (gCO_2e/MJ)	Direct GWP20 emissions (gCO_2e/MJ)
Soy biodiesel	15 – 38	16 – 40
UCO biodiesel	20 – 21	23
Green hydrogen	17	19
Hydrogen (grid-electricity)	191	207
Green methanol	1.2	1.2
Methanol (grid-electricity)	177	210
Blue methanol	79	89

Note: Blue methanol is produced through steam methane reforming with carbon capture.

Soy oil biodiesel

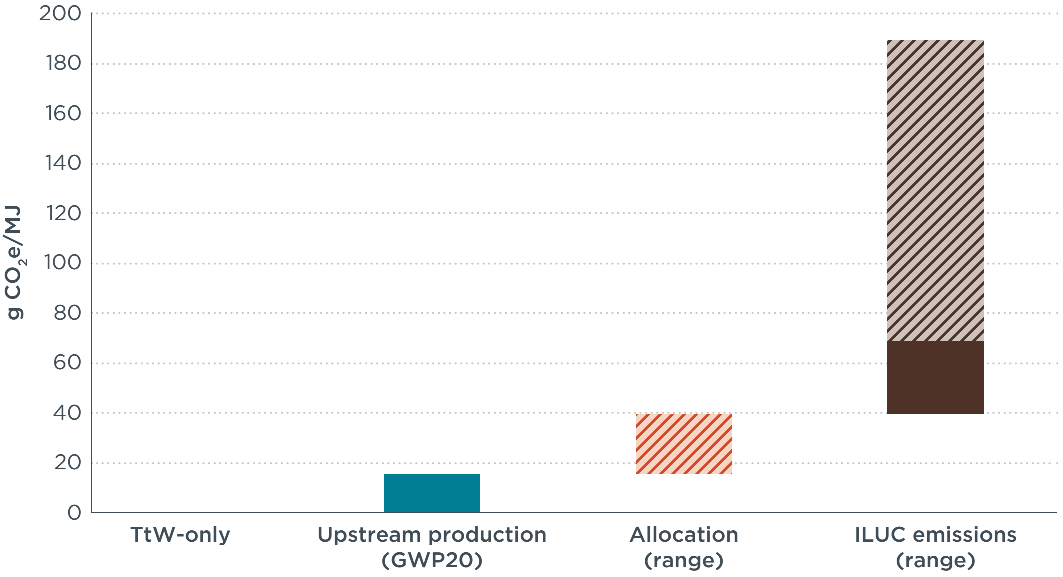

Figure B1. Range of potential life-cycle GHG emissions for soy biodiesel across different life-cycle scope assumptions and calculation methods. CO_2e values were calculated using AR5 GWP20 factors.

