Carbon Accounting for Sustainable Biofuels

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Abstract

The development of sustainable biofuels is at a pivotal juncture. They are recognised for their important role in decarbonising the transport sector – particularly for their potential to help reduce aviation and shipping emissions, and for their complementarity with EVs and energy efficiency measures in road transport. However, large-scale deployment of biofuels also raises concerns. The perceived climate benefit of biofuels depends largely on the carbon intensity of their supply. Thus, sound regulatory frameworks supported by transparent, science-based carbon intensity calculations will be required to attract the investments needed to scale up biofuel production. Using carbon accounting for policymaking purposes is further complicated by mixed reports on biofuel GHG emission results and the lack of consensus across methodologies.

The present study, prepared in support of Brazil’s G20 presidency, examines such complexities and discusses regulatory approaches for accounting biofuel carbon intensity across various regions. It highlights the main reasons for variability of lifecycle GHG emissions of biofuels and emphasises that impacts of land use change are a major source of disagreement across different policy frameworks. It concludes that policies need to adopt pragmatic approaches to foster verifiable and performance-based continuous improvement of sustainable biofuels.

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Table of Contents

Executive summary

Carbon accounting is of increasing importance in biofuel policies around the world.

Carbon accounting is a generic term that refers to the assessment of GHG emissions, based on lifecycle assessment principles, and covers the whole biofuel supply chain and final use. GHG performance is expressed as carbon intensity in grammes of CO_2-equivalent per megajoule of produced biofuel (gCO_2-eq/MJ), which includes all gases with global warming potential. Carbon accounting is already considered in policymaking. Road transport, a significant generator of carbon emissions, is a sector where in the coming five years, nearly 40% of fuel demand will be covered by policies incentivising lifecycle carbon reductions, marking a shift from traditional biofuel blending mandates.

The development and use of transparent and internationally agreed GHG accounting is key for the deployment of sustainable biofuels. Sustainable biofuels play an important role in decarbonising transport. They complement the carbon reductions offered by electric vehicles and other energy efficiency measures in road transport and are expected to play an increasing long-term role in aviation and shipping. Sustainable biofuels can also provide benefits in terms of energy security and job creation, including in rural environments. However, large-scale deployment of biofuels, especially crop-based, raises sustainability concerns in some areas, mainly related to land use, net GHG emission balance, and unintended impacts on biodiversity or food prices. These concerns can undermine the credibility of biofuels as a sustainable option, and in some cases pose a barrier to investment and trade. Using carbon accounting for policymaking purposes is further complicated by mixed reports on biofuel GHG emission results and the lack of consensus across methodologies.

The present study, prepared in support of Brazil's G20 presidency, examines such complexities and discusses regulatory approaches across regions. The study aims to identify main commonalities and differences between carbon accounting frameworks. It examines the main contributors to biofuel carbon intensity, their impact and the associated level of uncertainty in quantification. The study also reviews potential interventions to improve biofuel carbon intensity and discusses policy implications and priorities.

GHG accounting is handled similarly across most biofuel policy frameworks, except regarding land use change. Results for "core LCA" values (that represent emissions associated with the supply chain, excluding land-use change) can vary widely among similar biofuel pathways, but methodologies are robust, and causes are well understood. The three main causes for the wide ranges in core LCA results are related to regional differences, methodological choices, and data input quality and representativeness. While some regional disparities reflect actual practices and local context (e.g. electricity emission intensity or fertiliser consumption), others can be solved by addressing issues resulting from methodological choices (such as co-product handling methods or system boundary setting) or data quality.

Impacts of land use change can be considerable and are a major source of disagreement across different policy frameworks. Emissions caused by direct land use change (the conversion from a previous non-cropland category to bioenergy cropland) can be observed and quantified. However, indirect land use change (when bioenergy growth generates an indirect expansion of cropland into high carbon stock land elsewhere) deals with international economic dynamics that need to be modelled and cannot be measured or verified. Indirect land use change is the main cause of disagreement around biofuels GHG accounting, due to the high uncertainty of results and the risk of arbitrariness when attributing an indirect land use change (iLUC) value to a certain feedstock and biofuel pathway. This calls for alternative policy approaches.

Biofuel carbon intensity can be improved with supportive policy frameworks and appropriate verification procedures. Several aspects of biofuel production can be improved to reduce GHG emissions. For example, in the cultivation process, which is one of the biggest contributors to biofuel supply chain emissions, several innovative solutions have recently started being introduced. These include adopting more sustainable farming practices like multi-cropping, reduced tillage, and low-emission fertilisers. Applying compost, digestate or biochar, can also contribute to the accumulation of soil carbon stock. Emissions can be further reduced by using renewable energy to supply process heat and electricity demand. New technologies such as carbon capture, coupled with biofuels production, can potentially lead to negative GHG emissions values. However, such interventions are likely to increase costs and require market and policy frameworks that reward biofuel pathways with higher GHG emission reductions, underpinned by measurable and verifiable lifecycle data.

Policies need to adopt pragmatic approaches to foster verifiable and performance-based continuous improvement of sustainable biofuels

Policies need to enable the measurement and verification of data for GHG accounting. To achieve this, they should be underpinned by methodology and data best practices that support the use of transparent and consistent

methodologies. Relevant frameworks should foster consistent application of system boundaries across different biofuel pathways based on various feedstocks (including wastes and residues), manufacturing processes and coproducts, as well as the fossil fuels they replace. Collection and use of data that correctly reflect actual practices and regional conditions should be systematically encouraged.

To significantly accelerate the deployment of sustainable biofuels, **policies should stimulate upscaling of the best technologies as well as promoting continuous improvement based on up-to-date GHG performance metrics.** More specifically, governments should consider:

- **Establishing policies that reward better GHG performance and drive continuous improvement** Transparent and consistent GHG accounting, accompanied by robust verification processes as appropriate, should allow policies to differentiate the performance of biofuels and promote continuous GHG emission reductions, regardless of the feedstock or technology.
- **Prioritising support to measures with significant GHG reduction potential that can be quantified with high certainty and fostering additional measures with less certain quantification while ensuring robust verification steps**. While some GHG emission reduction impacts are easier to quantify, others present less certainty when quantifying GHG emission reduction. For this second group of measures, robust verification and certification is required to double-check their effective GHG emission reduction.
- **Addressing indirect land use change (iLUC) concerns by adopting risk-based approaches in the near term and striving to develop global land use policies over time**. Indirect land use change values cannot be measured or verified, only modelled. In the short term, qualitative risk-based approaches offering the additional possibility of complying with the requirements of low-iLUC-risk are a good alternative option. These can address potential impacts and encourage improvement instead of attempting to quantify indirect emissions in terms of gCO_2-eq/MJ for a given biofuel pathway. In the longer term, policies should evolve from modelling impacts to managing the causes of indirect land use change by enforcing everywhere direct land use regulations and supporting improved agricultural land management.

Carbon accounting should be part of a broader portfolio of policies encompassing other sustainability criteria and compliance methods to minimise undesired impacts. Policies should protect food and water security, monitor and shelter biodiversity, while taking other socioeconomic factors into account. Biofuel policies would need to be designed to be flexible during periods of tightness in global agricultural markets, to avoid amplifying the size or duration of agricultural price spikes.

Enhanced stakeholder engagement and international cooperation is key for increasing consensus on carbon accounting for sustainable biofuels. This includes further strengthening active collaboration among international organisations such as the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO), fostering cooperation with agriculture policy developers, including biofuels and relevant coproducts in broader policies promoting an integrated circular (bio)economy, and encouraging consistent protocols and regulations for carbon accounting in voluntary carbon markets.

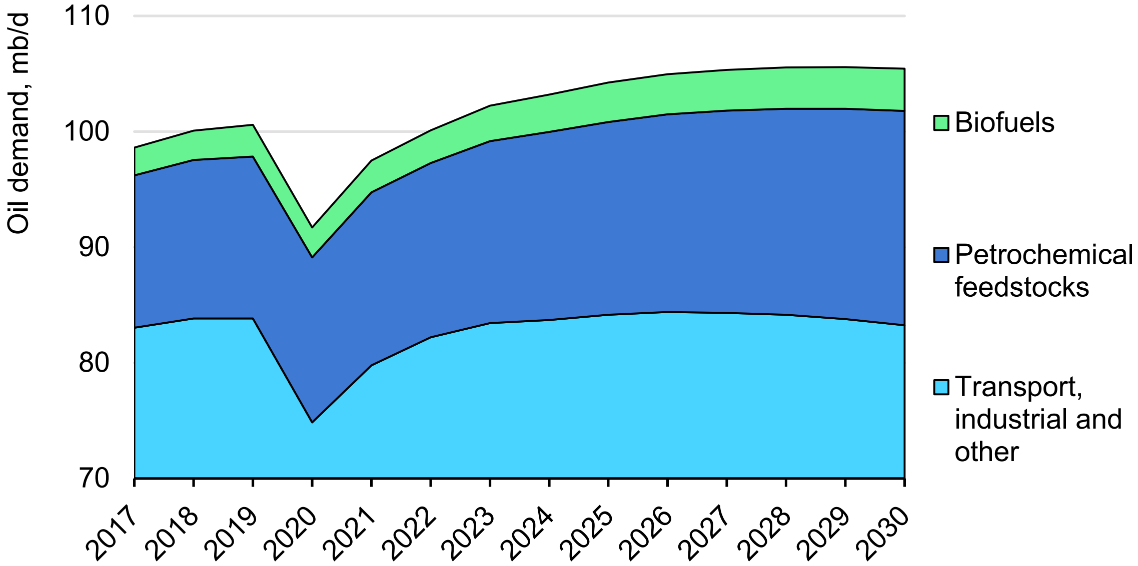
Chapter 1. Introduction

Transport fuel demand

Global oil demand is forecast to plateau towards the end of this decade as energy transitions gather pace and transport fuel demand goes into decline (Figure 1.1). Nevertheless, led by continued expansion in air travel and petrochemical feedstock uptake, total oil consumption (excluding biofuels) is forecast to rise to nearly 102 million barrels per day (mb/d) by 2030, 2.6 mb/d above the 2023 level.

Some economies, notably the People's Republic of China (hereafter "China") and India, will continue to register growth throughout the forecast period. By contrast, oil demand in advanced economies may have already peaked – a result of the sweeping impact of vehicle efficiency improvements and electrification.

Figure 1.1 World oil demand, 2017-2030



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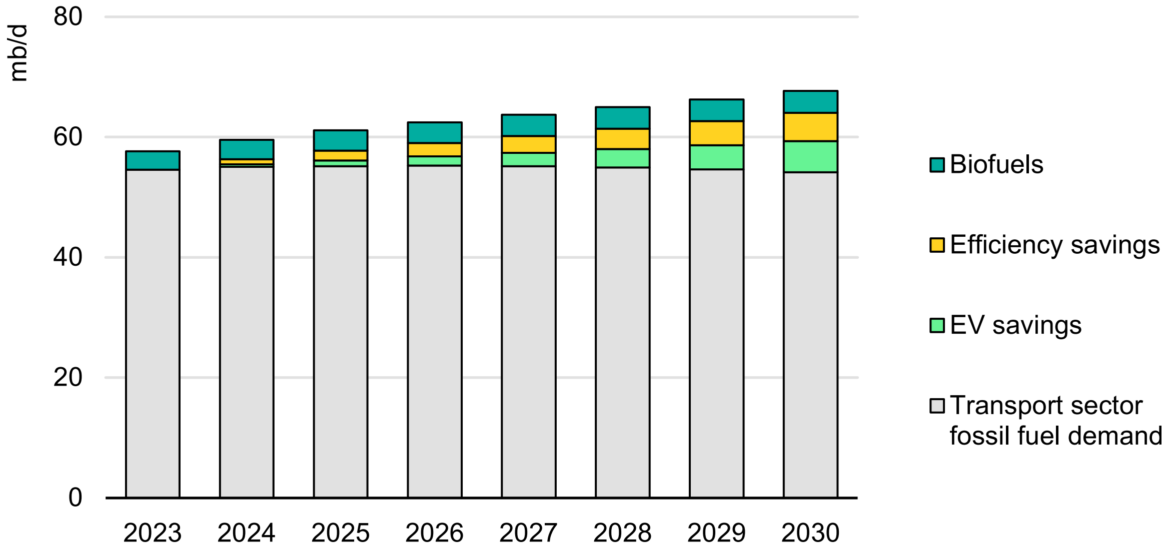
Source: IEA (2024), Oil 2024: Analysis and Forecast to 2030.

Oil demand from the transport sector is set to decline from 2026 owing to efficiency improvements, rapid hybrid and electric vehicle (EV) uptake and increased biofuel use (Figure 1.2). However, the pace of change varies across transport modes and depends on the potential for direct electrification. Global road fuel demand is already plateauing in 2024, and total transport demand is close behind. EV sales are set to remain on a strong growth trajectory, resulting in significant fuel savings.

