# Diverted harvest

*Environmental Risk from Growth in International Biofuel Demand*

*Cato Sandford, Chris Malins, Josie Phillips*

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## Acknowledgements

Cover image by Jane Robertson Design.

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# Executive summary

Governments around the world have adopted biofuels as a means to achieve policy objectives in climate, agriculture, industry, and trade. Over the last two decades, this has engendered a rapid increase in production and consumption of biofuels – a trend that appears set to continue in years to come. On the international stage, in 2023 the Government of India launched the Global Biofuels Alliance consortium with the stated goal of "expediting the global uptake of biofuels". While the Global Biofuels Alliance and most governments nominally agree that biofuels should be sustainable, the market is still dominated by first-generation biofuels produced from food crops that require large areas of arable land, are linked to environmental and biodiversity impacts around the world, and that are associated with problematic indirect land use change emissions.

In this study, we describe the biofuel policies of the nine leading global producers: the USA, Brazil, the EU+UK, Indonesia, China, India, Argentina, Canada, and Thailand. We analyse their levels of feedstock demand, and the commensurate impacts on land use and greenhouse gas (GHG) emissions. Based on stated future policy intentions, we also project how biofuel supply and feedstock demand may evolve to the year 2030. For the purposes of this analysis, we shall generally examine the implications of countries meeting their stated goals, though as will be seen, it is not always certain whether they will be achievable in practice.

Considering all biofuel types consumed in the case study countries, we estimate that about 32 million hectares (Mha) of land was dedicated to biofuel feedstock production in 2023[1]. The greatest impacts originate from the USA and Brazil. This use of land implies a 'carbon opportunity cost', as we can consider an alternative scenario where the land is allowed to store carbon by returning to a more natural state. Following a methodology developed by the Institut für Energie- und Umweltforschung (IFEU), we estimate that reversion of this area to forest and shrubland could provide a carbon sink of 428 Mt$CO_2$e/year[2]: significantly more than the 233 Mt$CO_2$e/year that is saved (excluding land use change emissions) by substituting biofuels with fossil fuels. Nature restoration would also bring parallel benefits to biodiversity and enhanced ecosystem services.

The increased use of biofuels under the case studies' biofuel policies could reduce demand for fossil fuels, but would also be associated with GHG emissions in the biofuel supply chain and emissions due to indirect land use changes. Under national targets for renewable fuels, we calculate that consumption of first-generation and crop-based second-generation biofuels is set to increase from 104 Mtoe (million tonnes of oil equivalent) in 2023 to 150 Mtoe in 2030.

Many policy frameworks favour the use of residual and waste lipids[3], which are commonly identified as being more environmentally-friendly than primary crop feedstocks (though this is contested, as the use of by-products and residues for biofuel production has been linked to competition with other sectors and displacement emissions as those sectors back-fill diverted resources with primary feedstocks). Moreover, the limited potential for scaling up supply of these feedstocks leads us to estimate that 92% of the 2030 biofuel demand will come from

[1] This is the 'net' land requirement after recognising that biofuel co-products such as distillers' grains and oilseed meals are returned to the feed market, as this reduces the effective land demand.

[2] Mt$CO_2$e is megatonnes of carbon dioxide equivalent (using GWP100 factors).

[3] Primarily used cooking oil and low-grade animal fats.

food-type feedstocks. As such, demand for cropland is projected to rise by 20 Mha (63%) to 52 Mha in 2030.

Increased demand for cropland to satisfy biofuel targets will inevitably have knock-on effects throughout the global economy. Food markets can be expected to adjust to reduced supply by raising prices, which will affect demand patterns (for instance reduced calorific intake); simultaneously, farmers may move to intensify production from existing farmland and/or expand their cropland areas to meet the extra demand. The latter phenomenon is known as indirect land-use change (ILUC). Quantitative modelling of ILUC provides estimates of the land demand and land-based emissions associated with changing biofuel demand under assumed market conditions. Based on ILUC emissions estimates from the GLOBIOM-based analysis for the European Commission, we estimate that indirect land use change arising from increases in biofuel demand between 2023 and 2030 could release 149 $MtCO_2e$ that would otherwise be stored in biomass and soils. After accounting for supply chain and ILUC emission and for biofuels' direct benefits in displacing fossil fuels, we estimate a substantial increase in net emissions due to biofuel expansion: nearly 34 $MtCO_2e$/year by 2030.

The USA, Indonesia, India, and Argentina all show significant growth in emissions, as can be seen in Figure 1. This is due to expected increases in consumption of palm- and soy-oil biofuels with high ILUC emissions. In other case study countries, the climate impact of biofuel policy changes to 2030 is predicted to be roughly neutral (Brazil) or even positive (EU+UK, China, Canada, and Thailand).

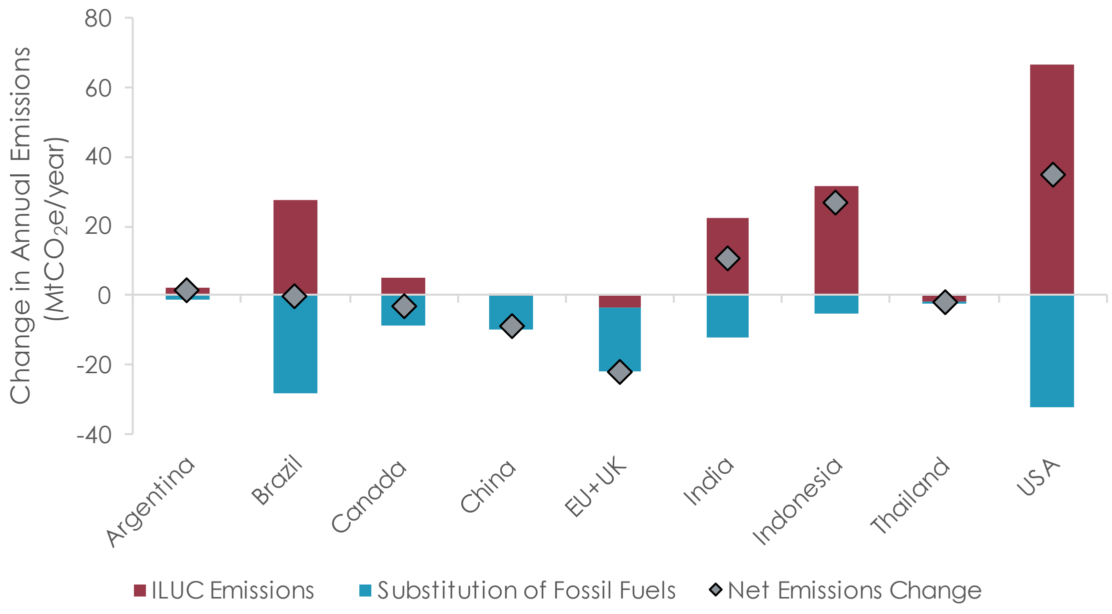


**Figure 1** **Estimated change in annual greenhouse gas emissions between 2023 and 2030 under the case study countries' biofuel policies, assuming GLOBIOM-based ILUC factors and neglecting any indirect emissions from residual lipids**

*Note: Positive values signify emissions increases, negative values are emissions decreases.*

For those countries where changes in biofuel policy deliver a net benefit, we identify three main contributing factors: (i) the phasing out of the use of high-ILUC palm oil biofuel; (ii) increased use of residual lipids; and (iii) expansion in the use of cellulosic biofuels (relevant for the EU+UK only). We note that we have followed the convention of not ascribing any indirect emissions to residual lipids, though as noted above, this simplification leads to overstating the net benefits of these fuels. While the ambitious targets for scaling up production of cellulose-based biofuels in the EU+UK could deliver significant GHG benefits compared to both first-generation biofuels and fossil fuels, it remains to be seen whether the evolving implementations of alternative fuels policy in the EU Member States and the UK will deliver commercialisation of these advanced biofuels and enable these targets to be met.

# Contents

# 1. Introduction

## 1.1. Why biofuels?

Governments worldwide have enacted policies to support the production and consumption of biofuels – bio-based alternatives to fossil fuels – in the transport sector. The key goals for these biofuel mandates include:

- Reducing greenhouse gas (GHG) emissions;
- Substituting imported fossil fuels with domestically produced resources;
- Supporting farmers and the agricultural sector; and
- Valorising wastes and residues.

Various policy instruments have been implemented to promote biofuel supply. These include quota systems and blending mandates that require fuel suppliers to incorporate alternative fuels in their products; differentiated taxation; greenhouse gas intensity reduction standards; subsidies for farmers to cultivate biofuel feedstock; financial support for bio-refineries through grants or loans; and investment in research and development.

In response to these measures, biofuel use has risen dramatically over the last two decades. This growth has come at a cost. Environmental NGOs and academic researchers have identified adverse impacts arising from biofuel production. The use of crops and croplands for biofuel feedstocks has encouraged the expansion of farming into previously unfarmed areas leading to land clearance, habitat loss, and significant GHG emissions from lost vegetation and soil disruption, and in some areas driving displacement of indigenous communities. Consequently, there is concern that some biofuel use has exacerbated rather than mitigated climate change. Additionally, the use of intensive agriculture to produce biofuel crops can affect soil health, water use, water quality, and air pollution. Taking land out of food production can also drive up food prices, potentially increasing poverty levels in some of the world's most vulnerable communities.

With these tensions in mind, this report examines current and emerging initiatives that promote biofuel use globally.

- ➢ The remainder of Section 1 establishes the types of biofuels and their feedstocks and introduces a global biofuel consortium.
- ➢ Section 2 reviews global biofuel consumption, focusing on nine of the top biofuel economies.
- ➢ Section 3 surveys environmental and social impacts associated with the production and consumption of biofuel feedstocks.
- ➢ Section 4 identifies national and international policies driving biofuel consumption and estimates the potential scale of biofuel demand in 2030.
- ➢ Section 5 provides a brief conclusion.

## 1.2. Biofuel feedstocks and production pathways

This section provides a brief technical overview of biofuel technologies. The production of biofuels can be categorised based on the origin of the feedstock, and the production pathway used to turn that feedstock into fuel. Biofuel feedstocks can include food-type crops, cellulosic crops, and biogenic residues & wastes. The applicable biofuel conversion processes depend on the nature of the feedstock – whether it contains oils/fats, starches/sugars, or cellulose/ligno-cellulose (Figure 2).

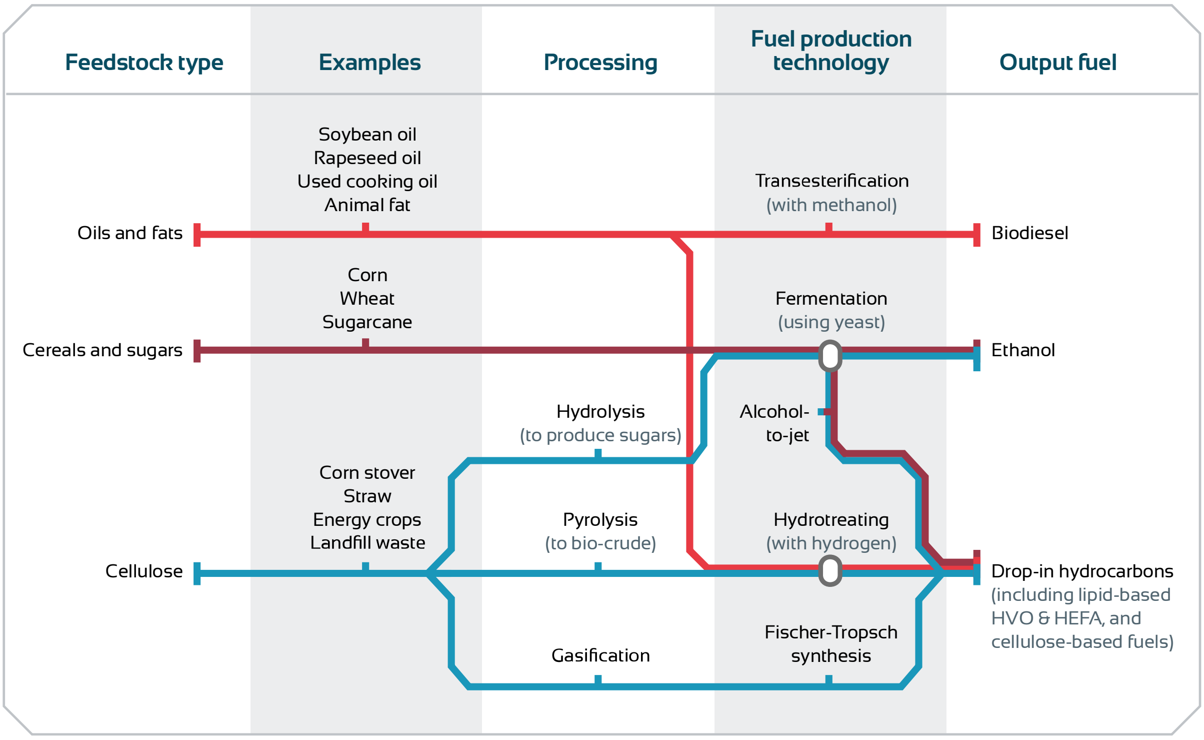


**Figure 2** **Biofuel feedstocks and production pathways**[4]

*Note: The reds and the blue indicate first-generation and second-generation feedstocks / production pathways, respectively.*

### *1.2.1. Food-type crops*

Food-type biofuel crops are rich in starch (e.g. corn), sugar (e.g. sugarcane), or oil (e.g. soybean or rapeseed). The vast majority of the world's biofuels production today falls into this category. Fuel conversion processes for these crops are well-established, with the main limitations on further production being feedstock availability, price, and policy support. These biofuels are often referred to as first-generation (1G) biofuels.

[4] Fuel nomenclature can get a little cluttered. In this report, the term 'biodiesel' refers to FAME biodiesel; 'HVO' (hydroprocessed vegetable oil) to hydroprocessed renewable diesel for road use; and 'HEFA' (hydrotreated esters and fatty acids' to hydroprocessed renewable jet fuel.

Sugars and starches are fermented into ethanol, which is then blended into petrol. A newer process, alcohol-to-liquid fuel (AtL), converts ethanol into hydrocarbons by reacting it with hydrogen. To the authors' knowledge, currently only one AtL plant operates at commercial scale, with a maximum output of around 40 million litres per year (U.S. Bioenergy Technologies Office, 2024). However, favourable policy signals are likely to spur further growth in this area. Another technology pathway, sugar-to-iso-paraffin (SIP), converts sugars directly to hydrocarbons without the intermediate alcohol step. This has yet to achieve commercial-scale operation.

Vegetable oils can be 'transesterified', a process in which the oil is reacted with methanol to produce FAME[5] biodiesel, or 'hydro-processed', where the oil is reacted with hydrogen to form hydrocarbons known as renewable diesel, renewable gasoline, or renewable jet fuel[6].

Ethanol and biodiesel are subject to blending limits in existing engines. Bio-based hydrocarbons on the other hand can be blended into conventional fossil fuels without restriction, provided they meet the technical specifications.

### *1.2.2. Cellulosic energy crops*

Cellulosic[7] energy crops include perennial grasses (e.g. Miscanthus), annual grasses (e.g. biomass sorghum), short rotation forestry (e.g. willow), and cover crops grown to stabilise soil and reduce runoff during agricultural off-seasons. These crops are considered to pose lower environmental risks than food-type crops (see Section 3.3) and can potentially deliver more biomass per hectare or per unit input. However, the associated fuel-production technologies are less developed.

Two generic avenues exist for producing fuel from cellulosic crops. The first is bio-chemical processing, which breaks down cellulose into its component sugars, which are then converted into fuels like cellulosic ethanol (following the pathways described in Section 1.2.1). The second is thermo-chemical processing, which includes biomass gasification followed by Fischer-Tropsch synthesis, or pyrolysis followed by catalytic upgrading. Both processes produce bio-based hydrocarbons as their final output.

### *1.2.3. Residues & wastes*

Residues & wastes are attractive biofuel feedstocks for financial, environmental, and regulatory reasons. They generally have lower prices than 'primary' feedstocks[8], and are available without creating additional environmental burdens. Residues & wastes also receive favourable treatment under regulations such as the EU's Renewable Energy Directive (RED) (see Section 4.1.3).

[5] Fatty acid methyl ester. This type of molecule contains oxygen and so is not a drop-in hydrocarbon.

[6] See Footnote 2.

[7] 'Cellulosic biomass' is taken to encompass cellulose, hemi-cellulose, and lignin.

[8] Although incentives for their use can drive their prices up.

The category of residues & wastes is broad, and the distinction between wastes, residues and products can be contentious. Some feedstocks are 'true' wastes which must be disposed of, while others have existing and/or potential future uses in other industries. Diverting the latter to the biofuel sector can have 'indirect' effects if a displaced waste or residue must be replaced with another primary material. For example, diverting low-grade animal fat for biofuel production may increase demand for palm oil in the oleochemicals and pet foot industries (Malins, 2023b). When these indirect GHG emissions are considered in lifecycle analyses, the sustainability benefits of residue-based biofuel can diminish or even disappear.