UCO renewable diesel

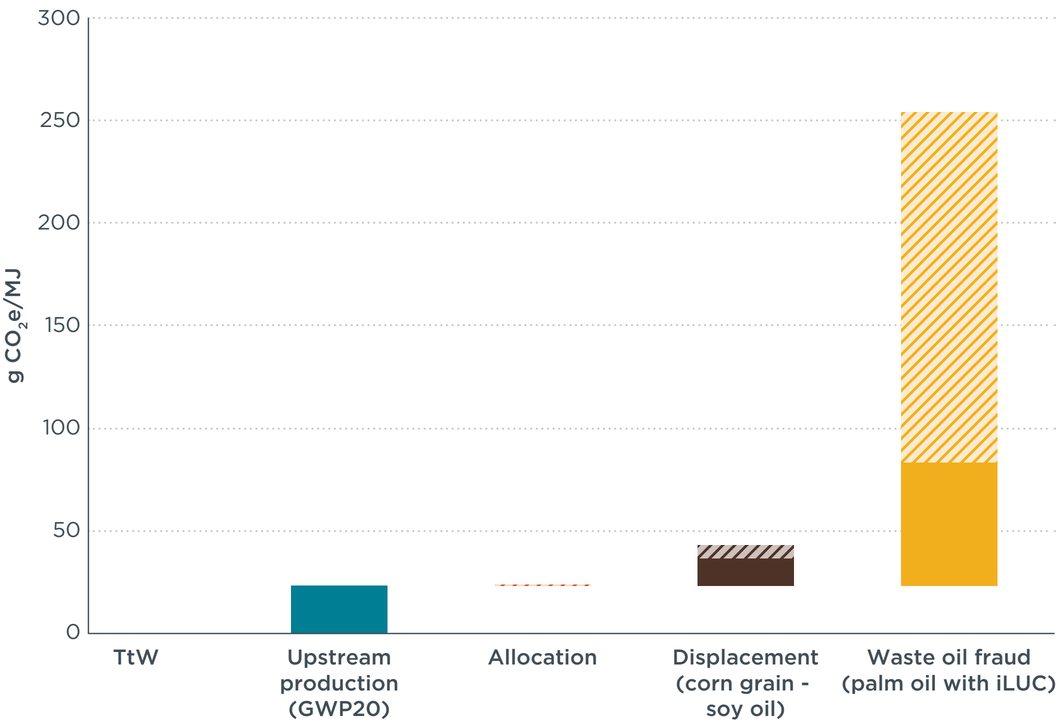

Figure B2. Range of potential life-cycle GHG emissions for UCO renewable diesel across different life-cycle scope assumptions and calculation methods. CO_2e values were calculated using AR5 GWP20 factors.

Hydrogen

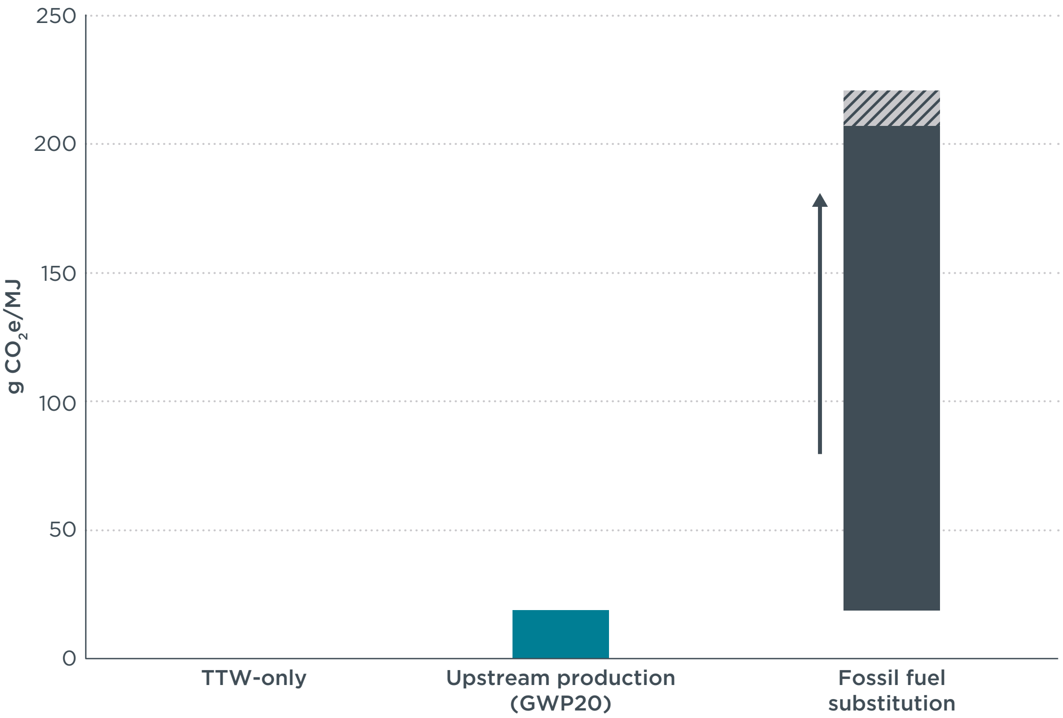

Figure B3. Life-cycle GHG emissions by production stage (electrolysis hydrogen) across different life-cycle scope assumptions and calculation methods. Hatched bars represent maximum CH_4 leakage rate. CO_2e values were calculated using AR5 GWP20 factors.