According to the IEA's Global EV Outlook 2024, sales could rise to roughly 17 million in 2024 (compared with 14 million in 2023), with nearly one in five new cars sold globally being an EV (battery electric or plug-in hybrid). This ascent is set to persist in the current policy environment, with total sales projected to reach 40 million between 2023 and 2030, when almost one in two new cars will be an EV. This will displace 5.2 mb/d of gasoline and diesel demand by 2030, with further reductions of 4.7 mb/d from greater fuel economy. Additionally, biofuel supply will grow from 3.1 to 3.7 mb/d in the same period. Post-pandemic changes in consumer mobility behaviour (related to remote and hybrid work routines) contribute a further 1 mb/d of transport sector fuel savings.

Figure 1.2 Biofuel, EV and fuel efficiency impacts on transport sector fossil fuel demand forecast, 2023-2030



Source: IEA (2024), Oil 2024: Analysis and Forecast to 2030.

Fossil fuel demand for long-distance transport modes such as aviation and shipping, which is less amenable to direct substitution, will continue to grow. However, fuel efficiency improvements are progressively slowing demand gains. For instance, while global flight activity returned to pre-pandemic levels over the course of 2023, current jet fuel/kerosene use remains about 5% below the 2019 value. Consumption is not expected to surpass pre-Covid levels until 2027, with strong underlying demand for air travel counterbalanced by major strides in aircraft fuel efficiency. Similarly, efficiencies related to International Maritime Organization (IMO) regulations are set to gradually erode marine fuel consumption.

Tracking biofuel progress

Biofuel demand has grown steadily in the past five years to just over 4% of global transport fuel consumption in 2024 on an energy basis. In the IEA's main forecast, based on existing policies and firm projects, demand growth accelerates from the historical rate, with biofuels making up more than 5% of global transport fuel demand by 2030. In fact, total biofuel consumption rises 20% from the 2023 level to near 6 exajoules (EJ) (3.7 mb/d) by 2030. Biodiesel and renewable diesel (hydrotreated vegetable oil [HVO]), blended with diesel, account for 40% of this growth, while ethanol blended with gasoline makes up 35% and biojet fuel blended with jet fuel comprises the remaining 25%.

Most new biofuel demand comes from emerging economies, especially Brazil, Indonesia and India. All three countries have biofuel blending targets, rising transport fuel demand and domestic feedstocks. Ethanol and biodiesel use expand the most in these regions. Although advanced economies (including the European Union [EU], the United States, Canada and Japan) are also strengthening their transport policies, volume growth is constrained by factors such as rising EV adoption, vehicle efficiency improvements, high biofuel costs and technical limitations. Renewable diesel and biojet fuel are the primary growth segments in these regions.

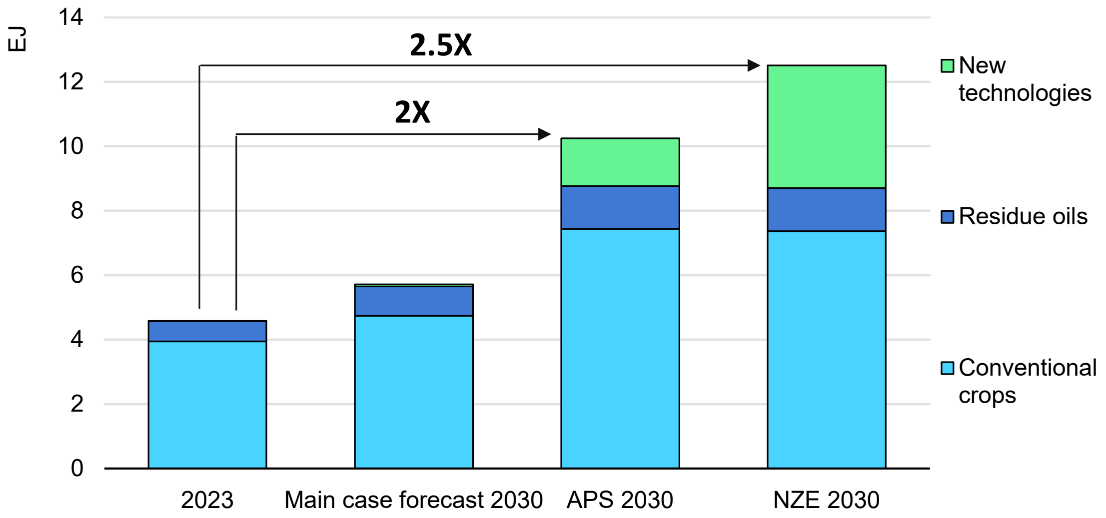
Crops were the main source of biofuel production in 2023 and are expected to support 85% of production by 2030. The share of crops used for ethanol production remains steady between 2023 and 2030. By contrast, the share of vegetable oils and residue oils (such as used cooking oil and animal fats) reserved for biodiesel, renewable diesel (HVO) and biojet fuel production is expected to expand considerably by 2030. For instance, residue oils jump from 50% of estimated collectable supply to 80% by 2030.

Meanwhile, the use of other feedstocks such as agricultural and forestry residues and municipal solid waste more than doubles to 2030, but accounts for only 1% of biofuel production globally. Using these other feedstocks often requires new processing technologies that are not yet commercially available, or new agricultural practices that are not widely used (e.g. growing conventional crops on marginal land; intercropping; double-cropping; and other approaches that can expand feedstock supplies while avoiding competition with food and feed production). It is also possible to reduce the GHG emissions of existing crops through activities such as reducing fertiliser use (see the Improving GHG Performance section).

Additionally, there is potential for much quicker deployment growth if proposed policies are implemented, feedstock sources are diversified, and new technologies are deployed in a timely manner. Under the IEA Announced Pledges Scenario (APS), biofuel demand is 80% higher than in the main case by 2030, while biojet fuel consumption is nearly three times higher, assuming that Brazil, India, the United Kingdom and Singapore implement their planned policies and the United States meets its Sustainable Aviation Fuel Grand Challenge targets (Figure 1.3).

From a feedstock and technology perspective, new technologies and practices account for nearly 15% of biofuel demand by 2030 under the APS, compared with just 1% in the main case. Technologies such as alcohol-to-jet fuel could provide a market for ethanol, for which demand will have been reduced by wider EV use and greater vehicle efficiency. Consistent carbon accounting approaches, which would assign a value to GHG emission reductions all along biofuel supply chains and award additional merit to technologies with lower lifecycle GHG emission intensities, can support this quicker growth.

Figure 1.3 Biofuel production by feedstock: Current, main case, Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2030



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Notes: APS = Announced Pledges Scenario. NZE = Net Zero Emissions by 2050 Scenario. “Conventional crops” refers to corn, sugarcane, soybeans, canola/rapeseed, palm oil and other crops. “Residue oils” refers to used cooking oil, animal fats, palm oil mill effluent and other residue oils. “New technologies and practices” refers to biofuel production from (lignocellulosic) agricultural and forestry residues, municipal solid waste and oil seeds grown on marginal land through intercropping, double-cropping and other approaches that do not otherwise compete with food and feed production.
Sources: IEA (2024), Oil 2024: Analysis and Forecast to 2030; IEA (2023), World Energy Outlook 2023.

Nevertheless, this amount of growth still falls well short of the more than doubling of 2023-level production needed by 2030 to put the world on the pathway to net zero emissions by 2050. More than doubling global production would require new biofuel policies and more ambitious deployment of new technologies. In all cases, internationally established sustainability frameworks would facilitate growth by stimulating trade and reducing investment risks while also encouraging and ensuring GHG emission reductions.

Increasing emphasis on GHG emission reduction policies

Biofuel uptake is strongly driven by supportive policies and regulations, based on key objectives such as ensuring energy security, reducing GHG emissions and diversifying fuel sources to mitigate the impacts of fossil fuel price volatility. Biofuels are recognised for their effectiveness in decarbonising transport and other hard-to-abate sectors.

However, large-scale biofuel use can also be associated with a number of economic, environmental and social risks, potentially leading to negative biodiversity impacts, the depletion of organic carbon in the soil, deforestation, objectionable labour conditions, disputes over land use rights and higher food prices, among other effects. It is therefore essential to adopt sustainable practices, advance technological innovations and implement supportive policies for biofuel production and use. Policy tools such as performance-based sustainability criteria, land use planning, adaptive blending requirements and other approaches are used to mitigate impacts in biofuel producing countries.

GHG accounting and carbon intensity

Biofuel sustainability can be quantified with the help of GHG emission accounting tools, used to calculate the lifecycle GHG emissions associated with a biofuel's production and use. The result is expressed in grammes of CO_2-equivalent per megajoule of biofuel produced (gCO_2-eq/MJ). CO_2-equivalent include not only CO_2 but also other gases with warming potential, such as methane or N_2O. In some policy frameworks, this is also known as carbon intensity or carbon accounting. In all cases, carbon refers to CO_2-equivalent, including CO_2, methane, N_2O and other greenhouse gases.

Common wordings in selected policy frameworks to address GHG emissions

Policy framework	Common wording
European Union, RED	GHG emission reduction / accounting
United States, RFS	GHG emissions / reduction
California, LCFS	Carbon intensity
Brazil, RenovaBio	GHG emissions, carbon intensity
CORSIA	Life cycle emissions values, GHG, carbon emissions
IMO	GHG emissions, GHG intensity

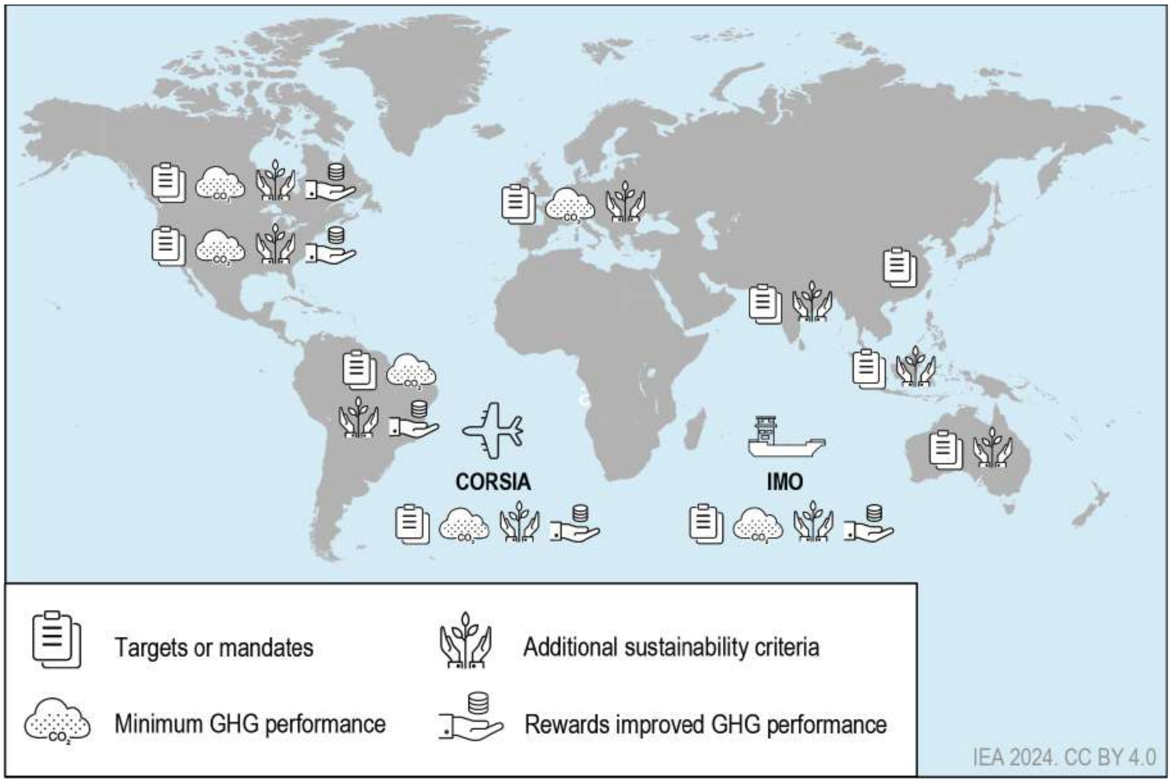
Chapter 2. Policy environment

Regulatory approaches

Biofuel production and use is driven by supportive policies and regulations, founded on objectives related to reducing GHG emissions, diversifying fuel sources to mitigate the impacts of fossil fuel price volatility, and improving energy security.

Figure 2.1 maps selected global biofuel policy frameworks and their main features in various regions and markets. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is an initiative developed by the International Civil Aviation Organization (ICAO) to address the increase in CO_2 emissions from international aviation. The International Maritime Organization (IMO) is also developing a similar regulation for international shipping. Both provide good examples of international biofuel policy frameworks.

Figure 2.1 Features of main regional and international biofuel policy frameworks



Notes: Regions/jurisdictions featured in the map are Canada, the United States, Brazil, the European Union, India, China, Indonesia and Australia. The IMO regulation is still under development, although important progress is expected before the end of 2024.

Volumetric targets or mandates (e.g. blending mandates), the most common form of biofuel regulation today, are used to develop markets and support investments. Globally, biofuel blending stands at nearly 6% on a volumetric basis, with major markets ranging from 4% (India) to 27% (Brazil). Medium-term targets for biofuels vary considerably by country in terms of ambition and type of goal. Across advanced economies, targets are increasingly being presented as regulated GHG intensity reductions, for instance in California's Low Carbon Fuel Standard (LCFS), Canada's Clean Fuel Regulations (CFR) and the EU Renewable Energy Directive (RED). These targets apply to the transport sector as a whole and not to biofuels specifically.