## 1.3. The Global Biofuels Alliance

The Global Biofuels Alliance (GBA) was launched in 2023 as an initiative of the Indian Government, with India's Ministry of Petroleum and Natural Gas serving as the secretariat (Suman, 2023). The GBA is a consortium of national governments and international organisations, as shown in Figure 3 and Figure 4. Its stated goal is (Government of India, 2023):

> *"to expedite the global uptake of biofuels through facilitating technology advancements, intensifying utilization of sustainable biofuels, shaping robust standard setting and certification through the participation of a wide spectrum of stakeholders".*

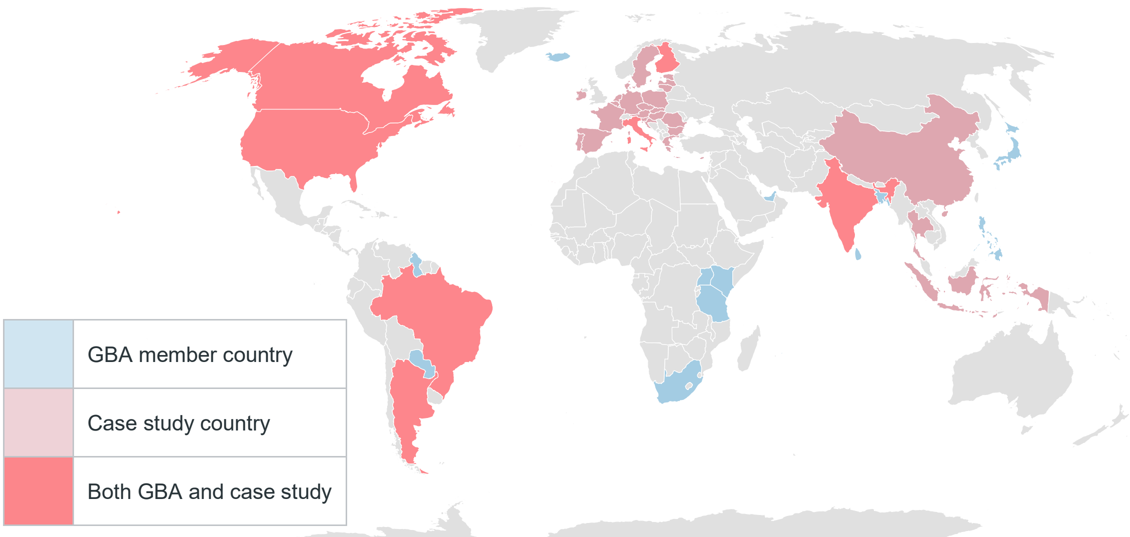


**Figure 3 Map of Global Biofuels Alliance national members in 2024, also showing the case study countries in this report**

*Note: The case study countries considered in this report are introduced in Section 2.2. They are the USA, Brazil, the EU+UK, Indonesia, China, India, Argentina, Canada, and Thailand.*


**Figure 4 List of Global Biofuels Alliance institutional members in 2024**

Among its national members are the two largest biofuel producers in the world, the USA and Brazil. In 2023, GBA members comprised about two-thirds of global biofuel production, amounting to over 74 Mtoe[9]. Although the GBA has been represented at several international meetings, its precise role has yet to be determined. In particular, it remains unclear how the GBA will balance its goal of increasing biofuel uptake with the environmental and social challenges associated with biofuel expansion.

During a 2024 G20 meeting, the acting secretariat outlined a ‘three-pronged work plan’ focussing on “assessing country landscapes, drafting policy frameworks, and conducting biofuel workshops” (Chakraborty, 2024)[10]. Additionally, the International Energy Agency (IEA), a GBA member, has proposed three priority areas (Moorhouse & Gupta, 2024): (i) expanding biofuel provision in emerging markets currently lacking de-fossilisation policies; (ii) accelerating global production of ‘advanced’ biofuels, which tend to pose a lower environmental risk; and (iii) developing a coherent international framework of sustainability standards (such as methodologies for estimating fuels’ lifecycle GHG emissions).

The formation of the GBA, alongside national biofuels schemes seeking to expand domestic biofuels industries, provides context for re-examining recent trends and stated objectives of countries’ national biofuels policy, including some of the sustainability concerns associated with the production and use of biofuel feedstock.

## 1.4. Note on data

For the analysis of past and future biofuel and feedstock demand we draw on a number of publicly available datasets. These include national biofuel reports published by the U.S. Department of Agriculture (USDA) Foreign Agricultural Service (FAS) – the so-called Global Agricultural Information Network (GAIN) reports; global stock-taking by the IEA and the Energy Institute; EU records from Eurostat; the data releases from the UK Department for Transport (2023a, 2024c); forward-looking country-level projections produced in partnership between the Organisation for Economic Cooperation and Development (OECD) and the UN Food and Agriculture Organisation (FAO); and agricultural yield data from USDA and FAO datasets

[9] Because of their different energy contents per unit volume, it is convenient to quote biofuel demand in energy units. In this report we use million tonnes of oil equivalent (Mtoe) as the standard energy unit. 1 Mtoe is equal to 41.87 petajoules (PJ).

[10] It has now been agreed to base the permanent secretariat for the GBA in India (Indian Ministry of External Affairs, 2024). Further announcements from the GBA may be expected during the COP 29 in November 2024.

(FAOstat, 2024; USDA Foreign Agricultural Service, 2024). We make appropriate citations when values from these datasets are used in the report.

Where they overlap, the sources are seldom fully consistent with each other, but discrepancies are mostly small and/or explicable. We do not present any systematic comparison in this report, but have endeavoured to resolve significant discrepancies through broader consultation of the literature.

# 2. Biofuel demand in major markets

## 2.1. Global demand

The IEA reports that 182 billion litres of biofuel were supplied in 2023, equal to about 110 million tonnes of oil equivalent (Mtoe) (IEA, 2024b). Almost all of this biofuel was supplied to the road transport sector (Figure 5), although policies are emerging to support increased production of 'biojet' fuel.

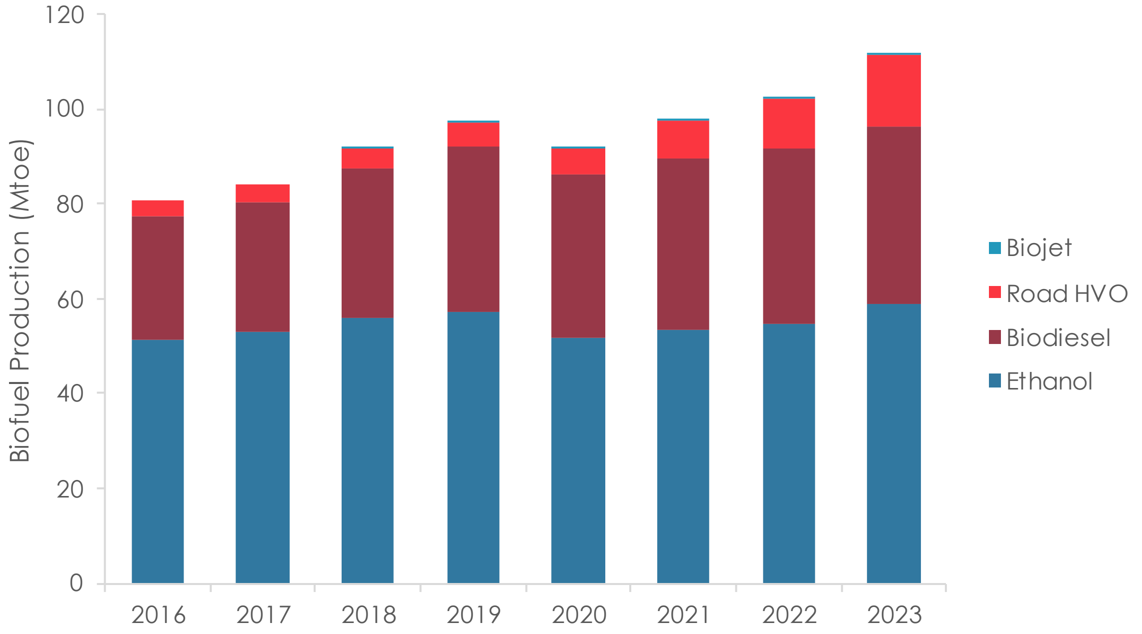


**Figure 5 Global biofuel production between 2016-23 in Mtoe**

*Note: For consistency with the rest of this report, conversions have been made to energy units from the volume values used in the original source.*
*Source: Adapted from IEA (2024b)*

Analysis by IEA (2022) indicates the variety of feedstocks used to produce these fuels (Figure 6). The vast majority (88% by energy) are food-type crops[11], with more limited contributions from used cooking oil, animal fats and other residues & wastes. In mass units, the biofuels industry used around 385 Mt of sugar globally in 2023, 188 Mt of starch, 39 Mt of vegetable oil, and 22 Mt of residues including used cooking oil (IEA, 2024b).

[11] The 'other crops' category in Figure 6 may include some cellulosic energy-crops, but given the lack of cellulosic fuel production capacity the actual volume will be negligible.

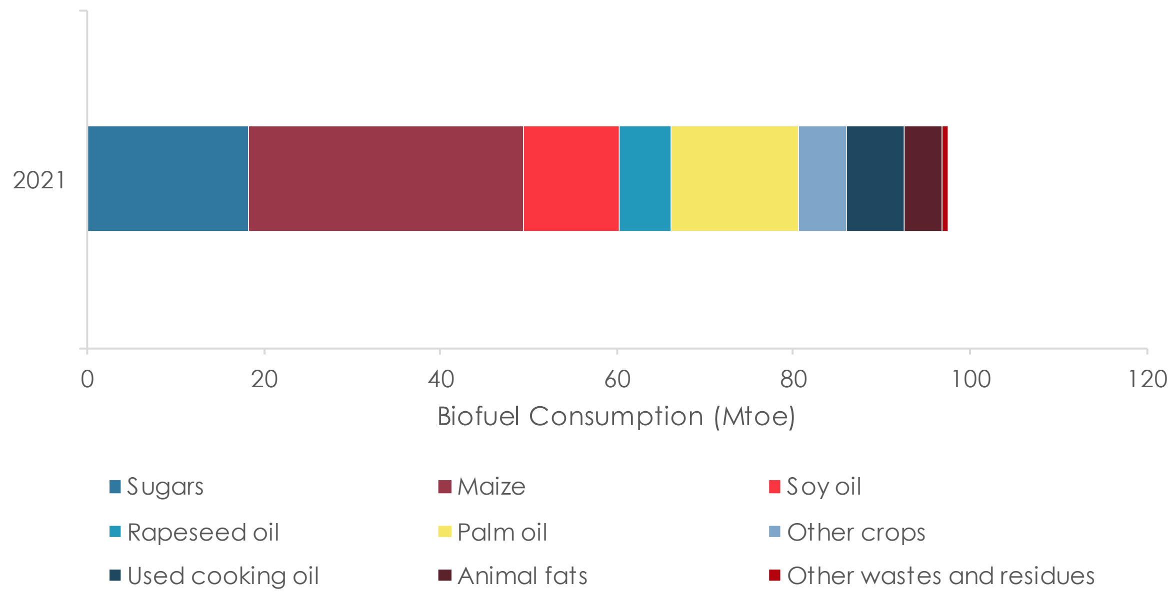


**Figure 6** **Global biofuel consumption in 2021, split into feedstock contributions**

*Note: For consistency with the rest of this report, approximate conversions have been made to energy units from the volume values used in the original source.*
*Source: Adapted from IEA (2022).*

The goals suggested for the GBA, in particular the expansion of biofuel use in developing economies, imply further demand for food-type crops. As will be discussed later in this report, this carries significant sustainability risks.

## 2.2. Case study countries

A handful of countries are responsible for the majority of global biofuel production and consumption. They typically have large agricultural sectors and have adopted climate change goals. For this report, we have chosen to focus on eight countries and the EU+UK (for simplicity we call these the nine 'case study countries'). These were chosen principally based on their high biofuel consumption and production volumes; Figure 7 details their contribution to the global supply over time, and Table 1 provides biofuel production quantities and shares for the year 2023. Five of the case study countries are members of the GBA, while four are not (cf. Figure 3)[12].

[12] The EU is included in the case studies but is not a member of the GBA. EU Member States Italy and Finland are party to the GBA.

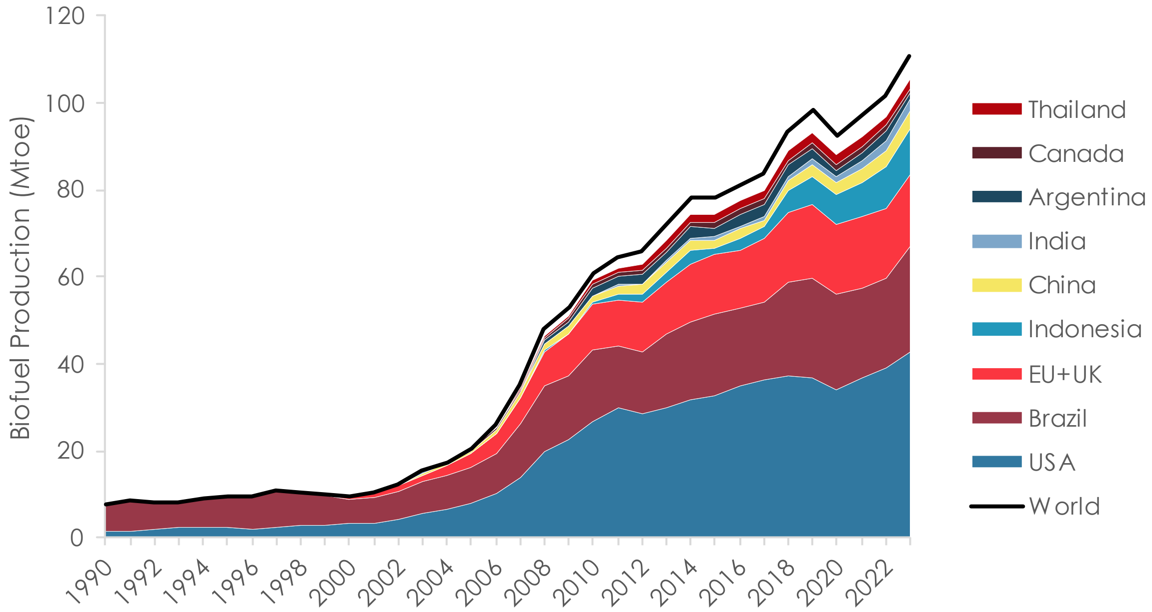


**Figure 7** **Production of biofuels over time for the case study countries**

*Note: The gap between the black 'World' line and the coloured country stack represents the rest of the world.*
*Source: Energy Institute (2024)*

**Table 1** **Biofuel production in 2023 for the case study countries**

| Production | USA | Brazil | EU+UK | Indonesia | China | India | Argentina | Canada | Thailand | RoW |
|---|---|---|---|---|---|---|---|---|---|---|
| PJ | 1,795 | 1,016 | 689 | 433 | 175 | 109 | 56 | 52 | 88 | 216 |
| Mtoe | 42.9 | 24.3 | 16.4 | 10.3 | 4.2 | 2.6 | 1.3 | 1.3 | 2.1 | 5.2 |
| World Share | 39% | 22% | 15% | 9% | 4% | 2% | 1% | 1% | 2% | 5% |

*Note: 'RoW' stands for rest of world.*
*Source: Energy Institute (2024)*

The balance between consumption and production of finished fuel for each of the case study countries is shown in Figure 8. Most countries have comparable levels of fuel consumption and production; though in the year 2023, China had relatively large net exports (37% of domestic production), while Canada had significant net imports (57% of domestic consumption). Global trade in biofuel feedstocks (rather than finished fuel), which is not captured by this data, is also sizeable; but it is not trivial to determine from general trade data which feedstocks are used in the biofuels industry versus other industries (cf. Malins & Sandford, 2022).

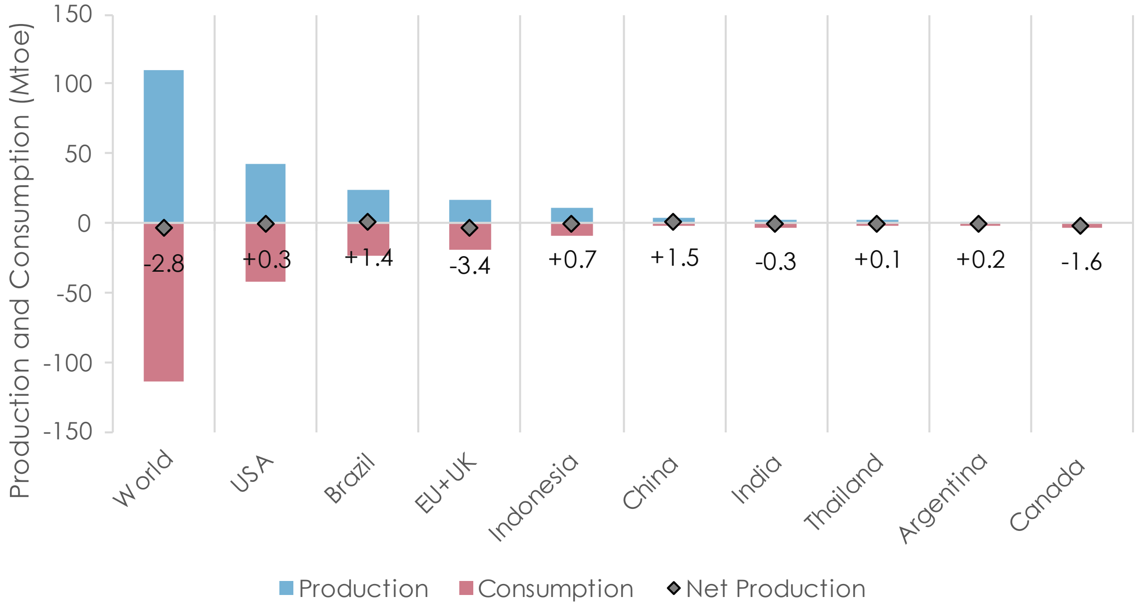


**Figure 8** **Production and consumption of biofuels in 2023 for case study countries, with net production value labelled**

*Note: Stockpiling between years means that global consumption is not necessarily equal to global production in a given year. Rounding and reporting inconsistencies in the dataset may result in global values that don't quite match the sum of country values.*
*Source: Energy Institute (2024)*

Table 2 presents country-wise feedstock consumption for the year 2023, based primarily on data compiled by the USA Government.