Methanol

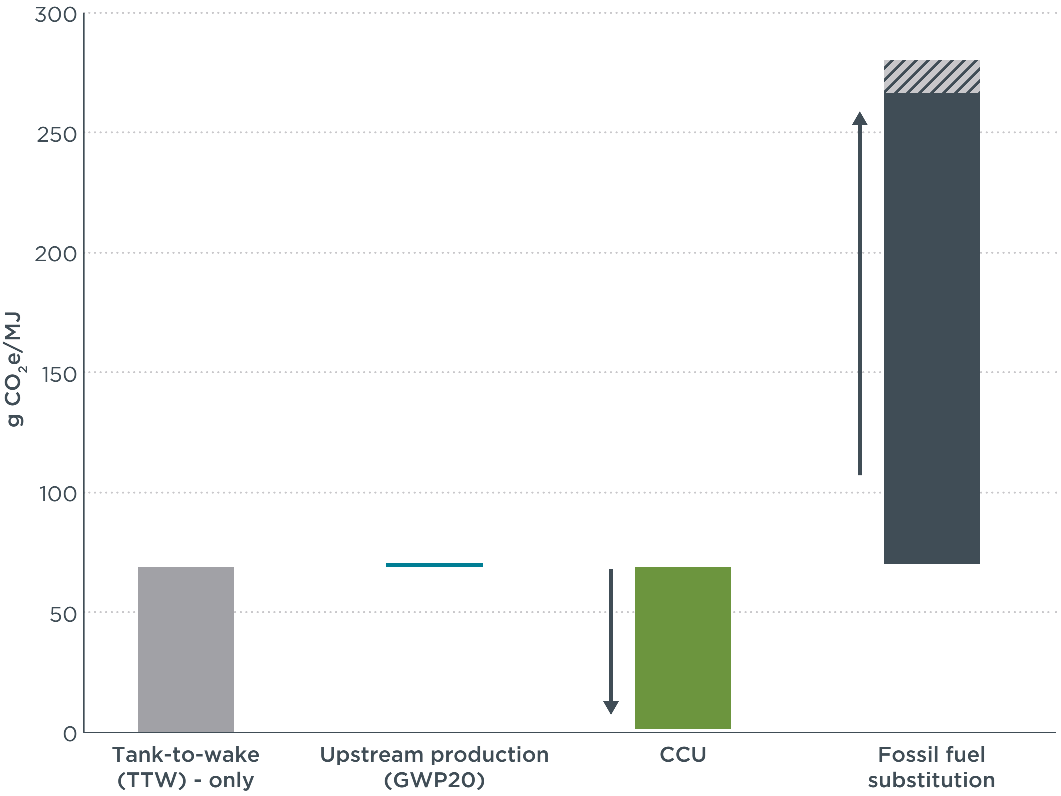

Figure B4. Range of potential life-cycle GHG emissions for green methanol across different life-cycle scope assumptions and calculation methods. Hatched bars represent maximum CH_4 leakage rate. CO_2e values were calculated using AR5 GWP100 factors.

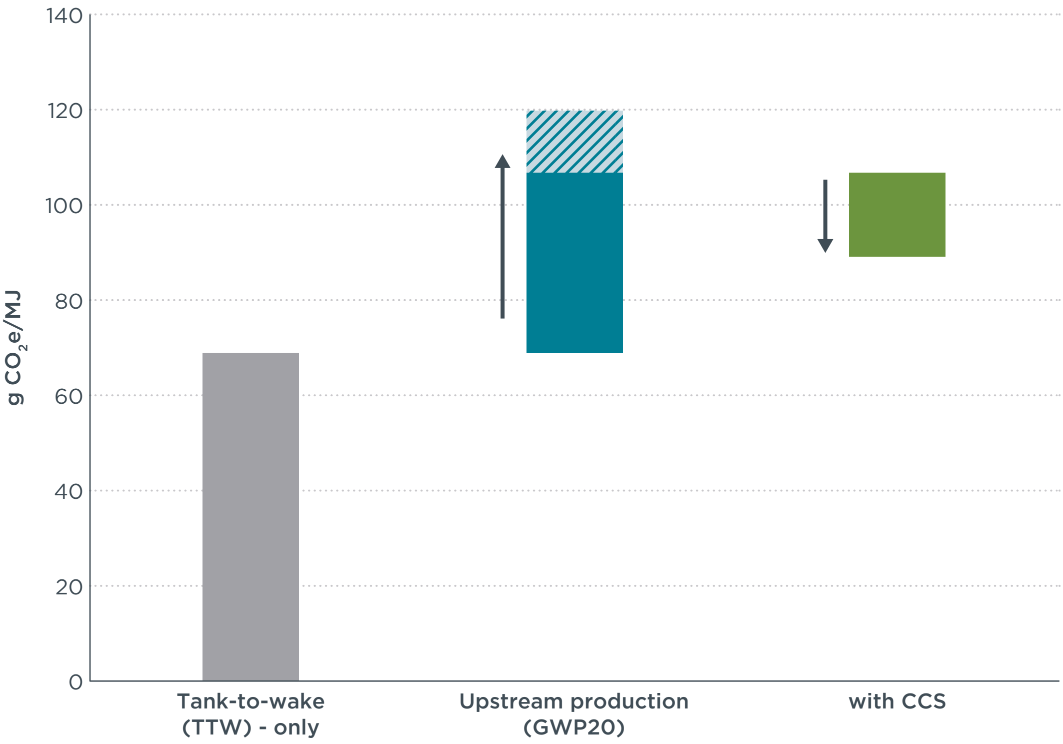

Figure B5. Range of potential life-cycle GHG emissions for methanol produced from steam methane reforming across different life-cycle scope assumptions and calculation methods. Hatched bars represent maximum CH4 leakage rate. CO2e values were calculated using AR5 GWP100 factors.

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