However, these GHG targets are often implemented in concert with volume or energy targets for biofuels. For instance, EU member states continue to use biofuel blending mandates to meet the EU renewable energy targets. In the United States, the Renewable Fuel Standard sets biofuel volume targets, and in Canada most provinces have blending mandates that often also include GHG performance requirements. In emerging economies such as India, Indonesia and Brazil, targets are set as fixed volumes. Brazil also includes GHG emission reduction ambitions in its RenovaBio programme.

Successful biofuel programmes also depend on a number of other policy interventions, such as stimulus for flex-fuel vehicles (in the case of Brazil), production and capital incentives, fuel standards and feedstock limits. While these other policy interventions certainly support biofuel investment and use, they fall outside the scope of this report.

Table 2.1 Current biofuel shares in transport fuels and near-term targets for selected countries, regions and CORSIA

	Current level*	Targets
Brazil	27%	Existing: Up to 27% ethanol blending; up to 35% under discussion 2025: Up to 15% biodiesel blending 2033: 74 million carbon credit reductions in the transport sector
Canada	8%	2030: 15% reduction in carbon intensity of liquid fuel sold in Canada from 2016 baseline
China	1%	2025: 50 000 t of sustainable aviation fuel to be used between 2022 and 2025
European Union	7%	2030: 14.5% GHG intensity reduction or 29% renewable content on an energy basis (including double-counting provisions)
India	4%	2025/26: 20% ethanol blending target 2030: 5% biodiesel blending target 2028/29: 5% compressed biogas blending target

	Current level*	Targets
Indonesia	17%	2025: 35% biodiesel blending target
United States	11%	2025: 22.3 billion gallons of ethanol equivalent (84.4 billion litres of ethanol equivalent)
ICAO	<1%	2030: Aspirational goal of 5% CO_2 emission reduction in aviation from using sustainable aviation fuel, lower-carbon aviation fuel and other cleaner aviation energy sources

*Volumetric shares of biofuels in total diesel and gasoline demand as of 2023.

In the next five years, nearly 40% of road transport fuel demand will be covered by policies incentivising lifecycle carbon reductions, marking a shift from traditional biofuel blending mandates. The value of these credits differs by market, with credits worth up to USD 0.26/litre for renewable diesel in the United States under the planned Clean Fuel Production Credit, and USD 0.03/litre for ethanol in Brazil according to average 2023 credit prices.

To reduce emissions from transport, most frameworks have also established thresholds for minimum GHG performance. Such requirements can be combined with additional sustainability requirements for biofuels to avoid negative impacts in other environmental categories such as biodiversity. A further measure could be to offer additional support for some specified feedstocks (e.g. animal manure for biogas production, or double-counting of feedstocks for advanced biofuels as defined in Annex IX of the EU Renewable Energy Directive).

Some biofuel policy frameworks also incorporate mechanisms that reward biofuel producers for improved GHG performance. Such rewards can take various forms: for instance, programmes such as California's LCFS set a carbon intensity benchmark for fuels, and biofuels with carbon intensity scores below the benchmark generate credits that can be sold to producers of higher-carbon fuels, rewarding biofuel producers for reducing GHG emissions. Under RenovaBio, Brazil’s national biofuels policy, better GHG performance results in the issuance of more decarbonisation credits (CBIOs) that biofuel producers can sell to fuel distributors that need to meet their decarbonisation targets.

Finally, governments also employ various measures to bridge biofuel cost gaps, stimulate production, expand market access, and protect consumers from price increases. For instance, the United States offers a biodiesel blending tax credit of USD 0.26 per litre and plans to extend this credit through the Inflation Reduction Act (IRA) with additional incentives for lower GHG emissions. India sets ethanol purchase prices at levels that allow producers to cover their costs and has reduced tax rates for ethanol and ethanol-blended fuels. In Brazil, fuel distributors must purchase decarbonisation credits (CBIOs) to meet the emission reduction targets established by the RenovaBio programme, which operates under a market-based approach. Across Europe, policy approaches vary: some countries such as France offer tax breaks on high-ethanol blends (85%), while others pass the costs on to consumers. Indonesia uses palm oil export levies to subsidise biodiesel costs.

Despite the potential of large-scale biofuel use to reduce demand for fossil fuels, it can also present economic, environmental and social risks. Various publications and wider scientific debates have examined the role and extent of these risks, prompting the adaptation of policy frameworks, the introduction of more diverse sustainability criteria and requirements in some regions and countries, and new approaches for assessing the impacts of bioenergy (e.g. ISO 13065). In any case, demonstrating the net lifecycle GHG emission reductions that can be gained with bioenergy is essential to obtain public acceptance and secure continuous future support through policy instruments.

Carbon accounting approaches

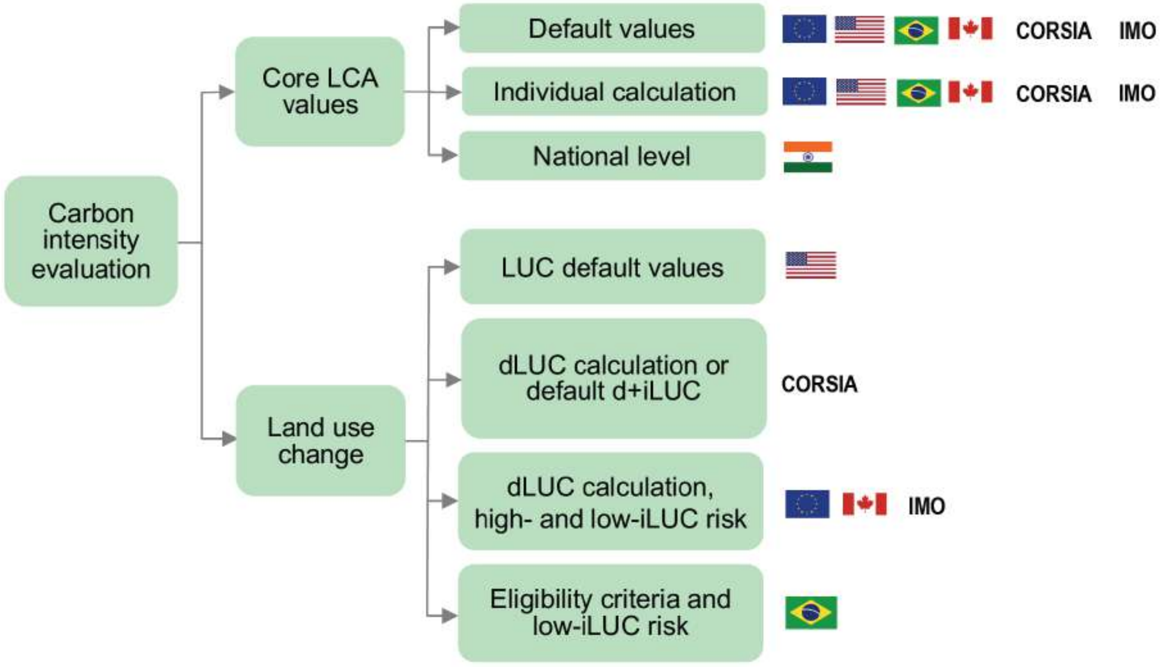
An important aspect regarding the sustainability of biofuels is GHG emissions associated with its production and use, as well as the emission savings in comparison to other fuels. These effects can be quantified with the help of carbon accounting, which involves calculating the lifecycle GHG emissions of producing and using of a biofuel.

Several policy frameworks provide specific guidance on calculating GHG emissions from biofuels and how compliance with GHG reduction requirements should be verified. These are based on widely recognised lifecycle assessment (LCA) methodology, including the ISO's 14000 series of environmental management standards, particularly ISO 14040 and ISO 14044. The ISO states that LCAs evaluate "environmental aspects and potential impacts throughout a product's life cycle (i.e. cradle-to-grave) from raw materials acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences." Biofuel carbon accounting generally takes only GHG emissions into consideration.

The various accounting approaches reflect regional conditions, the sector's development status and feedstock dependency (Figure 2.2). Emissions associated with producing and using biofuels – excluding land use change impacts – are referred to as "core LCA values" under the CORSIA framework and the California LCFS.

Several frameworks, such as those of the United States and Brazil, permit the use of default values for total or partial emissions, or the calculation of individualised pathways with specific standardised calculation tools (e.g. GREET in the United States, CA-GREET and other GREET-based calculators in California, and RenovaCalc in Brazil). In the European Union, biofuel producers can use default values that correspond to upper-bound (not average) emissions, or can calculate their own actual GHG emission values to demonstrate superior performance, based on a methodology defined in RED III allowing for the use of different calculators. Values are then verified through a certification system involving a third-party audit by an independent certification body.

Figure 2.2 Carbon accounting approaches in selected policy frameworks



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Notes: LCA = lifecycle assessment. dLUC/iLUC = direct/indirect land use change. In core LCA values, Brazil's RenovaBio presents default values for the agricultural phase only.

The main biofuel policy frameworks also differ in how emissions from direct and indirect land use change are considered. Direct land use change (dLUC) refers to the direct conversion of land from one use to another to produce biofuels, while indirect land use change (iLUC) occurs when biofuel production indirectly causes changes in land use elsewhere. Due to the indirect nature of iLUC it cannot be measured or verified, only estimated using economic models.

Frameworks such as the California LCFS, the US Environmental Protection Agency's (EPA) Renewable Fuel Standard (RFS) and CORSIA use customised models to estimate potential emissions from overall land use change for biofuel pathways and include them in regulations.

Meanwhile, biofuel producers selling their products in the European Union under RED III must individually calculate emissions from direct land use change based on a harmonised methodology if a relevant land use change event has been identified in their production processes. Emissions from indirect land use change are not quantified at the biofuel producer level. However, member states report iLUC emissions resulting from their policies to the European Commission using standardised default values for iLUC emissions across the European Union. Furthermore, the EU RED III includes detailed instruments to make biofuels with low iLUC risk eligible, while biofuels with high iLUC risk are subject to progressive quota limitations or are completely excluded in some sectors. Other regulations, such as CORSIA, IMO and RenovaBio, also consider low-iLUC-risk feedstock categories.

International collaboration

In addition to the various national policy frameworks, dedicated incentives and rules to develop global markets for sustainable fuels are required to promote the use of biofuels in international transport sectors such as aviation and shipping. The ICAO and the IMO, which are regulatory bodies under the UN framework, have formulated strategies to reduce GHG emissions in their respective sectors.

For instance, the ICAO developed the CORSIA scheme to address CO_2 emissions from international aviation. ICAO has set 85% of 2019 emissions as CORSIA's baseline from 2024 until the end of the scheme in 2035. The strategy involves phased implementation, with a pilot phase (2021-2023) for voluntary participation by states. The first phase (2024-2026) is similarly voluntary, but with more states participating. In the second phase (2027-2035), the framework will be mandatory for all states with significant international aviation activities, with certain exemptions.

To offset emissions that exceed the base levels, airlines are required to purchase carbon credits from projects that reduce or remove CO_2, such as reforestation or renewable energy initiatives. CORSIA also allows airlines to reduce their offsetting requirements by using CORSIA-eligible fuels, which include sustainable aviation fuels and lower-carbon conventional fuels.

The Fuels Task Group of the ICAO Committee on Aviation Environmental Protection develops the standards and methodologies for designating fuels as CORSIA-eligible. The Fuels Task Group has also established standards and methodologies for determining the sustainability of CORSIA-eligible fuels; requirements for certification schemes and a list of approved ones; default carbon intensity values (core and land use change) for a list of pathways and regions; and a detailed methodology for calculating actual carbon intensity. This methodology also addresses how to evaluate and verify low-LUC-risk practices (based on a yield-increase or an unused-land approach), and how to estimate new default LUC values using a combination of two different models (GTAP-BIO and GLOBIOM) and compare them afterwards. When direct LUC has taken place, the dLUC impact is calculated following a detailed methodology. Values from the dLUC calculation and the LUC model’s estimate are compared, and the higher amount is used in reporting.

The Fuels Task Group is continuously updating and improving methodologies related to eligible fuels for aviation. This working group and all ICAO committees enable in-depth international collaboration among countries and sector-specific organisations. In fact, CORSIA's work on eligible fuels – the first global market-based measure in any sector – represents a co-operative approach separate from individual national or regional regulatory initiatives.

Meanwhile, the IMO comprises 176 member states (which undertake to comply with IMO regulations and guidelines), three associate countries and 66 observing international organisations. IMO regulations for biofuels are included within its broader framework for reducing air pollution and GHG emissions from international shipping through various measures and regulations. Key elements are the Energy Efficiency Design Index (EEDI), which mandates minimum energy efficiency levels for new ships, encouraging the use of energy-efficient technologies and designs; the Energy Efficiency Existing Ship Index (EEXI), which regulates minimum energy efficiency levels in existing ship; and the Ships Energy Efficiency Management Plan (SEEMP), which requires ships to have a management plan outlining how they will improve energy efficiency, including operational measures and best practices. Furthermore, ships with gross tonnage of more than 5 000 must collect and report fuel consumption data to the IMO, which uses it to analyse and improve efficiency across the sector.