**Table 2 Feedstock consumption (Mt) for first-generation biofuels in 2023 for the case study countries**

| Feedstock | Argentina | Brazil | Canada | China | EU+UK | India | Indonesia | Thailand | USA | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Cassava (DM) | -- | -- | -- | 1.2 | -- | -- | -- | 0.9 | -- | 2.1 |
| Corn | 1.9 | 13.3 | 3.5 | 6.0 | 7.9 | 0.0 | -- | -- | 134.9 | 167.5 |
| Wheat | -- | -- | 0.5 | 0.6 | 4.1 | -- | -- | -- | -- | 5.2 |
| Rice | -- | -- | -- | 2.5 | -- | 2.0 | -- | -- | -- | 4.5 |
| Other starches | -- | -- | -- | -- | 1.5 | -- | -- | -- | -- | 1.5 |
| Palm oil | -- | 1.0 | -- | -- | 2.4 | 0.1 | 12.7 | 1.6 | -- | 17.8 |
| Rapeseed oil | -- | -- | 0.2 | -- | 6.4 | -- | -- | -- | 1.5 | 8.2 |
| Soybean oil | 1.4 | 4.7 | 0.0 | -- | 0.8 | -- | -- | -- | 6.0 | 12.9 |
| Sunflower oil | -- | -- | -- | -- | 0.3 | -- | -- | -- | -- | 0.3 |
| Sugarbeet (DM) | -- | -- | -- | -- | 1.7 | -- | -- | -- | -- | 1.7 |
| Sugarcane (DM) | -- | 101.9 | -- | -- | 0.9 | 5.8 | -- | 0.3 | -- | 108.8 |
| Molasses | 1.5 | -- | -- | -- | -- | 12.0 | 0.0 | 3.3 | -- | 16.9 |
| Oily wastes & residues | -- | 0.7 | 0.2 | 3.1 | 5.4 | 2.2 | -- | 0.0 | 7.1 | 18.6 |
| Total | 4.8 | 121.6 | 4.4 | 13.4 | 31.4 | 22.1 | 12.7 | 6.1 | 149.5 | 366.0 |

*Note: 'DM' means 'dry matter', i.e. feedstock without the water content. A '--' indicates that no feedstock is recorded in that country.*
*Source: USDA GAIN reports (Danielson, 2023; Das, 2024; Flach et al., 2023; Florence Mojica-Sevilla, 2024; Hayashi, 2024; Joseph, 2024; Prasertsri, 2024; Rahmanulloh, 2023); EIA data publication (U.S. Energy Information Administration, 2024a); UK RTFO data (UK Department for Transport, 2024c)*

# 3. Impacts of biofuel demand

## 3.1. The food and feed sector

### *3.1.1. Food versus fuel competition*

Approximately 90% of global biofuel production relies on food commodities, raising questions about how the growth of the biofuel market has affected global food supply. In 2023, the biofuel industry consumed about 200 million tonnes of corn, 8 million tonnes of wheat, 40 million tonnes of vegetable oil and enough sugarcane and sugarbeet to make 50 million tonnes of sugar (OECD, 2024). Malins (2023a) calculated that the energy in these feedstocks could meet the minimum calorific requirements of up to 1.3 billion people[13]. Meanwhile, the 2022 'State of Food Security and Nutrition in the World' report FAO et al. (2022) states that up to 800 million people in the world face hunger.

While statistics like these suggest an obvious tension between the biofuel industry and food supply, some industry commentators argue that the 'food vs fuel' issue is a myth. While it is well documented that the conflict between fuel and food is real and problematic, it is nuanced (Malins, 2017, 2023a). Global hunger is primarily driven by uneven food distribution and affordability to people on limited incomes, rather than by a lack of food production. Scaling back the biofuel industry would not directly resolve those distributional issues but it would reduce competition for available food resources and allow prices to fall.

Investigations into past food price crises (2007-08, 2010-12, and 2020-23) has produced a consensus that biofuel demand played a significant role, although its exact contribution among other drivers remains complex to pinpoint (Malins, 2017, 2023a). Even during non-crisis periods, numerous economic models have predicted that biofuel demand would lead to long-term increased food prices (Persson, 2016). Indeed, there has been a general rise in global food prices since the expansion of biofuel demand from the 2000s (Malins, 2023a). Inflation-adjusted index prices published by the FAO for cereals were 53% higher in the period 2007 to 2022 than 1991 to 2006; vegetable oil prices were 57% higher (Malins, 2023a). These price increases have significant human impacts, with studies projecting that biofuel mandates could push tens of millions of people over the poverty line (e.g. de Hoyos & Medvedev (2011); Wiggins & Mcdonald (2008)).

While the general trajectory of biofuel demand has been upwards since the year 2000 (Figure 7), regulators have occasionally moderated biofuel policies to take pressure off food prices. For example, since 2014 the EU has capped the contribution of food-based biofuels towards its regulatory targets in the Renewable Energy Directive (European Commission, 2015; European Union, 2018). Similarly, the USA's Environmental Protection Agency (EPA) explicitly considers the risk of undue impacts on food markets when setting obligated volumes under the Renewable Fuel Standard (U.S. Environmental Protection Agency, 2024). Meanwhile, the Governments of China and India have both restricted the use of food-based biofuel

[13] Note that this figure includes consideration of the co-products that are returned to the market (primarily as livestock feed) alongside biofuel production. Without considering these co-products the gross number would be 1.6 billion.

 

feedstocks following the 2007-2012 food price crises, while Malaysia delayed the introduction of B20 biodiesel blending following the most recent food price crisis (Chu, 2022).

Drives to expand biofuel production through the Global Biofuels Alliance, and policy initiatives to deploy alternative fuels in aviation, push in the other direction. Demand for vegetable oils in particular is at risk of further outstripping supply growth and causing another 'feedstock crunch' (International Energy Agency, 2022; Malins & Sandford, 2022).

The pressure on vegetable oils could be alleviated to some extent by improving systems for collection of first-generation residual feedstocks like used cooking oil and low-grade animal fat. In markets like the EU and the USA, where biofuel policies already favour the use of such resources, collection rates from restaurants are close to their economic limit, and this also holds for some exporting countries[14]. In other regions, however, notably South America and Africa, there is significant potential to improve collection rates. There is also potential to expand systems for collection of household waste oils, though the costs of distributed collection make this challenging (O'Malley et al., 2021). One market outlook suggests that global supplies of UCO could rise from 13 Mt in 2022 to 18-36 Mt in 2030 (GlobalData, 2023). International Energy Agency (2022) anticipates that the biofuel market shall increasingly become the dominant use for available UCO and residual animal fats, suggesting that biofuel production will consume 97% of the available supply by 2027 (enough to produce 24.1 billion litres of biofuel). The levels of residual oil consumption considered in this report (see Section 4.3.1), are consistent with these availability estimates. Even with this growth, in our projection residual oils deliver only a third of feedstock required for biodiesel and HVO in 2030.

### *3.1.2. Co-products from feedstock processing*

One important feature of the biofuel industry that some of its spokespeople have focussed on when discussing food versus fuel is the production of 'co-products': additional outputs produced alongside the biofuels themselves.

In the case of grain ethanol, the main co-product is referred to as distillers' grain and solubles (DGS). During fermentation, sugars and starches are consumed to produce alcohol, while other constituents of the grain such as protein, fat, and fibre, remain in the DGS. These DGS are sold back into the animal feed market, reducing the net loss of feed due to biofuel production. Because the protein from the grain is concentrated into the DGS, it can partly substitute protein feeds such as imported soy meal (although soy meal still has a higher protein content and preferred amino acid profile and therefore sells at a significantly higher price per tonne). The biofuel industry can sometimes seem to frame this protein feed replacement as a straight benefit, but in reality, is it is a trade-off for the feed market. When a tonne of feed wheat is processed for ethanol, that is a tonne that is not available for direct use as animal feed. Returning a third of a tonne of DGS to the livestock feed market reduces that impact but does not reverse it (Malins, 2023a).

In the case of biodiesel, the process of extracting vegetable oil from crops like rapeseed or sunflower seeds (through crushing) produces oilseed cake, another protein-rich livestock feed (though again lower in protein than soy meal). This co-product would still be produced,

[14] For instance, it is estimated that 60-80% of potential UCO supply in China, and 76-92% in South Korea, is already tapped (Kristiana et al., 2022).

however, if that vegetable oil were produced for the food market and used to reduce, for example, the EU's dependency on palm oil imports.

It is important to note that the return of co-products to the feed market is already considered in economic models predicting the impact of biofuel demand. This modelling has repeatedly predicted that biofuel demand will cause food prices to increase (Malins, 2017). Co-products are also considered in the assessment of the GHG emissions associated with biofuel cultivation and processing; in the EU accounting system this is done by 'allocating' the emissions proportionately between the biofuel and the co-product based on energy content. While co-products do moderate the food-price impact of biofuel production, they do not eliminate the fundamental tension between biofuel demand, food prices and availability.

## 3.2. Land use and land use emissions

Biofuel demand can stimulate the conversion of non-agricultural habitats into cropland. Using land for biofuels may not always deliver the best environmental outcomes, especially if compared to renewable electricity production or rewilding. This section provides a high-level exploration of these issues.

### *3.2.1. Required land area*

The feedstock demand in Table 2 can be translated into an implied demand for agricultural land. Figure 9 illustrates net land demand in each case study country based on national average yields reported by the FAO (FAOstat, 2024)[15]. The left side of the graph shows the total land area that must be dedicated to biofuel feedstock crops in order to meet biofuel demand; we refer to this as the 'gross' land requirement. As noted above (Section 3.1.2) producing biofuels from these crops generates co-products that would not otherwise be available. These co-products can reduce the overall demand for other agricultural products: for example, increasing the availability of rapeseed meal could reduce net demand for soybeans. The gross land use demand numbers on the left of Figure 9 therefore overstate the net land demand associated with the biofuel industry.

The right side of Figure 9 adjusts the gross figures to reflect the availability of these co-products by 'allocating' the land demand between biofuel and co-product proportionately based on energy content. For example, for corn ethanol 55% of the land demand has been allocated to the ethanol and 45% to the distillers' grains. Across the assessed countries, the net land demand after this allocation between co-products is just over half of the gross land demand – 32 million hectares (Mha) against 61 Mha.

[15] For palm oil, we use palm oil yield data reported by the U.S. Department of Agriculture (USDA Foreign Agricultural Service, 2024), as FAOstat reports only fresh fruit bunch yield.

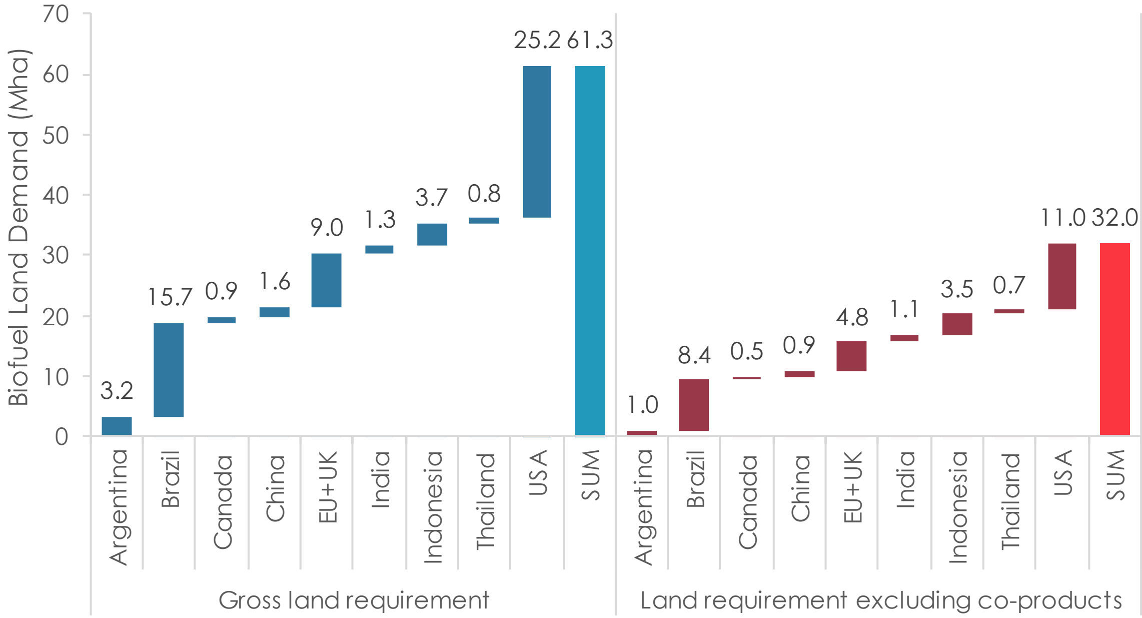


**Figure 9** **Land use for biofuel feedstocks in the case study countries in 2023, showing the total gross land requirement (left), and the land requirement once co-products have been discounted (right)**

The net land requirement of 32 Mha is substantial – comparable to the arable area of France (as reported by FAOstat) or the total land area of Italy. This land use supports the replacement of approximately 4% of the global oil demand for transport (cf. Frankl & Moorhouse (2023); IEA (2024b)), highlighting that liquid biofuels alone cannot fully achieve transport decarbonisation.

To put this in perspective, we compare the land requirement for biofuels to the area needed to produce an equivalent amount of renewable electricity using solar photovoltaics (PV)[16]. The productivity of a PV farm is often quoted in units of kWh/kWp/day (kilowatt-hours produced per kilowatt-peak of installed capacity per day). Assuming no shadow-casting obstructions and clean, optimally tilted fixed panels, power generation is governed primarily by latitude (which determines the angle and duration of sunlight), temperature, and cloudiness. As such, solar productivity varies both between and within the case study countries. For simplicity we use a single representative value of 3.9 kWh/kWp/day (European Commission Joint Research Centre, 2022; Solargis, 2024). We find that using PV to produce the 4,400 PJ of biofuels consumed in 2023 (Table 1) would require about 1.1 Mha of solar modules, or 3.4% of the land used for biofuels[17].

Arguably a more relevant comparison would be to consider the transport work that could be achieved in both cases. Due to the superior efficiency of electric motors, a unit of electricity can power a battery-electric vehicle (BEV) for more kilometres than the same amount of

[16] A similar analysis could be done for on-shore wind power, which has an even smaller land footprint than solar because the space between turbines can be used for productive and/or nature restoration purposes.

[17] For this calculation we assume an average area density of 0.08 kWp/m$^2$ for a solar farm. This is a low estimate, considering the generation rate of individual PV modules (cf. UK Alternative Energy, 2019) and the average spacing between modules in a solar farm.

energy supplied as liquid fuel to an internal combustion engine vehicle (ICV)[18]. Thus, switching from biofuels in ICVs to PV plus BEVs would require an even smaller fraction of the land area.

### *3.2.2. Carbon opportunity cost*

The climate benefits of biofuels are often assessed through 'lifecycle analysis' (LCA), which adds up emissions from producing and harvesting feedstock, transporting it to a bio-refinery, and processing it into biofuel. These emissions can then be compared to those associated with producing fossil fuels. By convention, LCA typically includes emissions from land conversion (when an area is brought into crop production for the first time i.e. 'direct land use change') but otherwise treats land as a free resource and overlooks the potential climate benefit of allowing the land to revert to a natural state or planting trees on it. This missed potential is referred to as the 'carbon opportunity cost'. LCAs may also ignore the emissions that could occur elsewhere when new land is brought into production to replace the feedstock now committed to biofuel use ('indirect land use change', ILUC).

Here we assess the carbon opportunity cost of current biofuel production by comparing the expected emission reductions of different biofuels, ignoring land use change emissions, with the carbon sequestration potential of forest regrowth on the same land area (based on carbon stock values documented in an Institut für Energie- und Umweltforschung (IFEU) study (Fehrenbach et al., 2023)[19]. The assumed biofuel carbon intensities are set based on consideration of regulatory LCA values and other relevant data points, and for the purpose of this calculation we assume that biofuels substitute fossil fuels on a 1-for-1 energy basis (i.e. one megajoule of biofuel consumption is assumed to avoid one megajoule of fossil fuel consumption).