The Initial IMO Strategy on Reduction of GHG Emissions from Ships (2018) and the revised 2023 strategy set targets to reduce the average carbon intensity of international shipping by at least 40% from the 2008 level by 2030, and to reduce total annual GHG emissions by at least 50% by 2050. Annual operational carbon intensity reductions are compulsory and will be measured and rated. Poor performers will be required to improve. Additionally, work to develop guidelines on lifecycle GHG intensity of marine fuels started in September 2021, following a Well-to-Wake approach. The last version of the guidelines was adopted in March 2024, although the IMO LCA framework is being further developed, as well as other aspects in IMO reduction of GHG strategy such as GHG emission pricing.

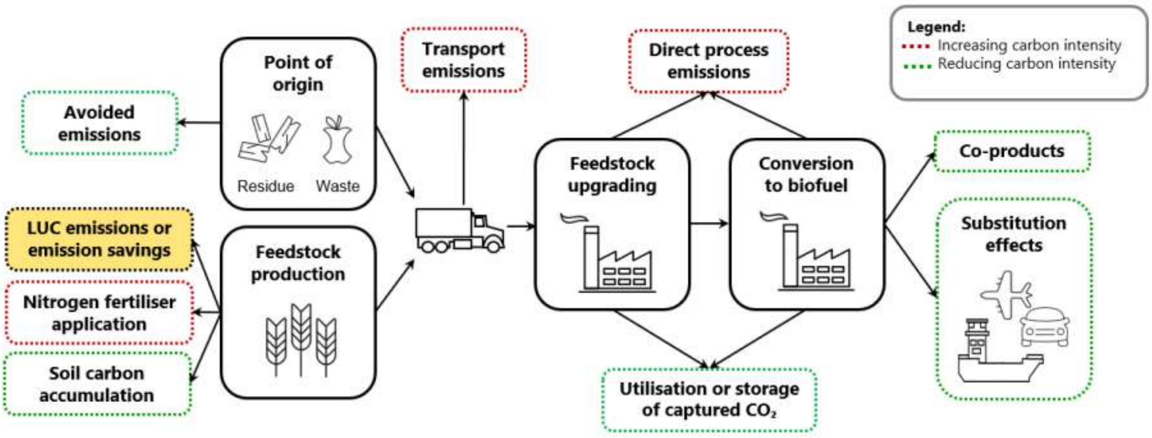
The two frameworks have some notable differences, however. For example, the ICAO primarily uses market-based mechanisms (carbon offsets) while the IMO's current measures are technical (design standards) and operational (management plans). Although CORSIA has global application, initial participation is phased and voluntary, whereas IMO regulations also apply worldwide but are mandatory once in force. CORSIA includes land use change values, while the IMO proposes a risk-based approach for iLUC. Nonetheless, both frameworks represent significant international efforts to address GHG emissions in global transport.

Chapter 3. Carbon intensity calculation

Lifecycle carbon intensity of biofuels

The GHG emissions performance of biofuels is influenced by various calculation parameters related to technical characteristics and local supply chain conditions, affecting carbon intensity to differing degrees all along the biofuel supply chain (Figure 3.1). A typical biofuel production pathway encompasses feedstock cultivation and/or collection, feedstock upgrading and the conversion process. These elements are connected by transport – primarily truck, rail and ship.

Figure 3.1 Main parameters considered in carbon intensity calculation for a typical biofuel supply chain



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CO_2 emissions from biofuel combustion are considered carbon-neutral, as the carbon in the biomass is produced through photosynthesis, which fixes CO_2 from the atmosphere and transforms it into biomass.

However, when biofuels are produced from agricultural feedstocks, important parameters to consider are the emissions associated with producing and applying synthetic nitrogen fertilisers, as well as emissions resulting from changes in soil carbon stocks due to either land use changes (LUCs) or specific agricultural practices. For instance, traditional nitrogen fertilisers, for which the fossil fuels used in their production must be recognised, can emit N_2O – a powerful GHG –

when applied to a field. Concerning soil carbon stocks, some agricultural practices such as applying biochar can increase the amount of organic carbon in soil, reducing overall supply chain GHG emissions.

While some changes in land use can raise GHG emissions (e.g. transformation from grassland to agricultural land), others can reduce emissions (e.g. reconversion of marginal or degraded land into agricultural land). LUC emissions are either direct or indirect. Direct land use changes (when bioenergy cropping replaces a different land use) is relatively well understood and can be measured and monitored over time.

However, indirect land use change occurs when a bioenergy crop replaces a food or feed crop and, as a result, food or feed production is displaced elsewhere to compensate for the gap. Only complex models that encompass energy and agricultural markets can estimate iLUC emissions.

Using biogenic wastes and residues as biofuel feedstock, which is obviously independent from land use change, can further mitigate emissions from these materials, as conventional waste treatment practices may produce significant GHGs. The RED III framework includes these avoided emissions (e.g. from animal manure) in its carbon intensity calculations.

As emissions from transport and conversion processes typically originate from the supply and use of energy carriers and process chemicals, using renewable fuels or renewable electricity can significantly reduce the impacts of the processing and transport stages. Furthermore, especially for fermentation and anaerobic digestion processes, capturing and subsequently using or sequestering the produced CO_2 can significantly reduce biofuel supply chain GHG emissions.

In some biofuel production processes, other coproducts are generated along with the biofuel, for instance corn oil or distiller’s dried grains with solubles (DDGS) for animal feed in the production of ethanol from corn, and steam and electricity produced from bagasse in sugarcane mills. Feedstock and process emissions are allocated to the different end products based on mass, energy or revenue, depending on the regulatory framework.

Methodological decisions

Both default and individual values for biofuel carbon intensity are typically calculated based on principles set out in a lifecycle assessment (LCA) methodology (as defined in ISO standards 14040 through 14044). LCA is a commonly recognised methodology for assessing environmental impacts of products and services, and it is applied widely in both science and industry. However, while LCA provides a solid framework, the ISO standards have a certain amount of flexibility in defining key methodological aspects. Consequently, factors such as system boundaries, coproduct handling principles and impact assessment methodologies are often specified in the rules governing the calculation of biofuel carbon intensities. Table 3.1 enumerates how some methodological aspects are defined under selected frameworks.

Table 3.1 Key methodological features under selected frameworks

	California LCFS	EU RED II / III	Brazil RenovaBio	ICAO CORSIA
Model for calculating default and individual core values	CA-GREET model	Default values for multiple pathways and methodology for individual calculations in RED II, Annex V	RenovaCalc tool	ICAO-GREET model and other tools
Model for calculating iLUC	GTAP-BIO and AEZ-EF	MIRAGE-BioF, GLOBIOM	--	Combination of GTAP-BIO and GLOBIOM
Coproduct allocation or displacement method	Energy allocation for fuel products; displacement method for DDGS and electricity surplus	Energy-based in general; exergy allocation for combined heat and power	Energy-based	Energy-based
LCA approach	Attributional and consequential (LUC)	Attributional	Attributional	Attributional and consequential (LUC)
Main emission factors database	CA-GREET	Biograce and JRC database	Ecoinvent	GREET and JRC, among others
Global warming potential (GWP) in use [IPCC protocol]	100-year GWP [AR4]	100-year GWP [AR5]	100-year GWP [AR5]	100-year GWP [AR5]

Notes: GREET = Greenhouse gases, Regulated Emissions and Energy use in Technologies model. CA-GREET = California GREET. IPCC = Intergovernmental Panel on Climate Change. JRC = EC Joint Research Centre. DDGS = distiller's dry grains with solubles.

Sources: California's LCFS 2020; RED III 2023.

Calculation models and tools

In addition to methodological principles, GHG calculation models and tools are another key element for implementing GHG-related biofuel policy requirements. However, the various GHG emission calculation processes and verification methods differ considerably.

Numerous countries have implemented procedures to calculate either default and/or individualised values for biofuel pathways in a consistent manner, enabled by a harmonised methodology and centralised calculation tools. Frameworks in the United States, Canada and Brazil utilise more centralised approaches, while under the EU RED and CORSIA frameworks, biofuel producers usually conduct GHG calculations themselves, followed by external verification (Table 3.2).

Table 3.2 Overview of selected GHG calculation models used by the main biofuel policy frameworks

	GREET	RenovaCalc	EU RED methodology*	Fuel Life Cycle Assessment Model
Jurisdiction	US RFS, CA LCFS, CORSIA and others, using different specific versions of the model	Brazil	European Union	Canada
Developer	Argonne National Laboratory, funded by the US Department of Energy	Brazilian research institutions (Embrapa, LNBR, Agroicone and Unicamp)	European Commission Joint Research Centre (JRC)	Environment and Climate Change Canada
Scope	Transport fuels and fuel and vehicle combinations	Different biofuels, transport fuels	Biofuels for transport, heat and electricity	Transport fuels
Main purpose	Comparison of energy use, vehicle emissions, fuel combinations	Assessing the GHG emissions performance of biofuels	Comprehensive GHG calculator for biofuel process chain elements	LCA of current and future fuels for transport applications
Featured feedstocks and technologies	More than 100 fuel pathways including petroleum fuels, natural gas fuels, biofuels, synthetic fuels, and hydrogen and electricity produced from various energy feedstock sources	First- and second-generation sugarcane ethanol, corn ethanol, biodiesel, biomethane and biokerosene	First- and second-generation biofuels from rapeseed, sugar beet, sugarcane, wheat, corn, barley, rye, triticale, palm oil, wood, used cooking oil, soybeans, etc.	Covers fuel and feedstock combinations under the Clean Fuel Regulations
Geographic input data availability	United States with some pathways from other regions	Brazil	Global supply chains with a focus on EU application	Mainly Canada, United States Mexico, India

*Available in RED Annexes V and VI.

Notes: Embrapa is the Brazilian Agriculture Research Institute. LNBR is Brazil's National Biorenewable Laboratory.

Table 3.2 calculation models focus on emissions stemming from biomass cultivation and its transformation into biofuels, and from transport. However, various other models have been developed to assess emissions linked to potential LUCs resulting from biofuel production. Some of the most relevant ones are the GLOBIOM and GTAP-BIO used in CORSIA for iLUC modelling, and the GREET CCLUB and the Blonk LUC impact model for dLUC.

Land use change evaluation

Emissions from direct and indirect land use change can contribute significantly to the carbon intensity of biofuels. Thus, policy frameworks have recognised their importance and integrated different approaches for taking them into account.

In the context of biofuel sustainability, the IPCC defines land use changes as modifications pertaining to six land categories: forest, grassland, cropland, wetland, settlements, and other land. This means, for example, that a transition from forestland or grassland to cropland is considered a land use change, while shifting from one crop to another is not. Cropland includes fallow land. Equally, changes in management activities, tillage practices or manure input are not considered land use changes under the IPCC definition.

Emissions from direct land use changes can be observed and quantified. Analysing alterations in carbon stocks over time – before and after use changes – can be a verifiable way to calculate important direct land use emission changes associated with feedstock production. Instructions on how to calculate emissions associated with direct LUC are included in the CORSIA methodology and in RED II, Annex VI B7.

In contrast, emissions from indirect land use change cannot be observed directly. Under policies such as CORSIA and the California LCFS, indirect land use change emissions are estimated by using global economic equilibrium models designed to evaluate market responses to feedstock or biofuel demand changes. Other policies such as the EU RED use a risk-based approach to promote feedstocks with low indirect land use change risks, avoiding the quantification of indirect land use change emissions.

Table 3.3 Overview of land use change evaluation in selected biofuel policy frameworks

	Consideration of dLUC and iLUC
California LCFS	Includes emissions from induced land use change (direct + indirect) using a single general equilibrium model covering both domestic and international LUC.
Brazil	Addresses direct LUC through eligibility criteria that include complying with Brazilian environmental legislation. Biomass from areas where native vegetation has been suppressed is banned.
European Union	dLUC values must be calculated when there has been direct land use change. dLUC on land with high carbon stocks is prohibited. Contribution from high-iLUC-risk feedstocks is progressively being banned. Low-iLUC-risk feedstocks can be certified.

	Consideration of dLUC and iLUC
India	Not included.
Canada CFR	Prohibition on high-iLUC-risk feedstocks.
CORSIA	Requirement to calculate and report individualised dLUC when there has been land conversion. Default LUC values are calculated by combining the results of two different models. When the dLUC value is calculated, the higher value between dLUC and iLUC is chosen. Biofuels obtained from land with high carbon stocks are prohibited.

Notes: dLUC/iLUC = direct/indirect land use change. CFR = Clean Fuel Regulations.

The need to use models to estimate iLUC arises from the complexity and interconnectedness of global agricultural markets and land use dynamics. However, the use of models is controversial, with critics highlighting several key issues. First, models often rely on numerous intricate assumptions and variables, leading to significant uncertainties and potential inaccuracies in their predictions. Second, iLUC models may overgeneralise, failing to consider regional differences in agricultural practices, land availability and economic conditions, and in general tend to inadequately account for technological advancements and improvements in agricultural efficiency that could mitigate negative impacts.

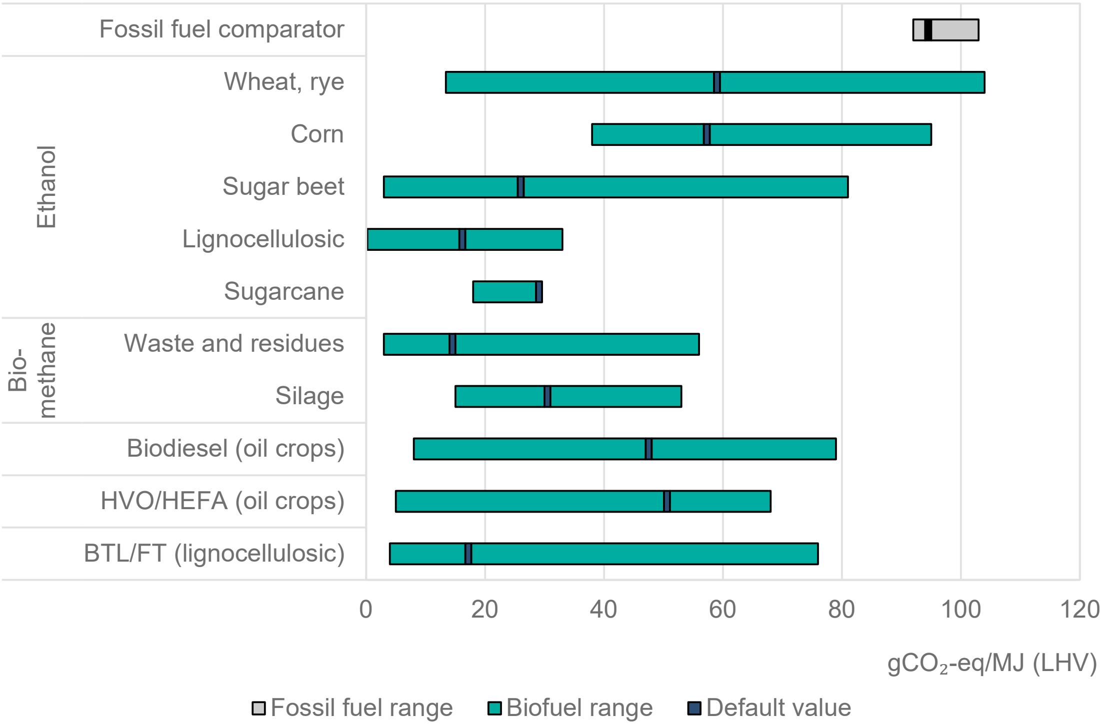
Additionally, models can be sensitive to input data, meaning that small changes in assumptions or among data sources can lead to vastly different outcomes. Furthermore, as models used to assess the economic response do not take illegal or informal activities that also contribute to land use change into account, they may be attributing their effects to the formal economy.

Hence, critics generally advocate for more transparent, robust and empirically grounded approaches to evaluate iLUC impacts.

Variability in calculation results

Although core lifecycle assessment of biofuels is well understood, the available literature shows a wide range of GHG emission results across different biofuel value chains. Figure 3.2 presents the carbon intensities of several biofuels cited by various sources, compared with RED default values. The wide range of results makes generalisation difficult and, above all, emphasises the importance of recognising the diverse factors that lead to calculation variabilities.

Figure 3.2 Core lifecycle GHG emission ranges in the literature for selected biofuels



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Notes: HVO/HEFA = hydrotreated vegetable oil/hydroprocessed esters and fatty acids. BTL/FT = biomass-to-liquid via Fisher-Tropsch. Values represent core LCA emissions, not including land use change emissions. For some biofuel pathways that involve the release of byproduct biogenic CO_2, capturing and permanently storing this CO_2 can significantly reduce the biofuel's carbon intensity, even to the extent that it becomes strongly negative. Default values are from Annex V of the EU RED II. The BTL/FT default value is based on gasification of farmed wood followed by Fischer-Tropsch synthesis, HVO/HEFA on rapeseed, biodiesel on soybeans, and lignocellulosic ethanol on wheat straw. Fossil fuel range represents gasoline values.

Sources: IEA internal data, and IEA analysis based on European Commission, Joint Research Centre, Padella, M. et al. (2019), Definition of input data to assess GHG default emissions from biofuels in EU legislation; Hennig, C., et al. (2012), Bioenergy production and use: Comparative analysis of the economic and environmental effects; Müller-Langer, F., et al. (2014), Benchmarking biofuels – a comparison of technical, economic and environmental indicators; Bacovsky, D., et al. (2010), Status of 2nd Generation Biofuels Demonstration Facilities in June 2010, Majer, S., et al. (2009); Implications of biodiesel production and utilisation on global climate – A literature review

All biofuel pathways encompass specific combinations of feedstock, regional origins, production processes and final products. In each pathway, there are three primary reasons for core LCA carbon intensity variability:

Regional differences – geographical variations in value chains, which affect factors such as biomass yield and transport distance, and data such as the emission intensity of the background energy system.

Methodological differences – variations in key methodological elements of GHG calculations, such as system boundaries, coproduct allocation and displacement principles.

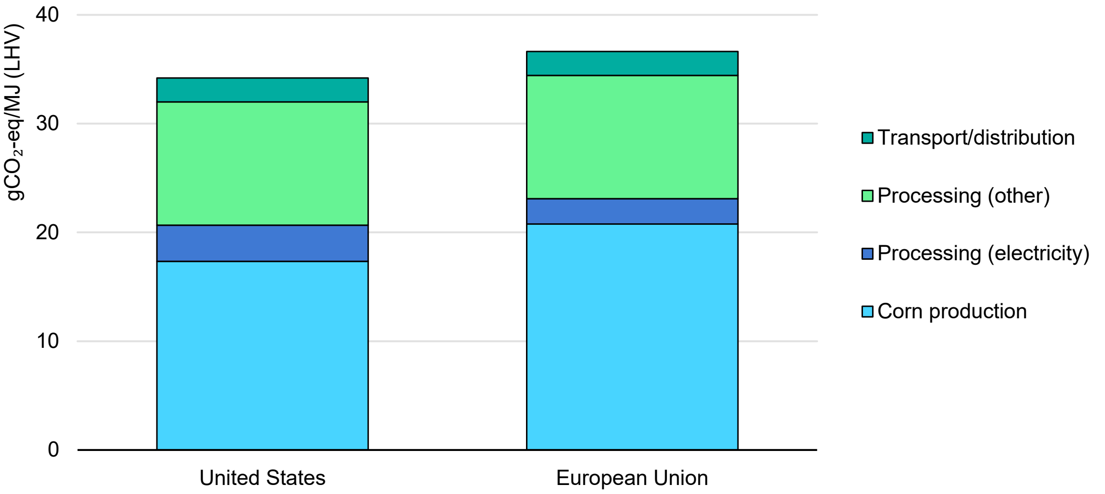
Data source differences – discrepancies in data for biofuel production, as well as for the upstream emission factors of process inputs and auxiliary materials, such as process chemicals and fertilisers.

These factors can significantly influence overall GHG calculation results, potentially leading to different outcomes for the same biofuel pathway when feedstock cultivation and biofuel production are conducted by different entities in disparate locations. To better illustrate the nature and potential significance of these elements, the following section examines examples of specific biofuel value chains and how their carbon intensity calculations are affected by variability.

Regional variations

Regional value chain variations involving factors such as biomass yields, transport distances and the emission intensity of the overall energy system can lead to significant carbon intensity calculation differences. For instance, GHG emission values are not the same for ethanol made from corn in the United States and in the European Union (Figure 3.3).

Figure 3.3 GHG emissions for corn-to-ethanol pathway, cultivated in United States vs European Union



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Notes: “United States” calculations are based on US corn cultivation values from ecoinvent 3.10 database. “European Union” calculations are based on values for corn cultivation in Switzerland and the EU electricity production mix, both from ecoinvent 3.10.

Overall GHG emissions are 34 gCO_2-eq/MJ for ethanol made from corn in the United States, versus 37 gCO_2-eq/MJ in the European Union. The differences stem from emissions associated with corn production (higher in the European Union) and process electricity use (lower in the European Union), leading to lower overall emissions for the US pathway.

It is important to note that regional differences are real, and it is important to account for them correctly. Methodologies should allow to use data and pathways that are representative of each country or region characteristics.

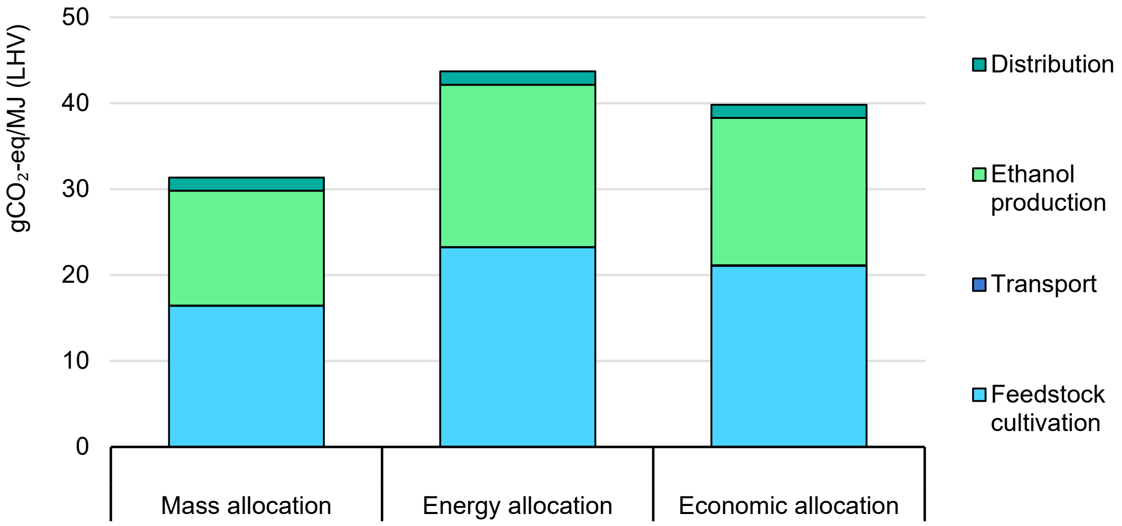
Methodological variations

Variations in key methodological aspects of GHG calculations, such as system boundaries and coproduct handling (allocation or displacement principles) can lead to significant carbon intensity calculation differences. Many biofuel pathways produce coproducts such as fodder, fertiliser and energy in addition to liquid or gaseous transport biofuels; these coproducts should be factored into the biofuels' carbon intensity calculations. International standards for lifecycle assessment, such as ISO 14040, provide guidance on the allocation of coproducts but often leave room for interpretation. There are several common coproduct handling methods: using an allocation ratio based on a product's properties (e.g. mass, energy or market value) or using a displacement GHG credit, assuming the coproduct is going to displace a similar product in the market.

Carbon intensity calculations under policy frameworks such as the EU Renewable Energy Directive, RenovaBio and CORSIA are standardised, requiring a single defined allocation method for all coproducts within a value chain (i.e. energy-based allocation, which generally reflects a higher energy-to-mass ratio for the biofuel). This approach ensures greater comparability among different biofuel pathways and allows for easier third-party verification, as it limits subjective choices, for example in displacement methods.

Depending on the biofuel pathway and the number/amount of coproducts, the allocation approach can affect carbon intensity calculations for the biofuel product. Figure 3.4 illustrates this effect for a starch crop-based bioethanol pathway, with ethanol and coproduct (DDGS) emissions allocated based on mass flow (31 gCO_2-eq/MJ), energy content (44 gCO_2-eq/MJ) and economic value (40 gCO_2-eq).

Figure 3.4 Impact of DDGS coproduct allocation on the GHG emissions of starch crop-based bioethanol



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Notes: LHV = lower heating value. DDGS (distiller’s dried grains with solubles) is a cereal byproduct of the distillation process that is commonly sold as a livestock feed. Data corresponds to EU average values.

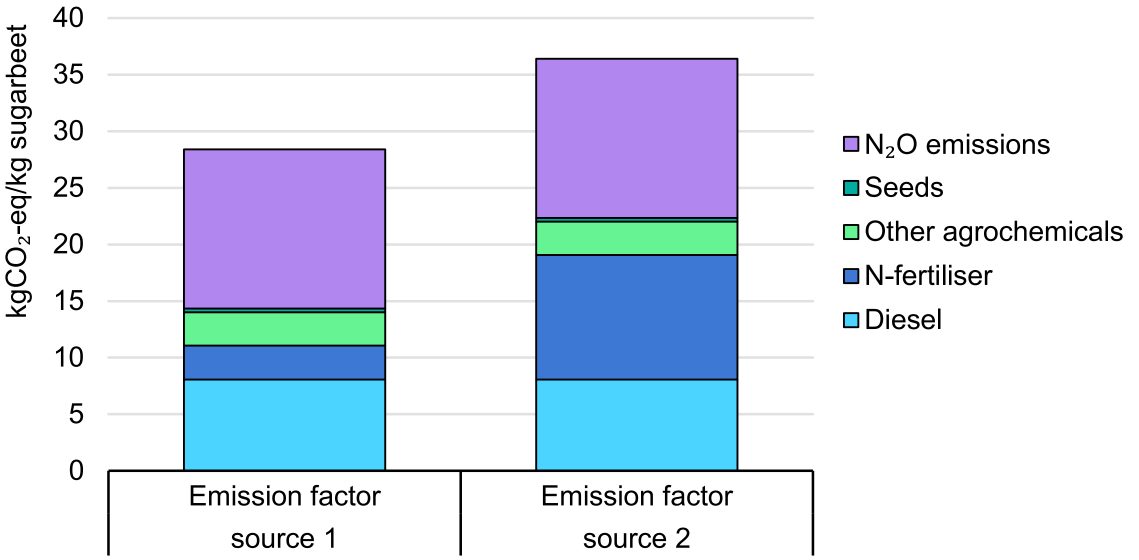
A special case is the consideration of byproducts, residues and waste streams, which, contrary to coproducts, do not share upstream emission burdens with the main products.