Figure 10 displays this comparison for of the achievable carbon benefits for biofuels consumed in a selection of our case study countries, with the vertical axis denominated in $gCO_2e$ per megajoule of biofuel energy. Fuel displacement estimates are guided by standard values for biofuel lifecycle emissions tabulated in Annex V of RED II (European Union, 2018), supplemented by nationally-specific lifecycle emissions for key fuels[20].

The land restoration values in Figure 10 must be understood as the hypothetical carbon sequestration on land currently used for biofuel feedstock if crop production were to immediately cease, per MJ of biofuel no longer produced. In the calculation, the carbon benefit of land restoration is spread over 40 years. Figure 10 reflects the 'net' land required for biofuel production rather than the 'gross' land use for crop production (cf. Section 3.2.1) – in

[18] For example, in the 'Well to Wheels' study undertaken for the European Commission's Joint Research Centre, the reference energy consumption for a passenger BEV was put at 372.1 kJ/km and for a passenger spark-ignition ICV is 1,403.3 kJ/km (Prussi et al., 2020) – a factor of about 3.8.

[19] Fehrenbach et al. (2023) assumed that carbon stock recovery would take 30 years, this is considered optimistic and we have revised it to 40 years (cf. Poorter et al., 2016).

[20] Using Mera et al. (2023) for Brazilian ethanol; GREET (including CA-GREET) for USA biofuels (Argonne National Laboratory, 2024; California Air Resources Board, 2019); palm oil lifecycle emissions estimates for Indonesia were influenced by Alcock et al. (2022); Canadian biofuel emissions were based on inputs from a number of sources (Government of British Colombia, 2024; Hoyle, 2020; Kostiainen, 2023; Navius Research, 2023); for Indian sugarcane and molasses we consulted references for south and north India (Hiloidhari et al., 2021; Uppalapati et al., 2024); Canabarro et al. (2023) provide LCA estimates for Argentina.

other words, the values are adjusted to reflect the reality that if all biofuel production halted then some land would be needed to compensate the reduced generation of co-products.

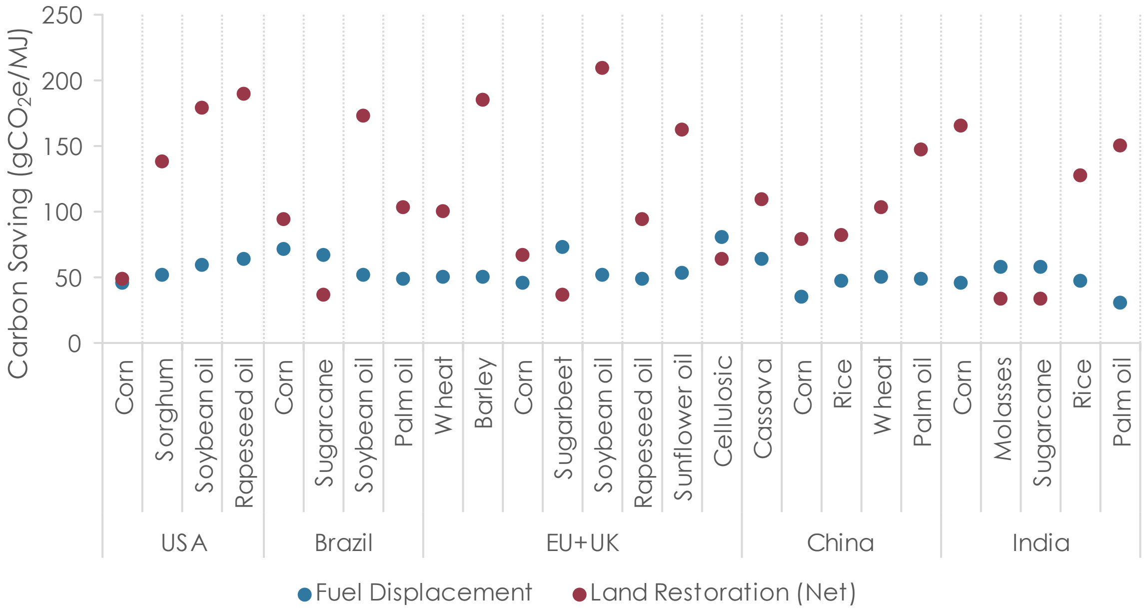


**Figure 10 Greenhouse gas saving from allowing land to return to a natural state versus using it to grow biofuel feedstock, per unit of fuel for major biofuel producers**

*Note: The units on the vertical axis are grams of carbon dioxide equivalent per megajoule (MJ) of biofuel used. For the land restoration analysis, this should be understood as the GHG saving from using an appropriately sized plot of land for restoration rather than producing a MJ of biofuel.*

The results indicate that in most cases, land restoration offers greater carbon benefits than using the land for biofuel production (the exceptions are for sugarbeet and sugarcane, though USA corn comes close[21]). Figure 11 below shows that if these results are multiplied up over the total biofuel consumption in the case study countries, land restoration would deliver hundreds of millions of tonnes more annual $CO_2$ benefit than could be achieved by displacing fossil fuels with biofuels: 428 $MtCO_2e$/year versus 233 $MtCO_2e$/year, based on 2023 consumption levels. Values are tabulated in Annex C.

[21] Sugarcane, for instance, scores well in this methodology because Fehrenbach et al. (2023) assumes that it is grown on tropical shrubland that has relatively low carbon stock next to other land types. Moreover, sugarcane plantations are credited with adding some below-ground carbon. Sugar crops also give high biofuel yields per hectare, and the bagasse residue from sugarcane processing can be used as a low-emissions energy source during fuel production.

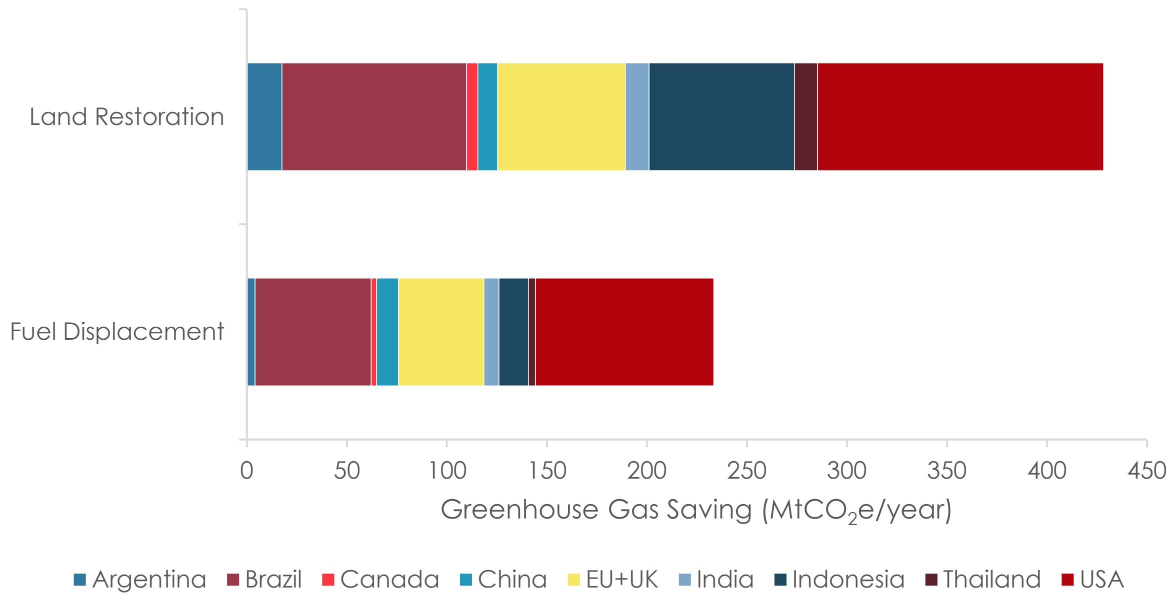


**Figure 11** **Greenhouse gas saving from allowing land to return to a natural state versus using it to grow biofuel feedstock, summed over fuels for each case study country**

*Note: This figure is based on 2023 consumption levels in the case study countries. As with Figure 10, land restoration values are for the 'net' biofuel contribution.*

### *3.2.3. Indirect land use change (ILUC)*

While carbon opportunity cost highlights that biofuel feedstock production may not be the most effective use of land for climate change mitigation, it remains a somewhat theoretical exercise. There is no global policy mechanism that could deliver the massive agricultural land abandonment and reforestation implied by Figure 11, and the analysis assumes that almost all the affected areas could be reforested successfully and (relatively) rapidly. A more conventional lens for examining the cost of land use for biofuel is indirect land use change (ILUC).

ILUC analysis uses economic modelling to generate scenarios showing how a given increase in biofuel production might be met in practice (or, equivalently, what might happen to the land currently used for biofuels if demand was reduced). ILUC analysis can be seen as a way to characterise the likely alternative uses for land given existing economic drivers; these alternative land uses come with GHG and non-GHG impacts (the latter including the potential for habitat loss and ecosystem degradation). In these models, additional biofuel feedstock comes from a combination of converting new land into cropland, increasing the productivity of existing systems, and reducing agricultural commodity demand in other sectors (this last possibility is part of the food versus fuel issue discussed in Section 3.1.1).

The scale of the ILUC impact depends on factors like relative crop yields, current crop market prices, the degree of substitutability of commodities (e.g. whether sunflower oil diverted from food markets is replaced by more sunflower oil or an alternative like palm oil), demand elasticity (e.g. the extent to which higher food prices reduces consumption), and the potential to increase productivity through modified agricultural practices. The effects of this land expansion include release of carbon sequestered in vegetation and soil, which can be quantified and expressed as an 'ILUC factor'. The level of emissions expected from land use change will depend on the extent to which different crops are connected to deforestation and other carbon stock losses. Because agricultural markets are interconnected, additional land conversion in ILUC models can happen diffusely around the world – e.g. producing extra biofuels in Europe can be associated with land use changes in Southeast Asia or South America.

Various economic equilibrium models incorporating these dynamics have been used to assess the impacts of increased in biofuel demand (Malins, 2021). As an example, the GLOBIOM (Global Biosphere Management) model has been used to produce ILUC estimates for the European Commission (Valin et al., 2015), and, more recently, to produce global estimates for the UN's International Civil Aviation Organisation (ICAO) in its development of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO, 2019; Malins, 2019).

Figure 12 shows the modelled net land use changes associated with meeting 1% of EU+UK energy demand in 2020 (123 PJ or 2.9 Mtoe) in Valin et al. (2015) using first-generation biofuels, disaggregated into four land use categories.

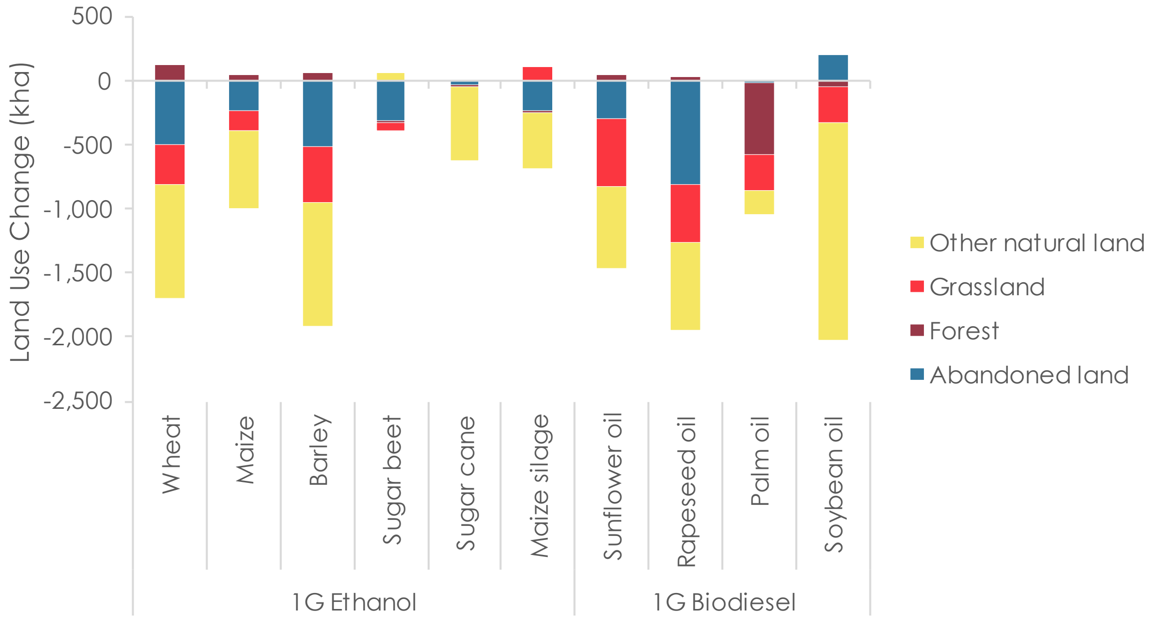


**Figure 12** **Global land use change arising from meeting 1% of EU+UK transport energy demand with 1G biofuels, from GLOBIOM modelling**

*Note: Negative values mean net reduction in land area; positive means net increase*[22].
*Source: Adapted from Valin et al. (2015)*

The corresponding modelled ILUC emissions are shown in Figure 13. This makes it evident that, due to the type of land being converted, some crop production systems are linked with much higher land-use change emissions than others. Notably, the Figure 13 results show palm oil and soy oil's land-use change emissions alone exceed even the full lifecycle emissions of petroleum-based fuels (cf. Malins, 2020a). Note that the Valin et al. (2015) analysis does not propose indirect emissions values for waste and residual oils (UCO, rendered animal fats) and in the analysis presented in section 4.3 we have treated those feedstocks as having zero indirect emissions. This will tend to overestimate the benefits of those biofuels, as there is evidence from other studies that they can be associated with significant indirect emissions (cf. Malins, 2023b).

[22] One outcome of the GLOBIOM model's complexity is that some land uses can show net increases despite an accompanying increase in cropped area – for instance small increases in net forest area associated with increased use of wheat ethanol. This result is likely to be driven by chains of substitution in the livestock industry – for example ethanol production implies increased distillers' grain production, and availability of distillers' grains for feed could encourage adoption of feedlot based livestock-rearing rather than extensive pasture-based livestock-rearing, and thereby relax pressure on forest land compared to the baseline.

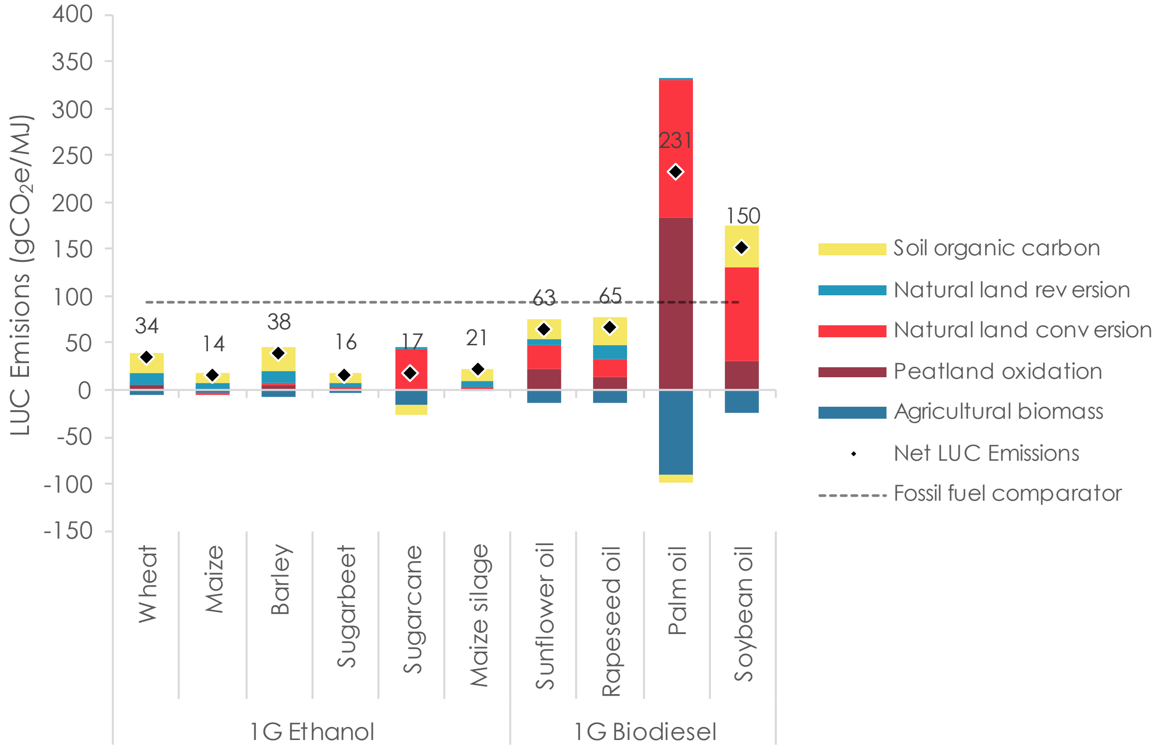


**Figure 13** **Global land use change emissions arising from consumption of 1G biofuel feedstocks, from GLOBIOM modelling**

*Note: The fossil fuel comparison line is set to 94 $gCO_2e/MJ$. This includes the entire lifecycle emissions of petroleum extraction, refining, and combustion, whereas the emissions for biofuels shown in this graph only cover land-use change, and not crop production or fuel conversion emissions.*
*Note: The term 'natural land conversion' refers to the carbon released from biomass when land use change occurs. The term 'natural land reversion' refers to the foregone carbon sequestration that would have occurred if the land used for biofuel crops had instead been abandoned and allowed to regrow.*
*Source: Adapted from Valin et al. (2015)*

The analysis in Valin et al. (2015) is now approaching ten years old, but remains the most recent ILUC analysis undertaken on behalf of the European Commission and continues to inform impact analysis of European policies such as ReFuelEU Aviation (Giannelos et al., 2021). These land use change results and associated ILUC emissions values are used in Section 4.3 to analyse the potential emissions consequences of further biofuel expansion in the case study countries. The Valin et al. (2015) results are based on biofuel feedstock demand within the EU, and therefore should only be considered indicative of the potential ILUC results from feedstock demand in other regions. Due to lower corn yields in the EU than the USA, the GLOBIOM cropland demand values for the corn scenario would be likely to overstate land demand for USA corn ethanol, and we have therefore adjusted all corn land areas by the ratio of EU yields to local yields as reported by FAOstat[23]. A different set of GLOBIOM results has been produced as part of the lifecycle analysis for the CORSIA aviation policy (see section 4.2.1 below) and differs in some assumptions from the EU work; these differences are discussed by Malins (2019).