Another potential methodological difference arises from the setting of system boundaries. While most regulatory frameworks for biofuels rely on attributional approaches for their core GHG values, estimating land use change requires a consequential approach. Additionally, not all methodologies take account of avoided emissions throughout the process chain, which can potentially come from avoided cultivation emissions (owing to improved agricultural management, cover crops, etc.), waste treatment (animal manure and avoided methane emissions) and carbon capture.

Data source variations

As LCA practitioners often rely on databases for information on upstream emissions of process inputs and auxiliary materials such as process chemicals and fertilisers, data source variability can also lead to differences in carbon intensity calculations for the same biofuel pathway.

Figure 3.5 Influence of different data sources on the carbon intensity of biofuel feedstock



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The study [Greenhouse Gas Emissions from Inorganic and Organic Fertilizer](#) reviews available emission factors for different fertilisers, which are an important input in agricultural production and a relevant parameter for calculating the carbon intensity of biofuels. For example, Figure 3.5 illustrates calculations of GHG emissions from sugar beets produced as feedstock for biofuel, using two different emission factors for the nitrogen fertiliser leading to either 28 gCO_2-eq/MJ or 36 gCO_2-eq/MJ.

Relevance of different parameters on overall carbon intensity

While all supply chain steps influence a biofuel's overall lifecycle carbon intensity, some factors are more relevant than others. For instance, parameters involving biomass cultivation generally have a particularly high relative impact on overall GHG emissions. Table 3.4 summarises the main parameters influencing the carbon intensity of biofuels. A more detailed table providing additional information, including on accounting complexity and quantification uncertainty, is included in the [Annex](#).

Table 3.4 Relative relevance of different of supply chain parameters for overall biofuel carbon intensity

Value chain element	Relevant parameters for GHG accounting	Relative relevance
Biomass cultivation	dLUC	High
	iLUC	High
	Fertilisation – production of fertilisers	High
	Fertilisation – application and losses	High
	Use of agricultural machinery for cultivation and harvesting	Low
	Soil carbon accumulation owing to improved agricultural practices	Medium to high
Use of residues for biofuel production	Loss of soil organic carbon due to the use of agricultural residues	Medium to high
	Avoided emissions in other product systems	Medium
Transport	Transport distance and type of energy carrier	Low to medium
Biomass conversion to biofuel	Emissions from energy consumption	Medium
	Emissions from the production of chemicals	Low
	Direct process emissions	Low to medium
	BECCUS* – process energy consumption	Low
	BECCUS – substitution effects	Medium to high

*Bioenergy with carbon capture and storage.

Chapter 4. From lifecycle assessments to policy making

While lifecycle assessment (LCA) models are already used in many countries to support policies and regulatory frameworks for biofuel sustainability, the plethora of methodologies and tools available – and the wide range of calculation results – signals the intricacy of using carbon accounting for policy making purposes. Achieving consensus on methodologies and a better understanding of the parameters influencing the overall carbon intensity of biofuels (as described in the previous chapter) could at least partially reduce the complexity and variability of results.

Nevertheless, some complexity and uncertainty will persist because it cannot be resolved at the methodological or technical expert level. Policymakers will therefore need to make decisions to account for this ambiguity in the most pragmatic and effective ways. It will also be important that policies foster continuous biofuel sustainability improvements, and that methodologies for analysis and verification are designed and implemented accordingly.

GHG emission thresholds

Many biofuel policies establish minimum GHG emission reduction requirements for production pathways to ensure that biofuels contribute effectively to national GHG reduction targets (Table 4.1). Compliance is typically demonstrated by comparing a biofuel's carbon intensity with a reference value, usually based on a mixture of petroleum-derived transport fuels. To streamline the process, default or standard values are often used. These values may be included directly in policy instruments, such as the RED III Annex, or provided by authorised entities such as the US Environmental Protection Agency (EPA) for the Renewable Fuel Standard.

Table 4.1 Biofuel GHG reduction requirements in selected policy frameworks

	GHG reduction thresholds
United States (RFS*)	20% reduction in conventional biofuels compared with fossil fuels, 50% for advanced fuels and 60% for cellulosic biofuels
Brazil	Specific annual GHG reduction 2024 target: 16-17% reduction; 2033 target: 25% reduction
European Union (RED III)	50% reduction compared with fossil fuels when operational before 2015, 60% when start of operations is 2015-2020, 65% in or after 2021
India	No specific GHG requirements
CORSIA	10% reduction compared with fossil fuels

*The Renewable Fuel Standard programme.

A biofuel's carbon intensity must fall below the target or threshold value to be in compliance with (and benefit from) these programmes. The required GHG reduction is usually defined as a percentage decrease from the fossil fuel reference value. Furthermore, the minimum threshold can become stricter over time. For instance, the EU RED III mandated a 50% reduction before October 2015; 60% between November 2015 and December 2020; and 65% for plants commissioned from 2021 onwards.

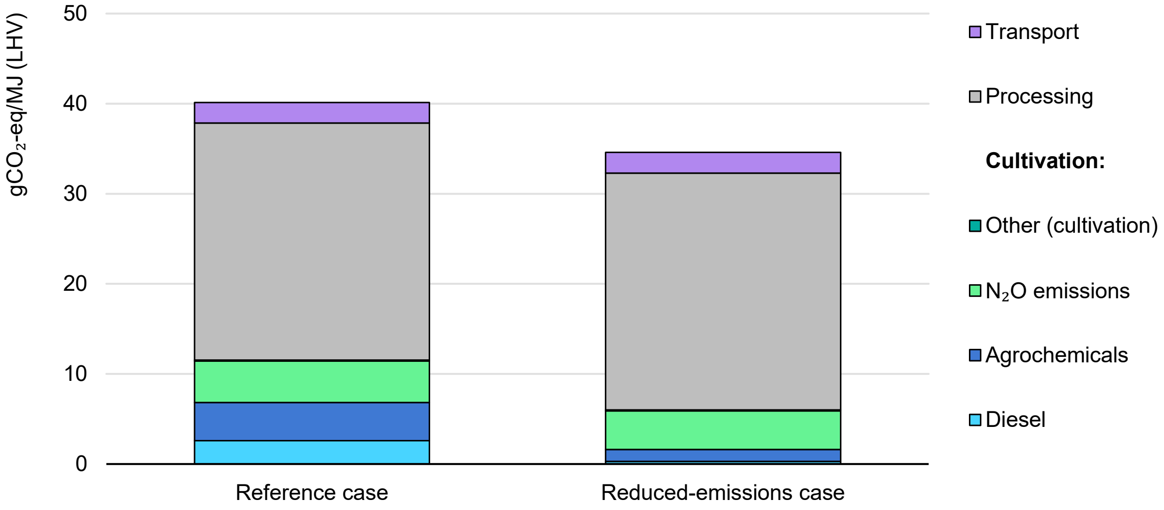
Improving GHG performance

The main sources of biofuel carbon intensity in core LCA are well known and can be tackled by the various parties involved in biofuel supply chains if policies are put in place to incentivise them. For example, interventions in the following three areas can improve biofuels' GHG performance.

Cultivation and farming

Optimising the cultivation process by adopting more sustainable farming practices can reduce emissions significantly. Sustainable agriculture can be achieved through practices such as tailored fertilisation, minimising pesticide use, secondary crops, cover crops, using a nutrient management plan, applying compost and biochar, and adopting reduced tillage to increase soil carbon stocks, decrease reliance on agricultural diesel and reduce potential nutrient volatilisation.

Figure 4.1 Biofuel GHG emission reduction potential using low-emission fertilisers and fuels in cultivation and farming, for sugar beet-to-ethanol pathway



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Source: IEA analysis based on RED II; Vaneeckhaute, C. and E. Walling, (2020), Greenhouse Gas Emissions from Inorganic and Organic Fertilizer.

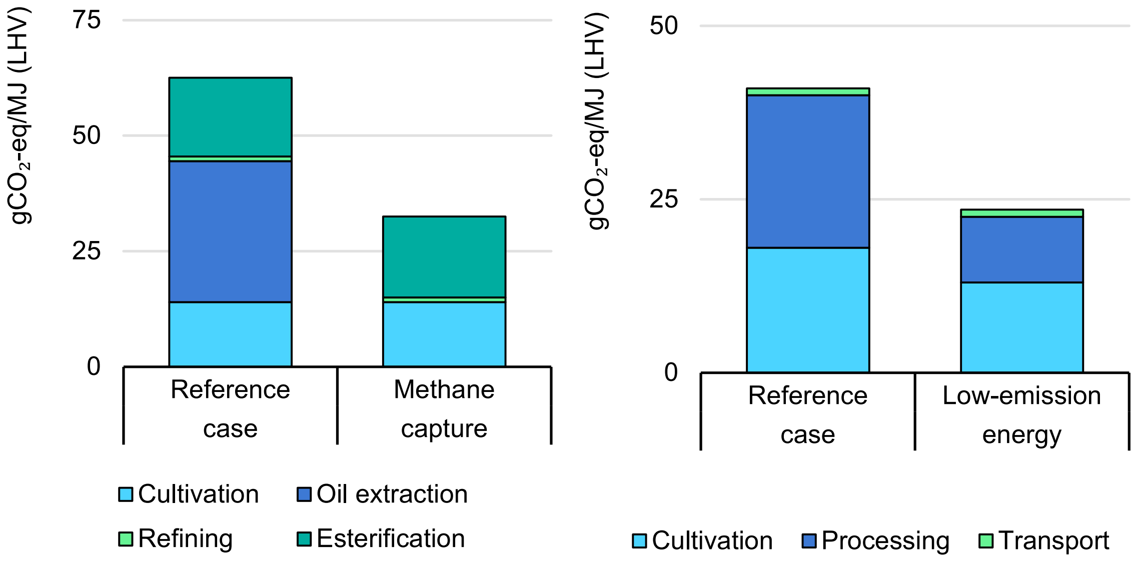
Figure 4.1 illustrates GHG emissions from the cultivation and farming of sugar beet-based ethanol in two different cases. While the reference case assumes the use of conventional fertilisers in cultivation and fossil fuels to run the agricultural machinery, low-emission organic fertilisers and biofuels are employed in the improved case, resulting in a 48% drop in cultivation-related GHG emissions.

Policy programmes should therefore recognise and incentivise emission reductions at the farming stage to promote GHG performance improvements.

Processing of biofuels

In palm oil-based biofuel pathways, the treatment of palm oil mill effluent (POME) is a significant source of emissions, mainly because of the substantial CH_4 (methane) emissions released during the anaerobic digestion of organic material in the wastewater. However, these emissions can be addressed by enclosing POME treatment systems and flaring the methane emissions or using them for electricity, heat or biogas production. Figure 4.3 (left panel) shows a reference-case open palm oil mill effluent treatment system and an improved case in which POME is treated in a closed system that captures CH_4 emissions, leading to an overall 44% reduction in GHG emissions.

Figure 4.2 Biofuel GHG emission reduction potential using palm oil mill methane capture (left) and renewable energy to process sunflower seeds into biodiesel (right)



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Notes: Calculations are based on the Biograce I model. Right graph: electricity grid carbon intensity is the average for the EU grid mix.

The right-hand panel of Figure 4.3 illustrates a sunflower-to-biodiesel pathway. In a typical biodiesel production process, the largest contributor to GHG emissions is the transesterification step, primarily due to steam generation, electricity consumption and the production and transport of chemicals consumed in the reaction.

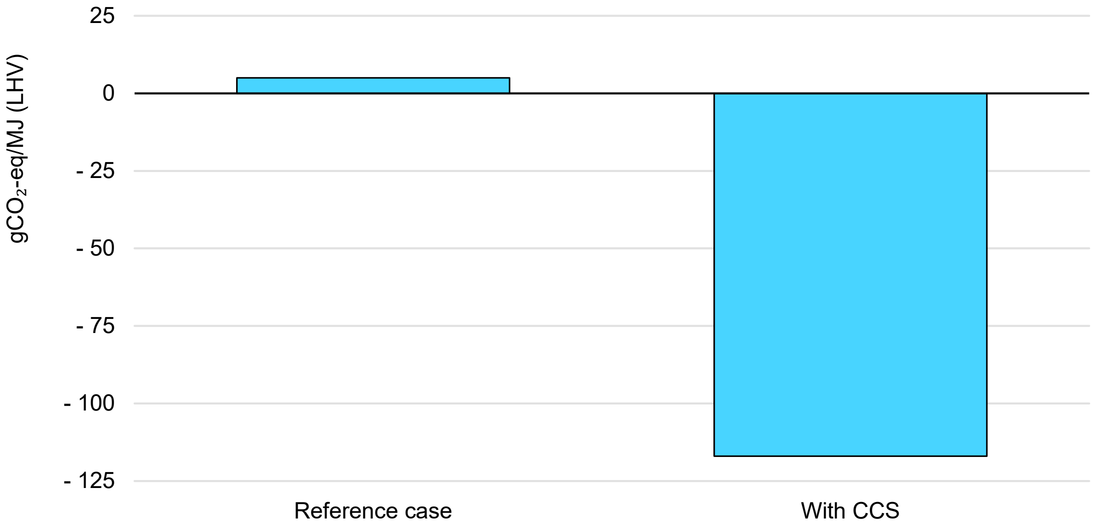
As the electricity used in the production processes of several biofuel pathways is typically sourced from the local electricity grid, the grid's carbon intensity can significantly influence the carbon intensity of biofuel production. However, these emissions can be addressed by, for example, switching to low-emission electricity sources. In Figure 4.3 (right), the reference case uses fossil-based energy inputs and electricity from a local grid, while the improved case demonstrates low-emission energy inputs, leading to a 43% reduction in GHG emissions.

Capture and storage of biogenic CO_2

Some biofuel production processes are associated with the release of considerable biogenic CO_2 as a byproduct, including pathways that use fermentation or gasification, or the upgrading of biogas to biomethane. In these examples, CO_2 is released in a highly concentrated form, making its capture relatively affordable (less than USD 30/tCO_2). Storing the captured CO_2 permanently underground would remove CO_2 from the atmosphere and result in negative carbon intensity for biofuels produced in this manner.

Other ways to achieve negative carbon intensities for biofuels include producing a solid, high-permanence biochar coproduct (a mixture of carbon and ash) that can be applied to soil.

Figure 4.3 GHG emission reduction potential using carbon capture and storage for forest residue-based Fischer-Tropsch production using gasification



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Note: CCS = carbon capture and storage.
Source: IEA analysis based on IEAGHG (2021), Biorefineries with CCS.

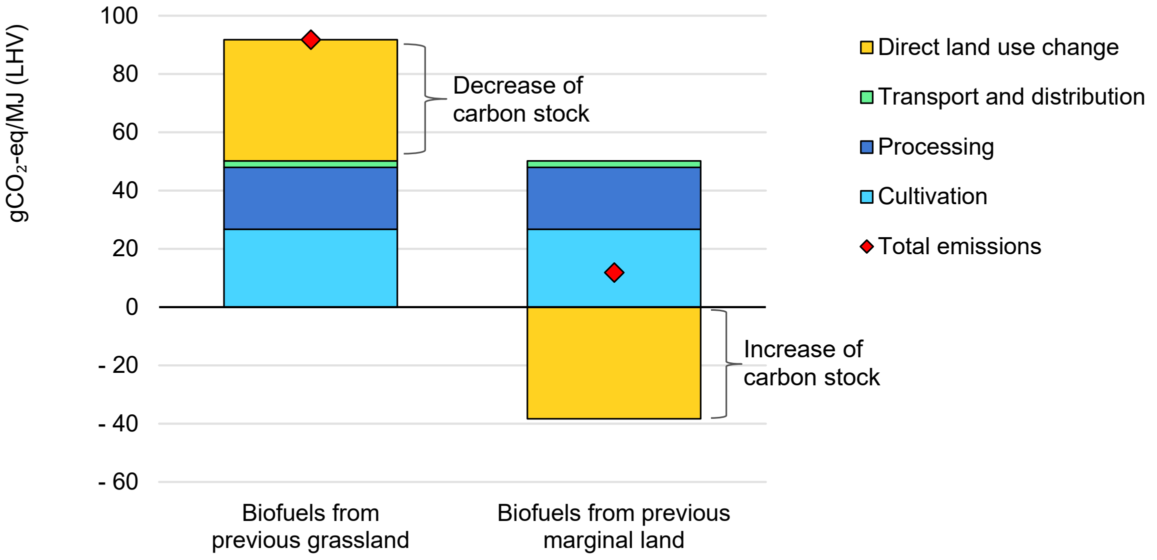
Figure 4.3 shows how the capture and underground storage of biogenic byproduct CO_2 from a biomass gasification plant producing synthetic (Fischer-Tropsch) hydrocarbon fuels can generate a significantly negative carbon intensity. In the example case, based on forest residues, emissions fall from 5 gCO_2-eq/MJ to a deeply negative -117 gCO_2-eq/MJ.

Direct land use change

Direct land use changes (dLUCs) are yet another key source of biofuel emissions. dLUC refers to the conversion of land to biofuel feedstock production, which can lead to either losses or increases in biomass, dead organic matter and soil organic carbon stocks. Other emissions, such as from biomass burning, are also often accounted for in dLUC. Emissions from land use change are not inherent to any specific biofuel pathway and are highly context dependent. In fact, they can result from any production activity in general if appropriate safeguards are not in place.

Figure 4.4 illustrates a wheat-to-ethanol pathway based on two different changes in direct land use: the conversion of grassland into agricultural land (for biofuel feedstock production), and the conversion of marginal land into agricultural land. In the grassland case, carbon stocks drop significantly and overall emissions for the biofuel pathway are higher. In contrast, for the marginal land, feedstock cultivation leads to an increase in carbon stocks and decreased emissions.

Figure 4.4 How direct land use change can affect net wheat-to-ethanol GHG emissions



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Direct LUC impacts vary significantly depending on the type of land converted and the resultant changes in biomass, dead organic matter and soil organic carbon stock. For instance, converting grassland or forest into agricultural land can result in substantial emissions, whereas converting degraded or marginal land can lead to emission savings, reducing total GHG emissions from 92 gCO_2-eq/MJ to 12 gCO_2-eq/MJ (Figure 4.4).

It is important to note that dLUC effects must be calculated based on actual data whenever possible, as it is difficult to make generalisations regarding the magnitude of these emissions.

In contrast with dLUC effects, which can generally be observed explicitly, measured and attributed to a specific activity, the impacts of indirect land use change have to be modelled because they cannot be generally observed directly. Frameworks such as CORSIA and the LCFS use economic equilibrium or partial equilibrium models to assess market responses to additional demand for biofuel feedstocks. iLUC emissions of the produced fuel can be estimated based on this information.

Uncertainty and impact

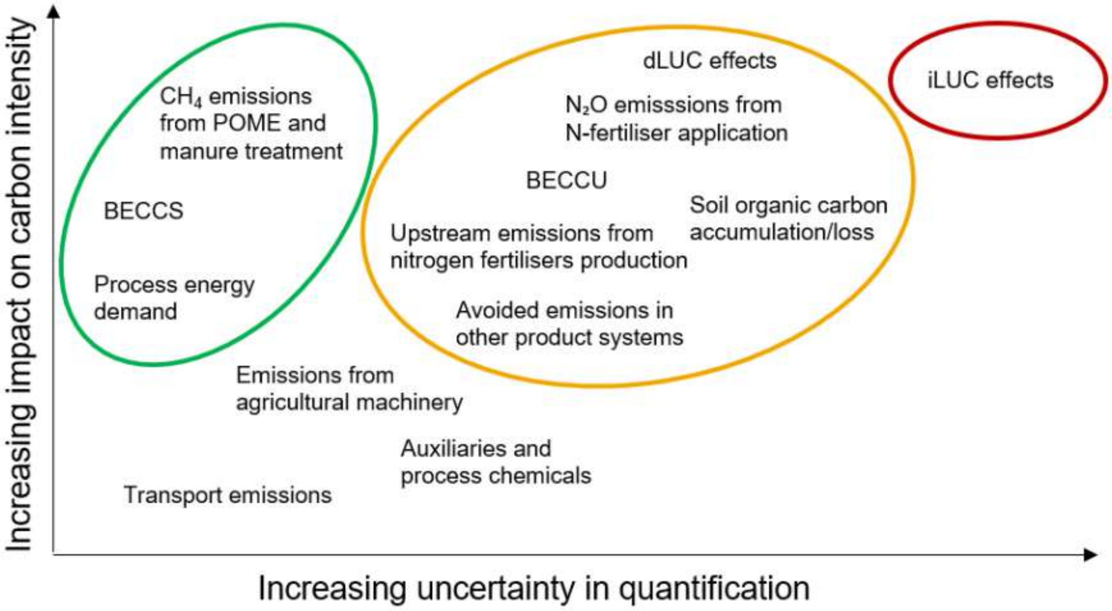
The foregoing examples illustrate the complex and diverse array of factors affecting the carbon intensity of biofuels. As a result, biofuel pathways based on identical feedstocks and employing the same conversion technologies can yield significantly divergent GHG emission reductions. However, understanding the significance of the various factors is crucial to develop effective incentives to further reduce GHG emissions.

Figure 4.5 groups the main determinants of GHG emissions in biofuel pathways by their relative impact on emission reductions (vertical axis) and by the uncertainty associated with quantifying their emission reductions (horizontal axis). For factors that have higher uncertainty, final GHG reductions after their implementation can be very different from initial theoretical calculations, so final achievements must be verified. The visual representation of these two axes can help policymakers identify how policy interventions could most effectively improve GHG performance.

The green circle highlights parameters that have a potentially high impact on the carbon intensity of biofuel pathways. Additionally, the quantification of these effects is associated with relatively lower uncertainty. These interventions – which include advanced wastewater treatment to reduce emissions from oil mills; CO_2 capture and storage from conversion processes; and the use of renewable energy throughout the biofuel value chain – are accessible strategies for biofuel producers to improve their GHG performance.

Leveraging the GHG reduction potential associated with these parameters may, however, require additional technical installations, leading to increased production costs. Nevertheless, they can be addressed relatively quickly and easily if the right incentives are in place, such as price premiums for biofuels that achieve additional GHG2 reductions.

Figure 4.5 Impacts and uncertainties of the main biofuel carbon intensity determinants



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Notes: BECCS = bioenergy with carbon capture and storage. BECCU = bioenergy with carbon capture and utilisation. POME = palm oil mill effluent. dLUC = direct land use change. iLUC = indirect and use change.

Parameters in the yellow circle, such as direct land use change emissions, emissions associated with nitrogen fertiliser application and the capture and utilisation of biogenic CO_2, have a relatively strong impact but are more complex to quantify for various reasons and present greater uncertainty. Policy or market incentives that economically reward biofuels with high GHG reduction potential could help mitigate emissions associated with these parameters. However, it is important that policy measures include additional effort and attention to verify GHG reduction effects in practice, as emission reduction calculations can be unreliable. Using certification as a verification instrument could be a viable option for policymakers to ensure that expected GHG reductions are in fact achieved.

Finally, emissions from indirect land use change (iLUC, in the red circle) have potentially high impact, influenced by factors such as overall biofuel targets and the market shares of different biofuel feedstocks. Quantifying iLUC emissions within policy frameworks that promote biofuels typically relies on models that assess how markets respond economically to increasing biofuel demand and the resulting land use changes. Therefore, this quantification cannot be performed by individual market actors or biofuel producers. Given that the impacts of iLUCs are beyond the direct control of biofuel producers or verification instruments such as certification schemes, additional policy measures are essential. Effective land use policies, including the protection of food security, natural forests and areas with high biodiversity or carbon stock, are necessary to address these challenges.

Some regulations, such as those in the European Union and Canada, include an iLUC risk approach, wherein feedstocks that have a high potential iLUC risk are banned or limited. To recognise improved agricultural practices that do not involve iLUCs, several frameworks have a category for low-iLUC-risk feedstocks (the European Union, Canada and CORSIA). These practices, contrary to general iLUC estimates, can be verified at the project level and are therefore recommended as a way to minimise iLUC effects.

Chapter 5. Conclusions and policy considerations

To significantly accelerate the deployment of sustainable biofuels, policies should stimulate their continuous improvement based on up-to-date GHG performance metrics and compliance with other sustainability criteria, as well as upscaling of the best technologies. Countries should also demonstrate strong leadership by promoting consistent political guidance for GHG accounting, adhering to transparent methods and developing international standards. Governments should employ pragmatic, impact-oriented approaches to account for the varying levels of complexity and uncertainty inherent in lifecycle assessments of various biofuel pathways.

While detailed policy descriptions and roadmaps for their implementation are beyond the scope of this study, a list of key policy priorities is given below, underpinned by methodological and data best practices and international and stakeholder involvement.

Methodology and data best practices

Support the use of transparent and consistent methodologies, and the best available measurable and verifiable data for GHG accounting. GHG accounting relies on lifecycle assessments (LCAs) that are highly data-intensive and entail consistency- and representativity-related challenges. Data should come from credible, publicly accessible sources that can be cited and used for replicable analyses that strive to represent relevant geographical contexts and situations.