[23] Using the ratio of the average reported yields across the period 2017-2022.

## 3.3. Ecology and biodiversity

### *3.3.1. Agriculture's ecological footprint*

The increased demand for biofuels, from both first-generation and second-generation crops (see Section 3.3.2), has potentially serious ecological implications for soil health, water quality, biodiversity, and the sustainability of agricultural systems. A global review of the impacts of biofuel crops on local biodiversity found that local species richness and abundance were 37% and 49% lower at sites planted with first-generation biofuels than in sites with primary vegetation (Tudge et al., 2021). The study identified that areas of first-generation biofuel crops (soy, wheat, corn, and oil palm) supported less biodiversity than cellulosic biofuel crops, and that cellulosic crops supported less biodiversity than natural systems.

Biodiversity loss has been particularly pronounced in regions with high deforestation rates, especially where primary tropical forests are converted into monoculture plantations (Meijaard et al., 2020). Monocultures inherently lack the structural complexity and diversity found in natural ecosystems, making them far less hospitable to a wide range of species. The absence of varied plant life reduces the availability of food and shelter for insects, birds, and other animals, leading to a decline in local biodiversity (Foster et al., 2011). Furthermore, monocultures tend to be more susceptible to pests and diseases, often resulting in increased pesticide usage, which further harms non-target species and disrupts ecosystem functions.

The expansion of monoculture plantations such as oil palm in Southeast Aisa and soybean in South America has also impacted globally threatened species. Meijaard et al. (2020) highlights that palm plantations in Southeast Asia have severely affected populations of orangutans, Sumatran tigers, and pygmy elephants. Meanwhile, soy cultivation in the Amazon and Cerrado (Malins, 2020b) has led to declines in species such as jaguars and macaws (Lee et al., 2011). The reduction in species richness and composition following the conversion of forest to agricultural land (Foster et al., 2011; Savilaakso et al., 2014), disrupts ecological processes and limits species survival, even in patches of remaining standing forest (Banks-Leite et al., 2020; Püttker et al., 2020). The ongoing deforestation, particularly in biodiversity hotspots, thus poses a severe threat to global biodiversity. Figure 14 illustrates the extent of tree cover loss in Indonesia and Brazil, both key members of the GBA, highlighting the continuing deforestation pressure in these areas.

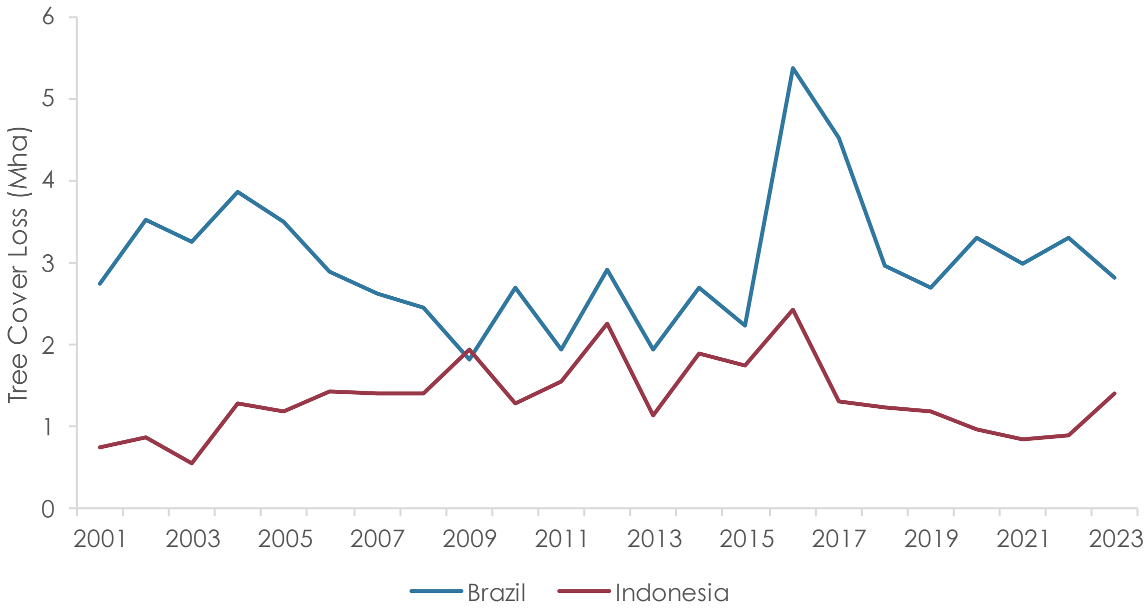


**Figure 14 Annual tree cover loss in Brazil and Indonesia from 2001 to 2023**

*Source: Global Forest Watch (2024)*

In temperate regions, where opportunities to expand into new lands are more limited due to extensive historical deforestation, agricultural intensification has become the norm. Large-scale intensive monoculture practices increase crop vulnerability to soil-borne diseases, emphasising the need for diverse crop rotations and other sustainable agricultural practices (Pérez-Brandán et al., 2014). The greater dependency on chemical inputs to sustain large-scale production of corn and soy in the USA have been shown to decrease long-term soil productivity, by reducing soil organic matter and damaging soil structure (Kopittke et al., 2019). This decline in soil health has significant knock-on effects for biodiversity, as soils support about 25% of global biodiversity (FAO et al., 2020), as well as food security and resilience to climate extremes.

Water is another critical resource affected by biofuel production, especially in water-stressed regions. Schnoor (2014) highlights that producing a tonne of corn for biofuels in the USA requires somewhere between 300 and 600 tonnes of water, depending on the region. This is particularly concerning in areas reliant on irrigation from aquifers, where unsustainable water usage rates are leading to competing water demands and the depletion of critical water sources. Figure 15 shows the water footprint of some common biofuel crops; for comparison, production of fossil petrol and diesel consumes less than 10 Mt/Mtoe[24].

[24] Calculated using default parameters in the 2023 GREET model (Argonne National Laboratory, 2024). This is focussed on USA refineries, but the critical point is that production of fossil transport fuels consumes orders of magnitude less water than biofuels per unit of energy.

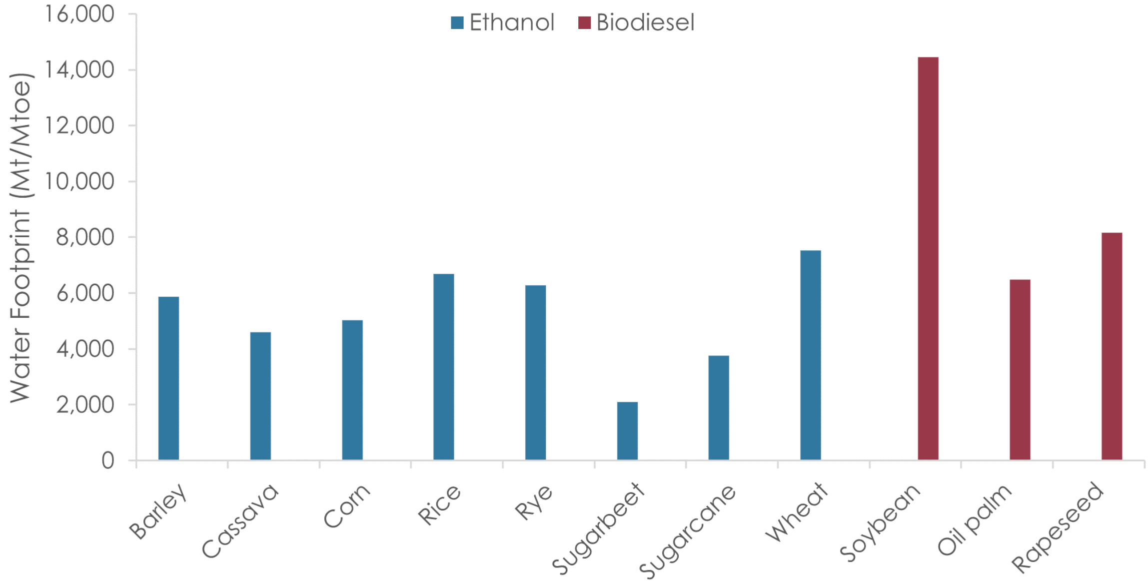


**Figure 15** **Global average water usage per Mtoe of output fuel for various bioethanol and biodiesel feedstocks**

*Note: This water footprint includes blue, green, and grey water demand. Overconsumption of any of these categories has biodiversity impacts, but it is generally the blue component that is of primary concern. See the original source for the break-down.*
*Source: Gerbens-Leenes (2018)*

In addition to water quantity, water quality is heavily impacted by biofuel crop production. Runoff from fertilisers and pesticides is a major contributor to inland and coastal water pollution, with serious implications for the ecology of waterways. Nutrient runoff, especially nitrogen and phosphorous, fuels eutrophication – a process that triggers harmful algal blooms in water bodies. These blooms not only block out sunlight needed by aquatic plants, but also deplete oxygen levels as they decompose, creating conditions unsuitable for most aquatic life. This oxygen depletion can lead to the formation of 'dead zones', areas that can no longer support fish, invertebrates, or plant life. A well-known example is the hypoxic zone in the Gulf of Mexico, which has suffered significant ecological damage due to nutrient pollution from agricultural runoff (Luna Juncal et al., 2023).

### *3.3.2. Second-generation crops and low-grade land*

Second-generation (2G) biofuel crops offer the potential for reduced ecological impacts compared with first-generation biofuels. 2G crops include perennial grasses like switchgrass and miscanthus, or short-rotation woody crops, all of which typically require fewer inputs than food crops and can contribute to improved soil health, water retention, and carbon sequestration (when established in an ecologically appropriate context). Dheri et al. (2022) demonstrated that perennial biofuel crops can increase SOC stocks and improve soil structure. Gelfand et al. (2013) highlighted the capacity of successional herbaceous vegetation on marginal land to mitigate GHG emissions, making them an attractive option for bioenergy production on low-grade lands. Stoof et al. (2015) reported that regions like the northeast USA have millions of hectares of marginal land available, with strong potential for bioenergy development without competing with prime arable lands.

However, challenges and uncertainties for the adoption of 2G crops remain, and the failure of cellulosic ethanol production targets in both the USA and Europe demonstrates that these systems continue to face significant barriers to large-scale viability. Past attempts to commercialise 2G crops have been hindered by economic and technological difficulties, and stalling momentum in the development of large-scale cellulosic biofuel facilities (Gomiero, 2018).

Some concerns related to biofuels, in particular regarding competition with food production, could be mitigated by promoting marginal land cropping models, and these have been central to policy discussions surrounding sustainable bioenergy production. Marginal lands, which are less agriculturally productive, are frequently portrayed as 'unused', 'underutilised', or 'available'. Muscat et al. (2022) cautions that such framing oversimplifies the complexities of competing land use claims: while using marginal land for biofuel production could avoid conflict with food production, there are ecological risks that must be carefully considered.

Khanna et al. (2021) argues that the definition and classification of marginal lands often does not fully account for the environmental and biodiversity outcomes. These lands often serve as habitat and refuges for wildlife or are part of larger ecological corridors, and may also support critical ecosystem services, such as soil erosion control, groundwater protection, and biodiversity enhancement (Burland & von Cossel, 2023). Some of these lands are fragile environments, vulnerable to soil degradation or habitat loss when improperly managed (Mehmood et al., 2017). As such, careful management approaches, such as biodiversity surveys and environmental impact assessments, are critical to ensure that biomass production on marginal lands does not harm local ecosystems and biodiversity.

As highlighted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), it is also worth pointing out that so-called marginal and unused lands may hold significant subsistence, economic, and cultural value for local and indigenous communities (Díaz et al., 2019). Land deemed unsuitable for large-scale agriculture or development still provides foraging grounds, grazing areas, medicinal plants, and other natural resources; indigenous peoples may have spiritual and cultural connections to their surrounding landscapes – landscapes which have already suffered degradation and destruction from development and agricultural clearance. To be considered sustainable, biofuel feedstock grown on marginal lands must be subject to consultations, impact assessments, and certification schemes which are sensitive to these issues.

# 4. Growing biofuel demand

## 4.1. Policy drivers in case study countries

This section outlines the biofuel policy landscape for each of the case study countries, focusing on targets and limitations for first-generation biofuels. Table 3 summarises the main policy drivers.

**Table 3 Major existing biofuel policies for case study countries, with emphasis on first-generation biofuels**

| Country | Major policy | Primary segments | Specified feedstock categories |
|---|---|---|---|
| USA | Renewable Fuel Standard (RFS) | Road | Corn ethanol, bio-based diesel, cellulosic fuel |
| | Tax credits | Road, aviation | Lipids |
| | State-level clean fuel standards (CFSs) | Road | Fuels judged on emissions intensity |
| Brazil | RenovaBio | Road | Fuels judged on emissions intensity |
| EU+UK | EU Renewable Energy Directive (RED III) | Road & rail, aviation, maritime | Food and feed crops, cellulosic crops and residues, lipid residues |
| | UK Renewable Transport Fuels Obligation (RTFO) | Road, aviation, maritime | Single-counted fuels, double-counted fuels, development fuels[25] |
| India | National Policy on Biofuels | Road | Purpose-grown crops, damaged crops, cellulosic |
| | Blending mandate | Aviation | None |
| Indonesia | Standard blend rates | Road | None |
| China | Tax incentives | Road | None |
| Argentina | Biofuels Law 27640 | Road | None |
| Canada | Clean Fuel Regulation | Road | Fuels judged on emissions intensity |
| Thailand | Alternative Energy Development Plan (AEDP) | Road, aviation | None |

*Note: This table shows policies which are already in place. Some initiatives which are at an early stage of discussion and/or enforcement will feature in the sections below.*

### *4.1.1. USA*

The primary national policy governing the use of biofuels in the USA is the Renewable Fuel Standard (RFS). Under the RFS, the EPA sets annual 'renewable volume obligations' – that is, designated volumes of biofuel that must be supplied each year (U.S. Environmental Protection

[25] Under the RTFO, single-counted fuels are largely first-generation crop-based biofuels. Double-counted fuels tend to be first-generation biofuels made from wastes and residues. Development fuels are second-generation biofuels and electrofuels.

Agency, 2023). The top-level obligation for ‘renewable fuel’ encompasses all biofuels meeting the eligibility criteria (e.g. minimum 20% GHG saving, no palm oil); for 2025 the obligation is to supply biofuel energy equivalent to 84.9 billion litres of ethanol. Within this overall target are sub-targets for biofuels made from feedstock other than corn, bio-based diesel (i.e. biodiesel and HVO/HEFA), and cellulosic biofuels (this obligation is mostly satisfied by biogas, which the EPA has categorised as a cellulosic fuel, and waivers). Recent supplied volumes and feedstocks are shown in Figure 16. Throughout most of the country, ethanol is blended into gasoline as ‘E10’[26].

In parallel with the RFS, states in the USA have established ‘low carbon fuel standards’ (LCFSs) – regulations that impose a declining benchmark for the average emissions intensity of fuel supplied to market. Emissions intensity reductions are delivered primarily by electrification and biofuels. The prime example is California’s LCFS, but systems are active in California, Oregon, and Washington. New Mexico has also authorised the creation of one; and other states have debated adopting one.

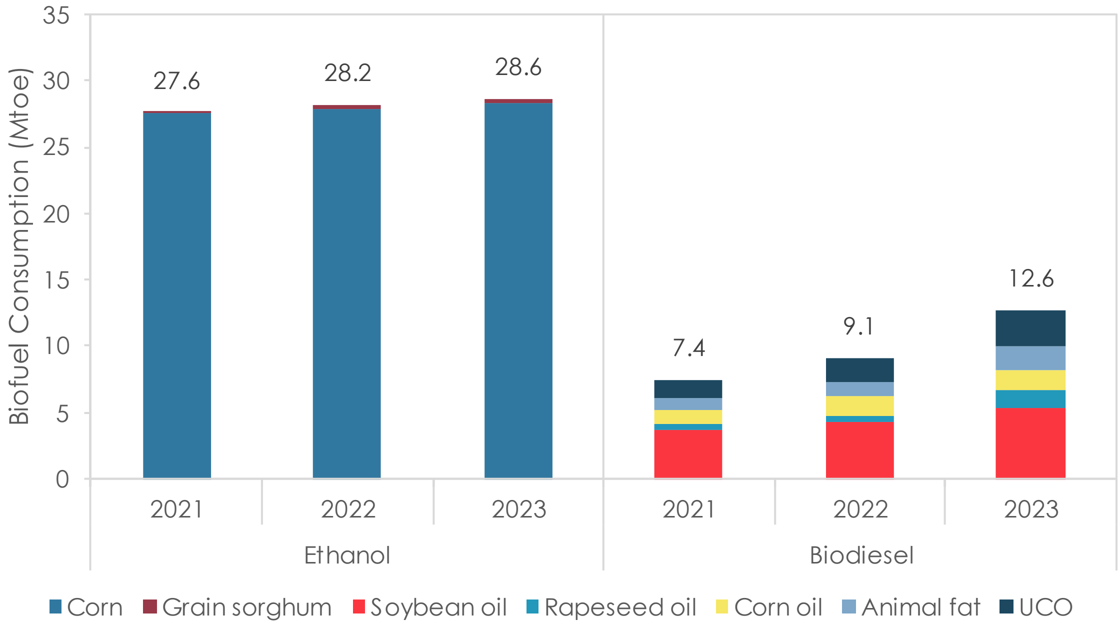


**Figure 16** **Consumption of biofuels in the USA by feedstock category, with total demand indicated**

*Note: As a reference point, gasoline consumption in 2022 was about 460 billion litres, or 350 Mtoe (U.S. Energy Information Administration, 2024c), and diesel consumption was 160 Mtoe (U.S. Energy Information Administration, 2023b).*
*Source: U.S. Energy Information Administration (2024a)*

[26] The E# indicate maximum volumetric shares of biofuel, so that E10 could designate an ethanol blend between 5% and 10%. In the USA case, the volumetric share of ethanol in gasoline is close to 10%.

Figure 16 shows that the vast majority of the USA's ethanol is made from corn –around 38% of the country's corn harvest ultimately goes into cars (U.S. Department of Agriculture, 2023)[27]. Soybean oil currently provides the greatest contribution to bio-based diesel feedstock, but the collection and import of residual and waste oils is growing to meet demand for low-carbon HVO, supported by the added value of low carbon intensities in state LCFSs (Gerveni et al., 2023; U.S. Energy Information Administration, 2024b). Both state and federal policies have sought to commercialise the cellulosic fuel industry, but poor policy design, technical challenges and competition from first generation fuels have stymied progress (Martin, 2024a, 2024b).

In future, unless the Federal Government adopts a higher standard ethanol blend than E10, the volume of ethanol consumed in the road sector will track demand for gasoline. Over the long term, that is likely to fall as the passenger vehicle fleet electrifies (cf. U.S. Energy Information Administration, 2023a); in 2030, we estimate ethanol consumption to be around 50 billion litres (25 Mtoe) in the road segment, down from 55 billion litres per year in the period 2021-23 (U.S. Energy Information Administration, 2024a). We note that this runs counter to recent EPA decision-making to increase RFS volumes over time (U.S. Environmental Protection Agency, 2023)[28]. To stabilise revenues in the face of electrification, the corn and ethanol industries are expected to pivot to production of aviation fuel using the 'alcohol-to-jet' (AtJ) process (recall Figure 2). As such, we shall assume that 2030 ethanol production experiences only a small reduction compared with its 2023 level[29].

Demand for lipid feedstocks is another story. Although diesel demand is falling gradually (U.S. Energy Information Administration, 2023a), meaning that biodiesel production is likely to stay around 6 Mtoe, HVO/HEFA production capacity is projected to surpass 26 billion litres (23 Mtoe) per year by 2030 (cCarbon, 2023; Gerveni et al., 2023). Some of this fuel may go to the aviation industry, as the U.S. Government's SAF Grand Challenge is targeting production of over 10 billion litres of alternative jet fuel – expected to be mostly HEFA – by 2030 (U.S. Department of Energy et al., 2022). In any case, since the supply of residual and waste oils is limited, much of the new feedstock will come from domestic and imported vegetable oil – mostly soy and canola (cf. Malins & Sandford, 2022).

### *4.1.2. Brazil*

Brazil is the second largest producer and consumer of biofuels in the world (Figure 8), ranking second in ethanol (after the USA) and third in biodiesel (after the USA and Indonesia). Since 2015, ethanol has provided 35-40% of energy in the road gasoline pool (Hayashi, 2024); as seen in Figure 17, this is split between ethanol blended with gasoline (for which the standard mix is E27[30]), and 100% ethanol used in flex-fuel vehicles (FFVs)[31], which are popular in Brazil. The share

[27] As discussed in Section 3.1.2, this corn does serve a dual purpose through the co-production of distillers' grains.

[28] Though we note that there is at the time of writing no visibility on where the EPA may set RFS obligations after 2025.

[29] The result of this assumption comes very close to the prediction of OECD (2024).

[30] The Brazilian Government is reviewing proposals to increase this to E30 (Mazzoni, 2024).

[31] Flex-fuel vehicles in Brazil are designed to run on any gasoline/ethanol mix, differing from US flex fuel vehicles which run on a maximum E85 blend.

 

of diesel-pool energy provided by biodiesel has risen steadily from 6% in 2015 to 11% in 2023. The standard biodiesel blend was set at B13 for 2023 and is scheduled to rise to B15 in 2025 (Hayashi, 2024).

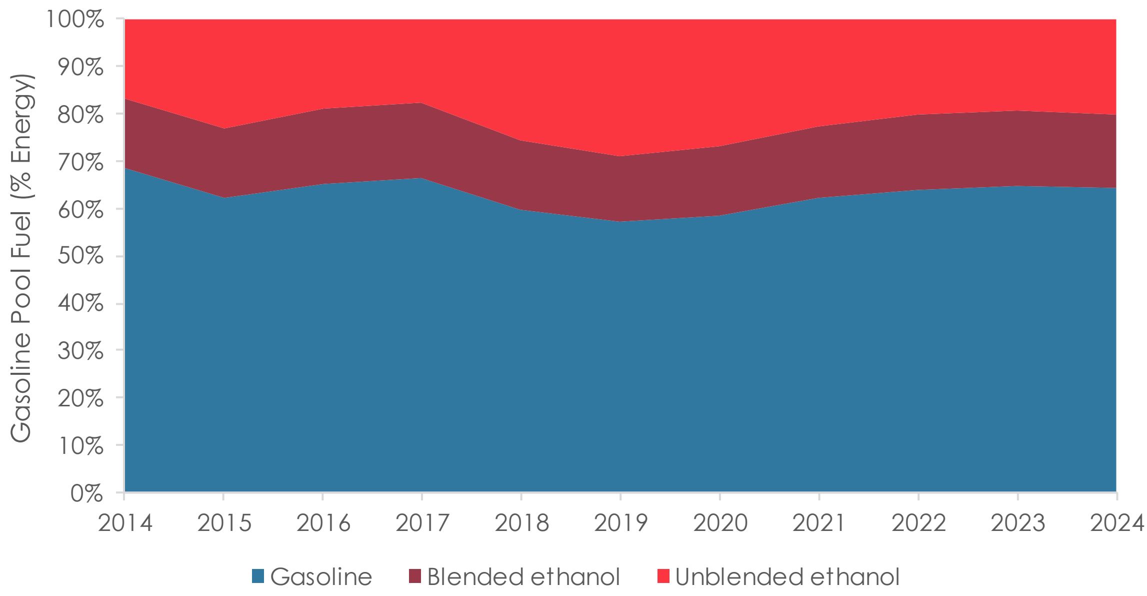


**Figure 17** **Historical share of Brazil's gasoline-pool energy consumption by fuel**

*Note: 2024 data is a forecast.*
*Source: Hayashi (2024)*

The majority of ethanol consumed in Brazil is produced from domestically-grown sugarcane: in 2023, 333 sugarcane-only and 17 sugarcane + corn plants produced ethanol from 326 Mt of sugarcane and 13 Mt of corn (Hayashi, 2024). This feedstock consumption represented about 50% of Brazil's domestic sugarcane and 10% of its corn crop (FAOstat, 2024). On biodiesel, 70-77% is made from soybean oil: in 2023 this came to 5.6 Mt, consuming about 45% of Brazil's domestic production (FAOstat, 2024; Hayashi, 2024). Around 700 kt per year of residual animal fat from Brazil's sizeable livestock industry is also used.

Since 2017, Brazil's primary policy for driving biofuel use has been RenovaBio. RenovaBio sets annual emissions reduction targets for each fuel distributor: in 2024, a total of 38.8 $MtCO_2e$ reductions will be required, with the three largest fuel suppliers, Vibra Energia, Raizen, and Ipiranga, having to redeem 9.5, 7.0, and 7.0 $MtCO_2e$-worth of emissions reduction certificates, called CBios (Agência Nacional do Petróleo Gás Natural e Biocombustíveis, 2024). CBios are issued to approved biofuel producers based on the reportable lifecycle emissions reduction compared to the equivalent fossil fuel[32]; the CBios can then be sold to fuel distributors with unmet RenovaBio obligations. Credit prices are currently in the region 100-110 BRL (20-22 USD) per $tCO_2e$ (Mazzoni, 2024).

[32] Biofuel production facilities are assigned lifecycle greenhouse gas emissions intensity scores using the RenovaCalc tool. The state-owned Brazilian Agricultural Research Corporation (Embrapa) conducts these assessments, which also include certification that feedstock production complies with Brazil's Forest Code.

Looking ahead, RenovaBio's 2030 target is for a 64.0 $MtCO_2e$ emissions reduction (Hayashi, 2024). A back-of-the-envelope calculation[33] suggests that this would require another 12 Mtoe of fuel supply in the year 2030, and nearly 21 Mha to grow the required sugarcane, maize, and soybeans[34]. Brazil does have a modest cellulosic biofuel industry, but it is currently export-oriented to take advantage of generous policy support in the USA and Europe.

In the aviation sector, biojet is eligible to generate CBios, and Brazil is starting to adopt policies to encourage the use of alternative fuels. A 2023 bill (Government of Brazil, 2023) commits to reducing the emissions intensity of domestic aviation by 1% per year starting in 2027, up to 10% in 2037. There is considerable interest in operationalising Brazil's existing biofuel industries to produce HEFA and AtJ aviation fuels (World Economic Forum, 2023). To achieve a 3% reduction in emissions intensity in 2030 would require substituting about 4% of fossil jet fuel with biofuel[35]. Taking a conservative estimate of 5 billion litres of fuel consumed by domestic aviation (Emboaba Moreira et al., 2018), Brazil would need 200 million litres of HEFA/AtJ to hit the 2030 target. This could be achieved by shifting some biofuel supply from the road sector, but it remains to be seen whether the construction and conversion of biofuel production facilities can keep pace with the transition. For reference, the IEA's 2023 'accelerated scenario' projects 142 million litres of biojet produced per year in Brazil in 2028 (IEA, 2024a).

### *4.1.3. EU+UK*

We shall first address EU biofuel policies before turning to the UK. Table 4 summarises the key components of the EU framework, the central pillar of which is the Renewable Energy Directive (RED) which establishes requirements for alternative energy in transport. The latest iteration, RED III (European Union, 2023c), allows EU Member States to aim their national policies towards meeting an energy target (in which case 29% of transport energy is required to be from renewable sources in 2030), or a greenhouse gas emissions intensity target (in which case a 14.5% reduction in emissions intensity compared to a fossil fuel baseline is required). See Baldino (2023) for a thorough discussion of RED III's features.

[33] Assuming ongoing improvement to biofuels' emissions intensity scores (an 8% improvement over seven years), and an expansion of Brazil's biofuels industry which is weighted 70:30 towards ethanol (IEA, 2022).

[34] For scale, the combined harvest area for these two crops was 72 Mha in 2022 (FAOstat, 2024).

[35] Assuming a 60-80% emissions saving for the biofuels, cf. (ICAO, 2021).

 

**Table 4 Key EU policies which support biofuel consumption**

| Policy | Regulated Party | Description |
|---|---|---|
| **Renewable Energy Directive (RED III)** (European Union, 2023c) | Member States[36] | Sets targets for the use of alternative fuels in all forms of EU transport and establishes sustainability criteria for the kinds of fuels that can contribute. Includes sub-targets for the use of 2G biofuels and electro-fuels. |
| **Emissions Trading Scheme (ETS)** (European Union, 2023a) | Fuel consumers | A cap-and-trade system where companies in designated sectors trade emissions allowances. Currently covers intra-EEA flights only, but this may be extended to cover international aviation and shipping (subject to a 2026 review). Biofuels' combustion emissions are counted as zero. |
| **ReFuelEU Aviation Regulation** (European Union, 2023b) | Fuel suppliers | Mandates minimum shares of alternative fuels to be used in EU airports, with a sub-target for electrofuels. Biofuels made from cellulosic crops, intermediate oilseeds, residual lipids, and other wastes and residues can contribute. |
| **FuelEU Maritime Regulation** (European Union, 2023d) | Fuel consumers | Mandates reductions in emissions intensity for operators of maritime transport arriving or departing EU ports. Compliance options include electricity, wind, biofuels, electrofuels, and fossil-derived fuels like LNG. Eligible biofuel feedstocks include cellulosic crops, intermediate oilseeds, and residual lipids. |

Since the first RED in 2009 (European Union, 2009), sustainability governance has been gradually strengthened, with limits placed on the contribution of biofuels made from 'food and feed' crops[37], and a phase-out by 2030 scheduled for 'high ILUC-risk' crops[38]. The RED III sets a sub-target for the use of advanced biofuels including cellulosic fuels, and several mechanisms exist to support the development of advanced biofuel technology – these include financing and technical development through Horizon Europe, the Innovation Fund, the InvestEU Biofuels Framework, the EU SAF Clearing House, and the Net Zero Industry Act. Nevertheless, to date the EU biofuel market has been dominated by first-generation fuels, though with a significant contribution from waste and residual feedstocks such as used cooking oil and low-grade animal fat. Figure 18 shows the historical feedstock mix.

[36] EU directives place obligations on EU Member States to enact national legislation that codifies the directive's goals, and to report progress to the European Commission. In practice, the RED will often translate to obligations on fuel suppliers in each Member State.

[37] More specifically, the language in RED III (European Union, 2023c) stipulates that the energy share of food and feed crops in each Member State should be no more than 1 percentage point higher than its share in 2020, capped at a maximum of 7%. Further analysis is presented in Table 6.

[38] Currently, the category of high ILUC-risk crops consists of palm oil only. Producers of palm oil and biofuels made therefrom may seek an exemption from the phase out through the 'low ILUC-risk' certification process (Sandford et al., 2024).

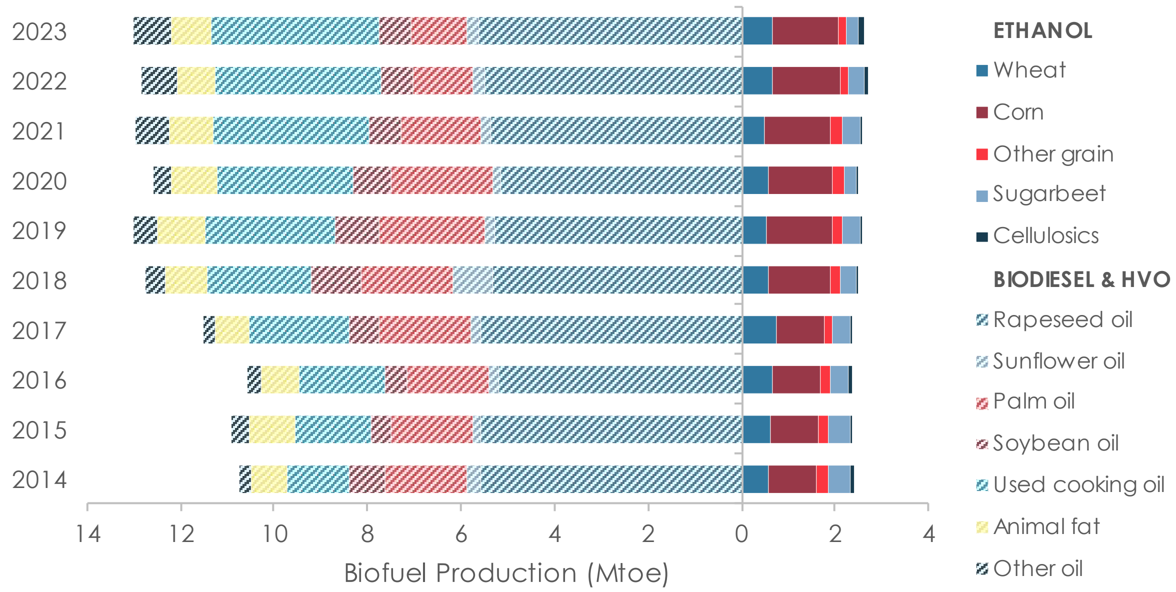


**Figure 18** **Estimated EU production of biodiesel and HVO (represented left of zero, hatched bars) and fuel ethanol (right of zero, solid bars), distinguished by feedstock**

*Note: HVO includes lipid-based HEFA for aviation applications.*
*Source: Adapted from Flach et al. (2023)*

Looking to 2030, the OECD projects 2.6 Mtoe of first-generation ethanol consumption, and 9.1 Mtoe of bio-based diesel made from virgin vegetable oil (OECD, 2024)[39]. Demand for first-generation crop biofuels – that is, those based on 'food and feed' feedstocks – will be limited by the RED III food and feed cap (Footnote 37). One exception to this cap is oilseeds grown as intermediate crops, which may simultaneously be able contribute to ReFuelEU Aviation or FuelEU Maritime targets; but given that the relevant crops, rotations, farm management strategies, and certification systems are still in research phase at present, a significant boom in production by 2030 would come as a surprise.