Foster consistent application of system boundaries across different biofuel pathways and the fossil fuels they replace. Sustainable biofuels can be produced using a wide range of pathways based on various feedstocks (including wastes and residues), manufacturing processes and coproducts. GHG assessments need to be transparent and comparable across different pathways to enable incentives for continual improvement and promote innovation. Performance evaluations should use actual supply chain data and reflect any improvements that could produce the best-performing biofuels, regardless of technological features or feedstock. Comparisons should be based on equivalent system boundaries.

Encourage the collection and use of data that correctly reflect actual practices and regional conditions. As information related to agricultural practices, processing and other biofuel production steps can vary significantly across countries and over time, policymakers need to ensure that models use up-to-date data that cover all current practices and uncertainties. Additionally, as regional circumstances (e.g. climate, type of land use and soil quality) can differ significantly from one area to another, data should represent real conditions, avoiding generalisations and extrapolations from one region to another.

Most frameworks make this possible by allowing the use of actual rather than default values, making it possible to producers to demonstrate better performance by certifying their value chains. However, new and streamlined approaches must be developed and put in place to allow small producers in all jurisdictions to participate using actual values.

Provide guidance on monitoring and measuring the verifiable effects of land use changes. Emissions from direct land use changes are relatively well understood and can be observed and quantified according to the IPCC’s six land use categories. Analysing alterations in carbon stocks over time – before and after use changes – is a measurable and verifiable way to assess important direct land use emission changes associated with feedstock production. Direct land use changes should be systematically included in carbon accounting methods and relevant policies.

In contrast, quantitative impacts of indirect land use changes allocated to a specific biofuel pathway cannot be measured or verified, only modelled. This makes it extremely difficult to objectively compare the GHG intensities of different biofuels or with other sustainable fuels (e.g. hydrogen and derived fuels).

Policy priorities

Establish policies that reward better GHG performance and drive continuous improvement. The carbon intensity of a biofuel pathway, expressed in gCO_2-eq/MJ, can be influenced and significantly improved over time if supportive policies are in place. Transparent and consistent GHG accounting, accompanied by robust verification processes, makes it possible to differentiate the performance of biofuels and to promote continuous GHG emission reductions, regardless of the feedstock or technology. Successful policies have been implemented in some jurisdictions for several years already – notably Brazil and California, where carbon credits are allocated based on individual GHG performance.

Prioritise support measures that have significant GHG reduction potential and can be quantified with low uncertainty. Such measures include energy efficiency improvements, methane capture from the treatment of manure and palm oil mill effluent, improved biogas/biomethane plant design and CO_2 removal through enhanced agricultural practices or new industrial processes such as biogenic CO_2 capture and storage.

Foster the use of additional measures that have relatively strong emission reduction impacts but less certain quantification, and put appropriate verification procedures in place. These include soil carbon stock improvements, more sustainable fertiliser production and use, and the capture and utilisation of biogenic CO_2 for other purposes (e.g. e-fuel production). Carbon intensity calculation methodologies and verification procedures should be adapted to reflect improvements in a transparent and consistent manner.

Address indirect land use change (iLUC) concerns with risk-based approaches in the near term and strive to develop global land use policies. Although the potential for iLUC impacts is considerable, this parameter is the most complex and uncertain one to quantify. iLUC values cannot be measured quantitatively or verified, only modelled. Moreover, different modelling runs can produce divergent iLUC estimates for the same biofuel pathway, not providing the consistency needed to formulate effective GHG reduction policies. Nevertheless, governments must take iLUC into account. Given concerns with respect to uncertainties and the risk of arbitrariness inherent in iLUC modelling, when policymakers address potential impacts they should consider alternatives such as risk-based approaches and direct measurements that are effective and broadly applicable for global iLUC analysis, instead of attempting to quantify indirect emissions in terms of gCO_2-eq/MJ for a given biofuel pathway.

In the short term, qualitative risk-based approaches that offer the additional possibility of complying with low-iLUC-risk requirements are a good option to address potential impacts and encourage improvement. In the long term, policies should evolve from modelling impacts to managing iLUC causes by enforcing everywhere direct land use regulations and supporting improved agricultural land management. At all times, governments should consider transitory measures to address exceptional food security concerns triggered by economic, geopolitical or extreme weather conditions. Biofuel policies need to be designed to be flexible during periods of tightness in global agricultural markets, to avoid amplifying the size or duration of agricultural price spikes.

Provide clear, consistent guidance on other sustainability criteria. Lifecycle GHG emissions are only one of several biofuel sustainability attributes to be considered when expanding biofuel production and use. Importantly, sustainability criteria should be the same for all biofuels and other sustainable fuels. A growing number of policies are also being designed to protect food and water security, monitor biodiversity, take other socioeconomic factors into account - including the supply of secure and affordable energy - and mitigate impacts of land use changes beyond GHG emissions.

Stakeholder involvement

Foster co-operation with agriculture policy developers for more effective holistic policies. Promoting improvements in agricultural management is crucial to boost agricultural efficiency and yields; increase land productivity (through the use of cover crops and multicropping); and enhance soil carbon stocks (by employing sustainable practices and applying organic soil improvers such as biochar and biofertilisers). Collaboration with the agriculture sector is essential to promote improvements in crop-based biofuel sustainability while addressing the broader issue of sustainability in agriculture in general.

Include biofuels and relevant coproducts in broader policies to promote an integrated circular (bio)economy. Including biofuel coproducts and waste in support measures and fostering positive synergies with other sectors (e.g. agriculture and municipal waste treatment) can create a ripple effect in GHG emission savings from biofuel production. Biogenic CO_2, digestate, oilseed cake, biorefinery residues and similar products are part of a circular (bio)economy that complements climate action with resource efficiency.

Strengthen active international collaboration on carbon accounting, both within and among international organisations. Co-operation in scientific and technical areas remains dynamic, with data and model revisions, updates and developments ongoing. In the policy arena, key international collaborations are led by the International Civil Aviation Organization (ICAO) and more recently the International Maritime Organization (IMO), both regulatory bodies under the UN framework. Through these organisations, countries are building consensus to measure and verify internationally used and traded biofuels. In the medium and longer term, the approaches should converge. Moreover, international collaboration on carbon accounting should be as inclusive as possible, reflecting the global diversity and potential of biofuel pathways, encompassing not only advanced economies but also emerging and developing ones.

Support innovation in technologies that can provide negative-emission fuels. Bold long-term commitments to achieve net zero (such as in the CORSIA and IMO schemes) will rely on negative-emissions to offset residual releases in hard-to-abate sectors. Biofuels have the potential to be coupled with carbon dioxide removal (CDR) technologies such as BECCS and biochar production. Unlocking the high-level emission reduction potential of biofuels will require innovation – and regulatory incentives that reward accordingly.

Encourage consistent protocols and regulations for carbon accounting, including in voluntary carbon markets. Other initiatives not regulated by national legislation, such as international GHG protocol corporate accounting and reporting standards to drive corporate climate action, are also emerging in the wider portfolio of tools to reduce fuel emissions. Governments should recognise the increasing importance of the private sector and voluntary market programmes in helping accelerate low-emission-technology development. However, carbon accounting rules should be transparent and consistent with the best regulatory practices recognised by international platforms (as outlined in this report) to avoid misalignment and, consequently, lower predictability for investors.

General annex

Parameters influencing the carbon intensity of biofuels

Value chain element	Parameters relevant for GHG accounting	Why are they relevant?	Relative relevance	What makes the accounting complex?	Level of complexity	Level of quantification uncertainty	Verification of parameter calculation
Biomass cultivation	dLUC	Can result in a change in cultivation site carbon stocks	High	Accounting of the carbon inventory is based on regional/local parameters.	Medium to high	Medium	Identification of LUC event; quantification of change in carbon stock on the land
	iLUC effects		High		High	High	Not quantified at the producer level but modelled for the system
	Fertilisation	Nitrogen application and losses	High	Regional/local parameters influence the amount of N_2O released; detailed actual data are required.	Low to medium	High	Usually verified based on the amount of nitrogen applied at the cultivation stage, and on standardised assumptions
		Upstream emissions from synthetic nitrogen fertiliser production	High	Synthetic fertiliser production can create significant emissions if not based on renewable energy. Process-specific data are often not available.	Low	Low to medium	Emissions are typically calculated based on emission factors from LCA databases and recognised sources.

Value chain element	Parameters relevant for GHG accounting	Why are they relevant?	Relative relevance	What makes the accounting complex?	Level of complexity	Level of quantification uncertainty	Verification of parameter calculation
Biomass cultivation (continued)	Use of agricultural machinery for cultivation and harvesting	Diesel and gasoline use	Low	Can be estimated based on upstream emission factors for diesel and gasoline supply as well as for combustion processes	Low	Low	Typically verified based on actual consumption data and emission factors from recognised sources
	Soil carbon accumulation with improved agricultural practices	Can result in a change in carbon stocks on the production site	Medium to high	Soil organic carbon has to be measured regularly	Low	Low	Can be verified based on actual measurements of soil organic carbon over time
Use of residues for biofuel production	Loss of soil organic carbon	Agricultural residue use can deplete soil organic carbon	Medium to high	Regional/local production site data are necessary for individual assessments. Assessments should consider agricultural management effects on soil organic carbon over a longer time frame.	High	Medium	Can be verified based on actual measurements of soil organic carbon over time
	Avoided emissions in other product systems	Using wastes as bioenergy feedstock can help avoid emissions from the conventional treatment of these materials (e.g. manure, POME)	Medium	Assumptions regarding avoided emissions are necessary.	Medium	Medium	Can be verified based on standardised assumption and default values

Value chain element	Parameters relevant for GHG accounting	Why are they relevant?	Relative relevance	What makes the accounting complex?	Level of complexity	Level of quantification uncertainty	Verification of parameter calculation
Transport	Transport distance and type of energy carrier	Consumption of energy carriers and associated direct and upstream emissions	Low to medium	Can be estimated based on energy consumed in the transport process, and on upstream emission factors for diesel and gasoline supply as well as for combustion.	Low	Low	Typically verified based on actual consumption data and emission factors from recognised sources
Biomass-to-biofuel conversion	Energy consumption	Upstream emissions from fossil and renewable energy chains	Medium	Process-specific energy consumption data as well as the sources of process energy have to be known.	Low	Low	Typically verified based on actual consumption data and emission factors from recognised sources
	Auxiliary materials	Upstream emissions from the production of chemicals	Low	Process-specific consumption of input materials has to be known. The calculation can also be based on default values.	Low	Low	Typically verified based on actual consumption data and emission factors from recognised sources
	Direct process emissions	Biofuel production processes can be associated with direct emissions of non-CO_2 GHG emissions	Low to medium	Direct process emissions (e.g. from methane leakage, combustion, etc.) can be estimated based on default factors or emission factors if they are available. Alternatively, they have to be measured.	Low to medium	Low to Medium	Can be verified based on standardised assumption and default values

Value chain element	Parameters relevant for GHG accounting	Why are they relevant?	Relative relevance	What makes the accounting complex?	Level of complexity	Level of quantification uncertainty	Verification of parameter calculation
Biomass-to-biofuel conversion (continued)	BECCUS	Energy consumption for capturing (e.g. electricity)	Low	Process-specific energy consumption data as well as the sources of process energy have to be known.	Low	Low	Typically verified based on actual consumption data and emission factors from recognised sources
		Substitution effects (e.g. the substitution of fossil-based CO_2)	Medium to high	Potential substitution effects, and thus emissions avoided from using the captured carbon in other product systems, have to be known.	Medium	Medium to High	Can be verified based on standardised assumption and default values

Abbreviations and acronyms

APS	Announced Pledges Scenario
AtJ	alcohol-to-jet fuel conversion process
BECCUS	bioenergy with carbon capture and storage
CBAM	Carbon Border Adjustment Mechanism (European Union)
CFR	Clean Fuel Regulations (Canada)
CH_4	methane
CO_2	carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DDGS	distiller's dried grains with solubles
dLUC	direct land use change
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions and Energy use in Technologies model (US)
H_2O	water
HVO	hydrotreated vegetable oil (renewable diesel)
ICAO	International Civil Aviation Organization
iLUC	indirect land use change
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LCA	lifecycle assessment
LCFS	Low Carbon Fuel Standard (California)
LNBR	Brazilian Biorenewables National Laboratory
MJ	megajoule
N_2O	nitrous oxide (dinitrogen monoxide)
POME	palm oil mill effluent
RED	Renewable Energy Directive (European Union)
RFS	Renewable Fuel Standard (United States)
S	sulphur

Units of measure

bbl	barrel
bbl/d	barrels per day
bcm	billion cubic metres
bcm/yr	billion cubic metres per year
cm/s	centimetres per second
CO_2-eq	carbon dioxide equivalent (standardisation of different greenhouse gases)
gCO_2	gramme of carbon dioxide
gCO_2-eq/MJ	grammes of carbon dioxide equivalent per megajoule
gCO_2/kWh	grammes of carbon dioxide per kilowatt hour
GJ	gigajoule
Gt/yr	gigatonnes per year
$GtCO_2$	gigatonne of carbon dioxide

$GtCO_2$/yr	gigatonnes of carbon dioxide per year
GW	gigawatt
GWh	gigawatt hour
mb/d	million barrels per day

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