For 1G ethanol, both the level of consumption and the slate of feedstocks in 2030 as foreseen by OECD (2024) lie fairly close to those reported in 2023. For biodiesel & HVO, we note that consumption of 'high ILUC-risk' palm oil will be eliminated by 2030, and its contribution replaced by some other feedstock. Growth in the supply of residual oils (UCO and low-grade animal fat) may be moderated by increasing international competition for low-carbon feedstocks; but as we expect the EU to continue being an attractive export market, the absolute and relative contribution of these feedstocks to the biofuel pool continues to grow.

[39] A gradual decrease in biodiesel demand is likely to be counteracted by increasing HVO/HEFA demand.

Combining our estimates for ethanol and lipid-based biofuel, we calculate the contribution that 1G biofuels[40] make to the EU's energy mix in Table 5. Our demand projection satisfies the constraints on the food and feed share (calculated by dividing the energy contribution from food and feed biofuels by the total transport sector energy consumption in 2020), which cannot increase by more than 1% for each Member State. We note from the table that in 2030, food and feed crops comprise 3.6% of physical transport energy and 1G biofuels comprise 5.1%.

**Table 5** **Recorded and projected EU-27 production of food and feed biofuels and first-generation biofuels**

| Quantity | Unit | 2020 | 2030 | Note |
|---|---|---|---|---|
| Transport energy | Mtoe | 251 | 324 | 2020 from Eurostat (2024)<br>2030 from European Commission (2020) |
| Food and feed biofuels energy | | 11.2 | 11.7 | 2020 calculated from Flach et al. (2023)<br>2030 our projection |
| 1G biofuels energy | | 15.1 | 16.4 | |
| Food and feed biofuels share | % | 3.6% | 3.6% | Percentage of total transport energy in the given year |
| 1G biofuels share | | 4.9% | 5.1% | |

As already mentioned, RED III created a legally binding sub-target for 2.25% of the EU's physical transport energy to be made from 'advanced' biofuels[41]. For the purpose of this report, we assume that 1% will be based on cellulose derived from energy crops and the remaining 1.25% will be made from other 'advanced' feedstocks (see RED Annex IX Part A), including residues and wastes from agriculture, forestry, industry, and residential/commercial buildings. On this basis the EU would consume over 3 Mtoe of cellulosic-crop-based biofuels in 2030. In this report, we do not calculate any land demand or land use change emissions associated with the use of the waste and residual feedstocks from Annex IX Part A, (and fuels from those feedstocks are not included in the results in Table 9).

Discounting the potential indirect impacts of waste and residue consumption is a simplification adopted by many analyses, but it should be noted that in reality many of these feedstocks are associated with at least some land demand and or indirect emissions due to displacement from existing uses. The use of crude tall oil, for example, has been implicated in causing significant displacement emissions because it is already a fully utilised resource (Pavlenko & Searle, 2020), while concerns have been raised about potential mislabelling fraud in the supply chain for oil recovered from palm oil mill effluent, and the risk that batches of virgin palm oil are being labelled as residual oil (Flynn, 2024). There is also a bigger-picture caveat that the EU's sub-target for advanced biofuels is ambitious, and it is far from certain that the requisite biofuel production capacity and feedstock collection systems will be developed by 2030[42].

[40] As a reminder, '1G biofuels' includes both food and feed biofuels and first-generation biofuels made from wastes and residues like UCO and low-grade animal fat.

[41] More accurately, the obligation is for at least 5.5% to be made from advanced biofuels and fuels derived from green hydrogen. Of this, at least 1% must be the latter. The remaining 4.5% (or less) is 'double-counted', so at most 2.25% of physical energy must be advanced biofuels.

[42] It's worth noting in this regard that the RED II has already imposed binding intermediate sub-targets for the use of advanced biofuels, reaching 0.2% in 2022 and 1% in 2025 (double-counted). The 2022 target was not met by all EU Member States.

The UK was party to the original RED in 2009; since voting to leave the EU in 2016 its policy landscape has been able to develop independently, though it is still bound by legacy policy provisions, strong trade ties, and common standards for goods and services. The UK's Renewable Transport Fuels Obligation (RTFO), first introduced in 2008, places a requirement on petrol and diesel suppliers (but not suppliers of aviation and marine bunker fuels) to include a minimum share of liquid renewable fuels in their product, or buy surplus renewable fuel certificates from another operator. Reported 2023 fuel consumption is shown in Figure 19.

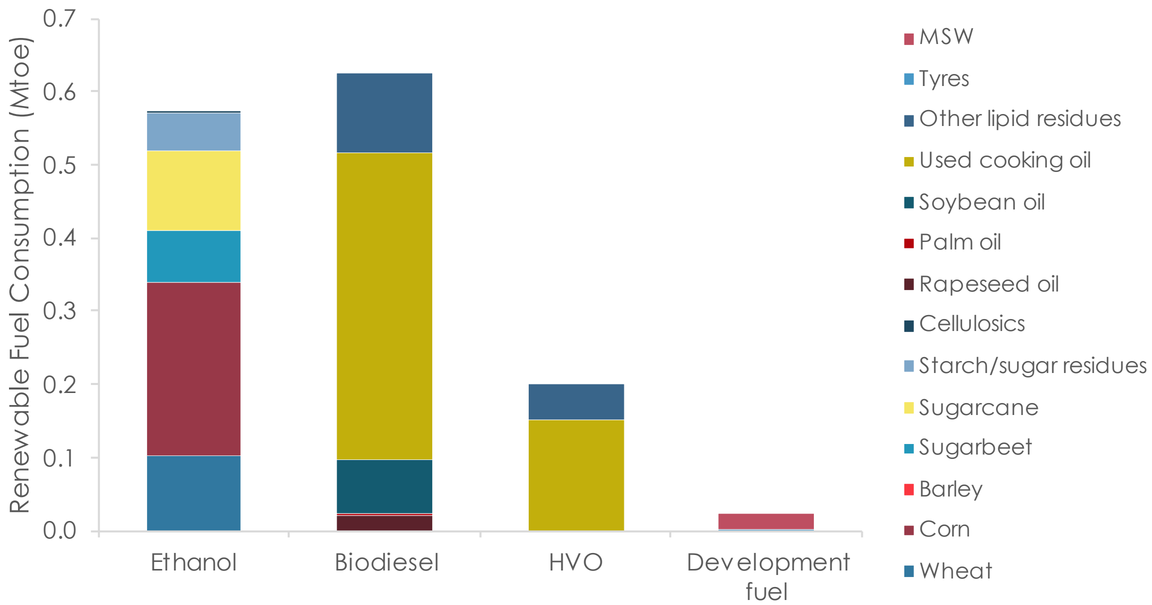


**Figure 19 UK renewable fuel consumption in 2023, split by feedstock**

*Note: The HVO category also includes lipid-based HEFA for aviation applications. MSW stands for municipal solid waste.*
*Source: UK Department for Transport (2024c)*

The 2023 obligation is set to 11.45% of obligated fuel by volume, increasing to 13.90% in 2030 (UK Department for Transport, 2023b). Fuels made from qualifying residues and wastes can be double-counted towards these targets, as can certain lignocellulosic crops; UK Department for Transport (2024d) lists the eligible feedstocks. In addition, there is a sub-mandate to incentivise production and supply of 'development fuels' (loosely speaking, these are second-generation biofuels and fuels made from renewables-based hydrogen); this sub-mandate is nominally 2.4% of fuel volume in 2030, which translates to 1.2% of physical fuel volume after correcting for double-counting (UK Department for Transport, 2021). Given that the 26.2 million physical litres of development fuel supplied in 2023 amounted to only 0.07% of road sector fuel consumption, reaching the UK Government's target will be challenging (UK Department for Energy Security and Net Zero, 2023b; UK Department for Transport, 2024c).

In parallel with the RTFO, the UK Government has developed its 'Sustainable Aviation Fuel Mandate' (UK Department for Transport, 2024a), which from 2025 will require airport fuel suppliers to blend an increasing share of alternative fuel. Table 6 shows how the Mandate is set to evolve, alongside its cap on lipid-based HEFA and the sub-mandate on 'power-to-liquid' (PtL) fuels. Eligible biofuels must be made from wastes and residues; we can therefore expect feedstocks like used cooking oil to be diverted into aviation biofuel production, potentially increasing demand for crop-based fuels in the road sector (Sandford & Malins, 2024).

**Table 6 Regulatory fuel volumes[43] required by the UK SAF Mandate, as a percentage of total aviation fuel consumption and ktoe**

| SAF Mandate Target | Unit | 2025 | 2030 | 2035 | 2040 |
|---|---|---|---|---|---|
| Main obligation | % | 2.0% | 10.0% | 15.0% | 22.0% |
| | ktoe | 225 | 1,238 | 1,918 | 2,918 |
| HEFA cap | % | 2.0% | 7.1% | 7.8% | 7.8% |
| | ktoe | 225 | 860 | 976 | 1,012 |
| PtL obligation | % | 0.0% | 0.5% | 1.5% | 3.5% |
| | ktoe | 0 | 58 | 166 | 360 |

*Note: We translate the regulation-defined percentages in this table into fuel volumes using a governmental demand projection which assumes sectoral growth (UK Department for Transport, 2024b).*

Starting with UK Government's sectoral energy demand projections (UK Department for Energy Security and Net Zero, 2023a), and assuming the split between petrol and diesel continues to follow recent trends (UK Department for Energy Security and Net Zero, 2023b), we estimate ethanol and biodiesel demand in 2030 based on E10 and B3 average blends. We assume that any PtL fuel available to the UK market will go towards fulfilling the SAF Mandate (cf. Sandford & Malins, 2024), meaning that the RTFO development fuel target will have to be met with cellulosic biofuel[44]. Based on the current feedstock mix, we treat cellulosic feedstocks as purely based on residues and wastes, with no contribution from biomass crops.

Once petrol hits the wall for ethanol blending, it makes sense to satisfy that the remainder of the RTFO target with drop-in 1G HVO. Currently, HVO consumed in the UK is made from residual oils (Figure 19); but, following demand modelling in Sandford & Malins (2024), pretty much all of this feedstock will likely be diverted to aviation, even accounting for growth in availability by 2030. Thus, the additional pressure to supply road HVO will translate into additional demand for virgin vegetable oils. Based on current demand patterns, we would estimate that lipids for the road segment will be 40% rapeseed, 56% soy, and 6% residual oils.

### *4.1.4. Indonesia*

Palm-based biodiesel dominates Indonesia's biofuel landscape, and standard road diesel is now a 35% biodiesel blend – up from 20% in 2018 – leading to an estimated 13 billion litres of consumption in 2023 (Rahmanulloh, 2023). Consumption of biodiesel is supported through cross-subsidies from taxation of palm oil exports. The Government of Indonesia has committed to raising the blending rate to B40 (Biofuels International, 2024; Christina, 2024b), and there are

[43] The SAF Mandate mechanism rewards fuels with lower lifecycle emissions intensity using weighting factors. This means that one physical unit of fuel may contribute more or less than one unit to targets for regulatory purposes.

[44] There is a strong possibility that the development fuel target will be missed, with fuel suppliers 'buying out' of their obligation in lieu of providing compliant fuel. Thus it is very reasonable to assume that there will not be surplus cellulosic or waste-based fuel to bring down the overall obligation.

reportedly plans to go up to B50 (Christina, 2024c; The Star, 2024). But overall consumption is limited by diesel-pool demand, as diesel engines account for only 13% of passenger cars and trucks (IEA, 2021b), and the most popular mode of transport is two-wheelers running on petrol[45]. This constraint on the use of palm oil contextualises the Government's announcement of an action plan for mandating biofuel use in flights departing from the country (Giam, 2024). The reported aim is for the blending rate to reach 2.5% in 2030 and 30% in 2050.

Indonesia is a major exporter of palm oil, but it exports comparatively little of its palm-based biodiesel, as seen in Figure 20. Analysts anticipate that elevated blending rates at home will cut into Indonesia's palm exports (Azhar & Tang, 2024; Jadhav, 2024). Palm farmers must be certified under ISPO and may voluntarily undertake further certification (from RSPO or ISCC, for example) to meet a higher level of sustainability assurance to access other markets. However, there is no obligation for palm oil mills or biodiesel producers to meet any form of sustainability certification, including any minimum GHG reduction threshold.

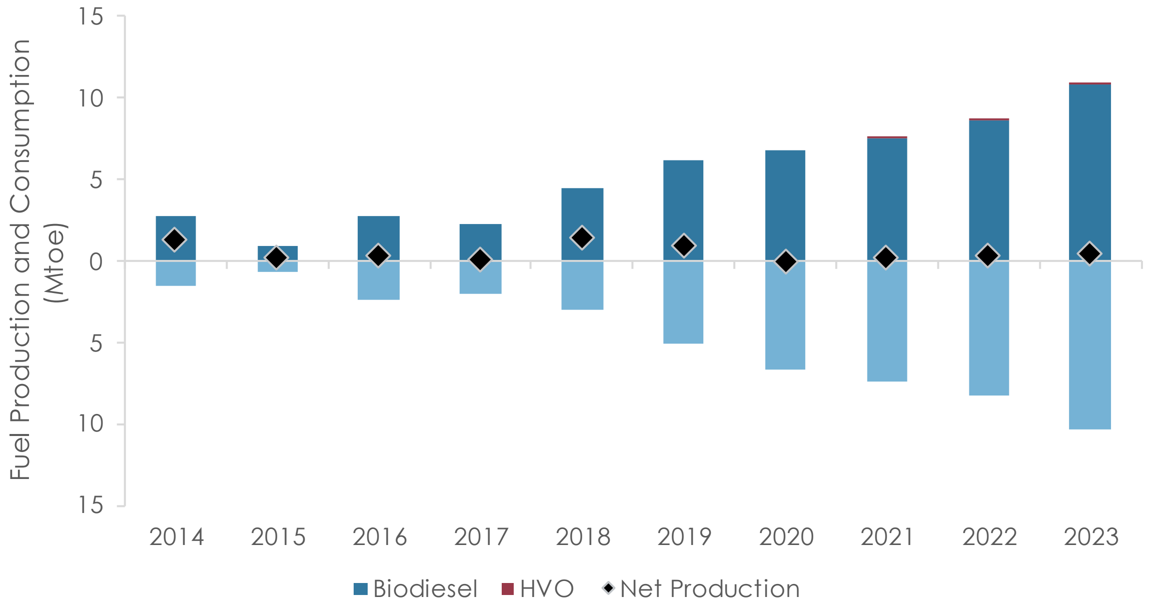


**Figure 20** **Production (above-axis, darker colour) and consumption (below-axis, lighter colour) of lipid-based biofuel in Indonesia**

*Note: HVO production, which began in 2021, remains small compared to biodiesel.*
*Source: Rahmanulloh (2023)*

Aside from biodiesel and HVO, a 2017 regulation called for a 20% blend of ethanol into petrol and a 5% blend of alternative aviation fuel by 2025 (Government of Indonesia, 2017). There is little prospect of meeting these targets given that consumption of both fuels was practically zero in 2023. Historically, nominal biofuel targets for Indonesia have not been met without an

[45] Around 125 million motorbikes were in use in 2022, and nearly 6.5 million were sold in 2023 (ASEANstats, 2024; Waterworth, 2023). Incidentally, in 2017 the Government of Indonesia adopted a target to get 2.1 million electric motorbikes on the road by 2025 (Mahalana & Yang, 2021); in light of lacklustre sales, the Government announced a subsidy scheme to get 1 million electric motorbikes on the road in 2024 (Kurniawati et al., 2023; Nangoy & Christina, 2023).

associated funding mechanism. Still, the Government of Indonesia is attempting to invigorate the country's sugarcane ethanol industry with a target to increase production from 215 million to 1.2 billion litres by 2030; some of this may be used in the transport sector in pursuit of the earlier E5 target (Rahmanulloh, 2023).

To support its plan to be self-sufficient in sugar by 2027, the Government of Indonesia has plans to develop up to 2 million hectares of sugar plantations in the Papua region (Christina, 2024a), but recent reports indicate that 30% of concession areas overlap with areas designated for protection (Jong, 2024). Additionally, the project risks undermining the rights of Indigenous Papuans, who rely on the land for traditional livelihoods. This underscores the tension between biofuel expansion and social and environmental safeguards within Indonesia's policy landscape (cf. the end of Section 3.3.2).

Projections by the IEA suggest a 15% increase in transport fuel demand over the period 2023 to 2028 (IEA, 2024b). Assuming a fixed export share[46] and a B40 blend rate, production of biodiesel and HVO would reach around 17.6 billion litres in 2030, requiring over 16 Mt of (presumably) palm oil. On the ethanol side, if Indonesia achieves a 1% blend the country will require about 430 million litres of ethanol made from 1.8 Mt of sugarcane molasses. Assuming the alternative aviation fuel target is enacted in law, there will also be around 0.2 Mtoe of palm-based HEFA demand in 2030.

### *4.1.5. China*

In 2024, China's biofuel industry is expected to produce 4.9 billion litres of ethanol, 2.9 billion litres of biodiesel, and 0.9 billion litres of HVO (Demoss, 2024); in energy terms, this equates to about 2.5 Mtoe, 2.3 Mtoe, and 0.8 Mtoe respectively. USDA reports that ethanol production is primarily motivated by agricultural surpluses of corn, rice, and cassava (Demoss, 2024); as such, the Chinese Government has not set longer-term targets to expand feedstock availability or production, and has withdrawn subsidies for food-based ethanol production (F. Li & Fan, 2023). Ethanol production has nevertheless kept pace with rising petrol demand in recent years, maintaining a national blend rate around 2% by volume (though consumption is concentrated in certain target areas rather than throughout the country).

The situation is somewhat different for biodiesel and HVO, which are reportedly made almost exclusively from UCO (note that China is a net importer of vegetable oils). The majority of this biofuel is exported, due in part to the Chinese Government's generous tax rebate on biodiesel exports, and in part to the incentives for UCO biodiesel under the EU's Renewable Energy Directive[47]. Domestically, the primary use of biodiesel is for non-road applications like stationary generators, fishing boats, and farm equipment (F. Li & Fan, 2023). Figure 21 shows that the consumption of UCO for fuel production has grown rapidly in recent years. Propelled by growing domestic and international demand, it is reasonable to expect that the industry will continue expanding: F. Li & Fan (2023) report 3.4 billion litres of new capacity in the planning pipeline.

[46] Though in the past, Indonesia has prioritised domestic biofuel consumption over the export market (cf. recent decisions reported in Jadhav (2024)).

[47] Over 92% of UCO biodiesel exports went to the EU (F. Li & Fan, 2023).

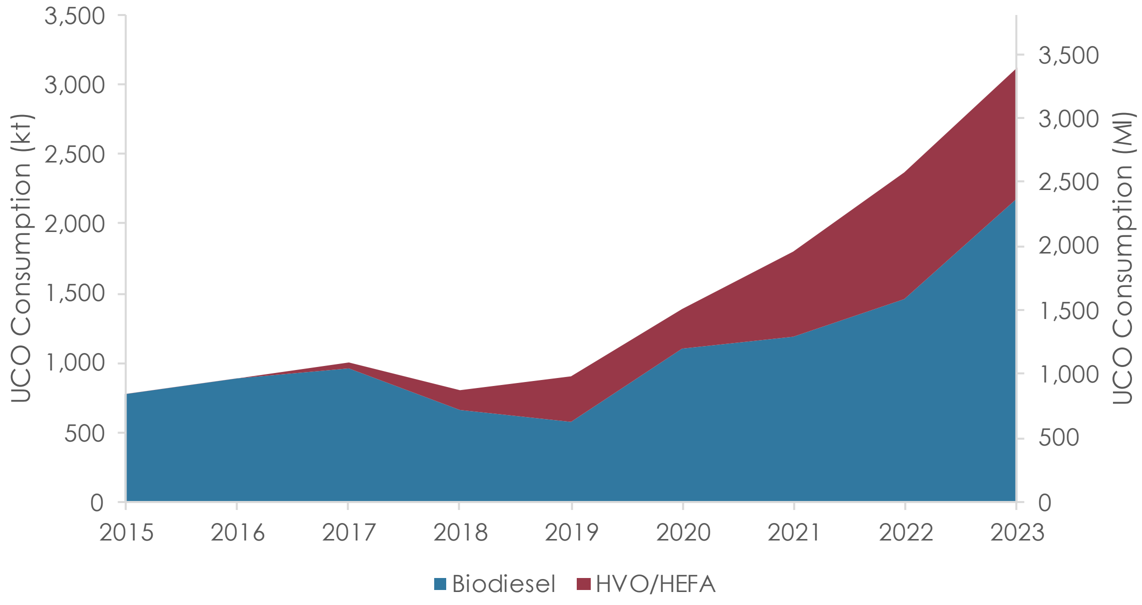


**Figure 21** **Reported consumption of used cooking oil (UCO) for biodiesel production in China, split by fuel**

*Note: This includes UCO-based fuel for export. As mentioned below, there are doubts over the genuineness of UCO exported from China.*
*Source: Demoss (2024)*

Demoss (2024) states that China does not enforce environmental safeguards or minimum GHG savings thresholds for biofuels (though exported fuel must comply with the regulations of the destination market). In recent years, concerns about fraudulent mis-labelling of virgin palm oil as UCO have been raised in the EU and the USA (Douglas, 2024; Suzan, 2023), and some Chinese producers have been suspended by certification bodies (ISCC, 2023). The USDA, however, reports that current produced volumes are consistent with rates of collection and that there is still potential to increase collection from 5.2 billion litres today (of which around 3 billion litres are used for fuel production) to 11 billion litres (Demoss, 2024).

Domestically, the Civil Aviation Administration China (CAAC) has targeted at least 50 kt cumulative consumption of alternative aviation fuel by 2025 (Ding et al., 2024; S. Li, 2024), with a 5% blend for domestic and international flights (about 3 Mt of fuel) considered a possibility in 2030 (Guo et al., 2023; S. Li, 2024). This, on top of the sizeable anticipated international demand for UCO-based aviation fuel, has encouraged production capacity to reach 0.4 Mt/year (S. Li, 2024), with a further 3.5 Mt/year announced or under construction (Demoss, 2024), and nearly 2 Mt/year that could be switched from road HVO to aviation HEFA (Guo et al., 2023)[48].

We estimate 2030 biofuel feedstock consumption in Table 7, assuming that there are no major shifts in domestic ethanol blend rates and no ethanol export market develops. We assume that efforts to alleviate fraud and dumping concerns in overseas markets are successful, such that

[48] Refineries produce a slate of fuel molecules; a facility optimised for aviation fuel may only produce 70% aviation-grade fuel, with the remainder appropriate for use in the road sector.

 

export volumes of lipid-based biofuels continue to grow. In our calculation, production roughly doubles from its 2024 level, tracking baseline trends for biodiesel and road HVO, and expanding to meet domestic and international aviation HEFA demand.

**Table 7 Estimates of feedstock consumption by the Chinese biofuel industry**

| Fuel | Feedstocks | Feedstock consumption (Mt) | |
|---|---|---|---|
| | | Estimated 2024 | Projected 2030 |
| **Ethanol** | Corn, rice, cassava, wheat | 12 | 15 |
| **Biodiesel, HVO, HEFA** | UCO, palm oil | 3 | 6 |

### *4.1.6. India*

India is the world's third largest producer and consumer of ethanol (Moorhouse & Gupta, 2024), and has spearheaded the formation of the GBA (Section 1.3). The 2009 National Policy on Biofuels emphasised the use of only non-food feedstocks (Shinoj et al., 2011) with updates in 2018 and 2022 that saw the Government of India seeking to increase consumption of a wider variety of domestically-produced biofuels. This is evident from the feedstock consumption in Figure 22 (cf. Business Standard, 2024; G, 2024). The Policy establishes technical standards for biofuel, government-guaranteed offtake prices (Indian Ministry of Petroleum and Natural Gas, 2022a), and financial support (called viability gap funding) available for building of new facilities and upgrading of existing ones[49]. On consumption, the Government is encouraging car makers to bring flex-fuel vehicles (FFVs) to the market (Sandil, 2024), and has lowered sales tax on biofuel (Indian Ministry of Petroleum and Natural Gas, 2022a, 2023).

[49] For instance, a scheme for setting up 2G ethanol plants (Indian Ministry of Petroleum and Natural Gas, 2022b).

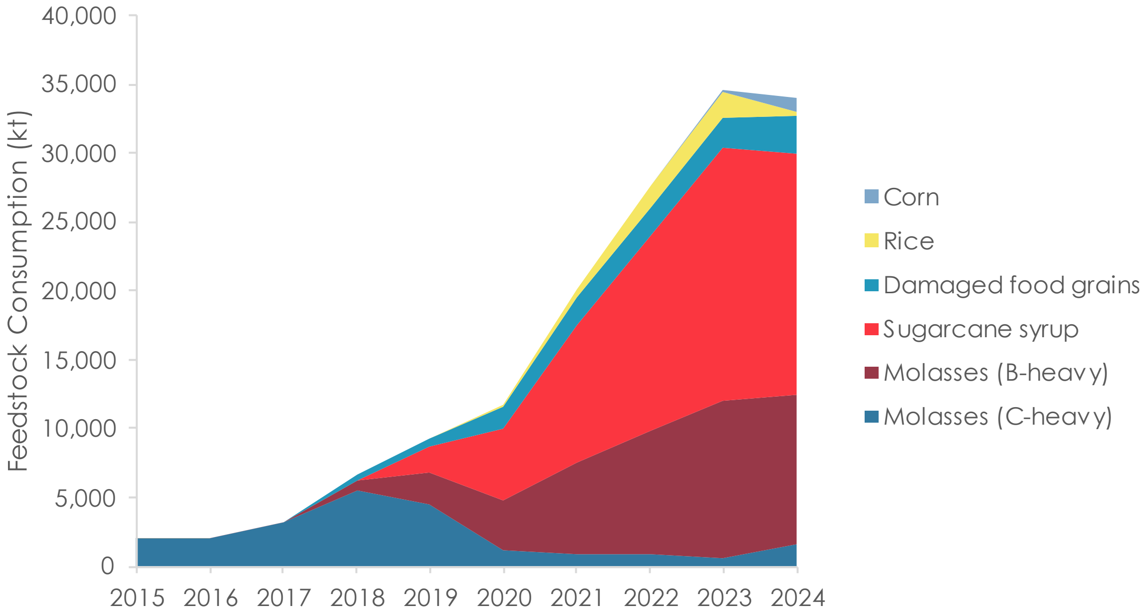


**Figure 22 Feedstock demand for fuel ethanol consumed in India**

*Note: Sugarcane syrup and the two grades of molasses are all made from sugarcane.*
*Source: Das (2024)*

The National Biofuels Policy established targets for a 20% blend of ethanol in road petrol in 2025 (brought forward from the original target year of 2030), and a 5% blend of biodiesel in road diesel. Blends in 2023 were 11.5% and 0.2% respectively (Das, 2024), so a considerable ramp-up of feedstock production and fuel production capacity would be needed to achieve the targets. This echoes past experience of India's nominal biofuel policy objectives being delayed or scrapped – for instance the original 20% ethanol blending target set for 2017 (Aradhey, 2015). Adverse weather conditions and insect damage in 2023 blighted the sugarcane from which nearly 90% of fuel ethanol is produced (Figure 22), and it may take time for crop availability to recover[50]. Hitting the 2025 ethanol target would require many millions of tonnes of feedstock (see Table 8) and at least 7 million hectares of cropland (Das, 2024).

India is a net importer of vegetable oil. The major lipid feedstocks used to produce biodiesel are imported palm oil and domestic UCO (Jamal, 2023). Combined consumption of these resources came to about 200 kt in 2023; but to hit India's 5% blending target for 2030, consumption will have to increase more than 20-fold to 4.4 Mt (Table 8). At the same time, demand for alternative aviation fuel would need to rise to deliver the National Biofuel Coordination Committee's mandated blend of 1% alternative fuel for international flights[51] by the year 2027-28, 2% by 2028-29, and 5% by 2029-30. Globally, the most mature aviation biofuel technology is lipid-based HEFA, but India's existing ethanol industry positions it for production

[50] In response, the Government of India has put measures in place to restrict sugar exports; but, conscious of impacts on food prices, it has also capped the use of sugarcane for ethanol production. India's increasing use of maize for ethanol production is also reported to be distorting the food market.

[51] International flights comprised 25% of India's 8.4 Mt jet fuel consumption in 2023-24 (Ramakrishna Y B, 2024).

 

of AtJ fuel and commercial-scale plants are already under development (Ramakrishna Y B, 2024)[52].

**Table 8 Annual fuel and feedstock demand implied by India's biofuel blending targets**

| Fuel | Blend | Fuel (billion litres) | Feedstock (Mt) | Major feedstocks |
|---|---|---|---|---|
| Ethanol | 20% in 2025 | 10.2 | 37.4 | Sugarcane (DM) |
| Biodiesel | 5% in 2030 | 4.5 | 4.4 | Palm oil and UCO |
| Biojet | 5% international fuel in 2030 | 0.2 | 0.1 | Palm oil and UCO |
| | | | 0.5 | Sugarcane (DM) |

*Note: We assume a 50:50 split in the contribution of HEFA and first-generation AtJ fuel for meeting the 2030 aviation target. We assume a 10% CAGR of international flights from India from 2023 to 2030. 'DM' denotes dry mass.*

### *4.1.7. Argentina*

Argentina's biofuel industry is driven by policies aimed at balancing domestic energy security, export opportunities, and environmental commitments (Mercatante, 2024; Timilsina et al., 2013). Biodiesel in Argentina is made from soybeans, and ethanol from a mix of corn and molasses. The 2021 Biofuels Law (Government of Argentina, 2021) set a minimum biodiesel blend of 5% (B5), which was raised to 7.5% in a 2022 resolution (Joseph, 2024). For ethanol, the blend is set at E12. Annual averages are shown in Figure 23.

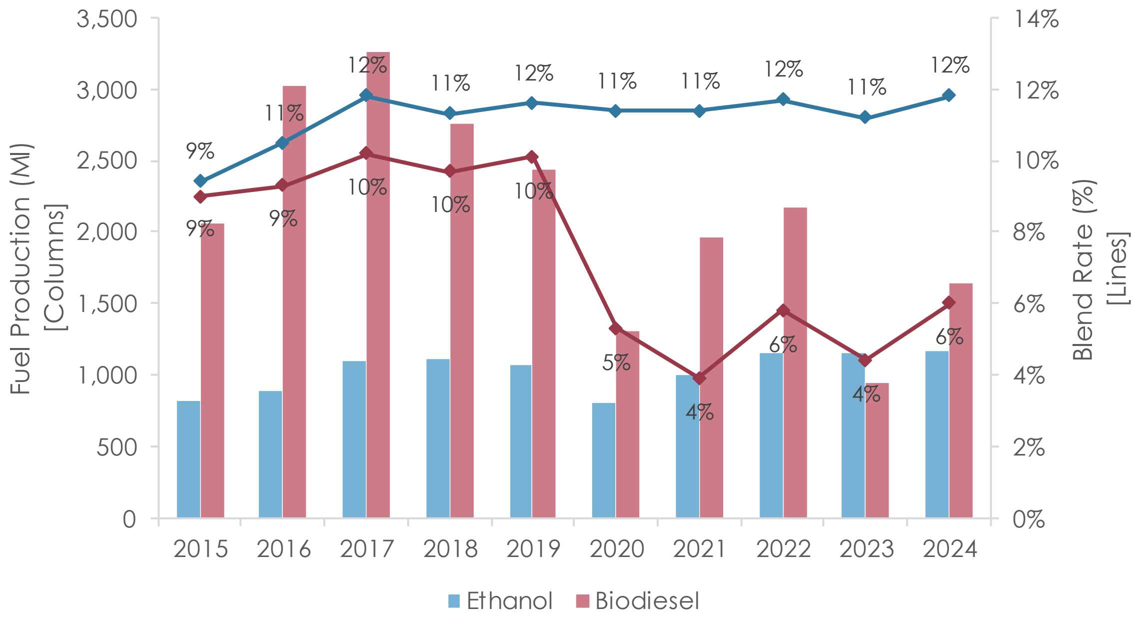


**Figure 23 Biofuel production and average domestic blend rates in Argentina**

[52] A demonstration flight using Indian AtJ was completed in 2023 (Gevo, 2023).

*Notes: Values for 2024 are forecast. Most ethanol produced in Argentina is consumed domestically, but a significant fraction of biodiesel is exported.*
*Source: Joseph (2024)*

Exports play a significant role in Argentina's biodiesel sector, with the EU a primary market expected to consume nearly half of Argentine production in 2024 (Joseph, 2024; Staricco & Buraschi, 2022)[53]. Biodiesel production volumes fluctuate significantly in response to crop productivity and market value. Export volumes are adjusted to moderate the impact on domestic consumption, though blend rates are still seen to vary (Figure 23). Since 2019, ethanol has been produced at 22 facilities whose output volumes have been relatively stable, despite adverse weather conditions in some growing years. Total production is projected to be 1.2 billion litres in 2024, and the vast majority of this will be consumed domestically (Joseph, 2024; Vega et al., 2024).

Research by Timilsina et al. (2013) indicates that increases in international biofuel and feedstock prices tend to benefit Argentina's economy by boosting GDP and social welfare. However, domestic policies, such as biofuel blending mandates, may lead to small economic losses by reducing export volume. A significant development on the horizon is the proposed bill by the Liga Bioenergetica, a coalition of biofuel-producing provinces. The bill aims to increase the domestic ethanol blend to 15% by 2026 and the biodiesel blend to 15% by 2027. Additionally, the bill proposes the removal of price regulation, a change which may aim to make the domestic market more profitable, especially in light of potential fluctuations in export demand as Argentina seeks to balance its domestic consumption with its role as a major biofuel exporter (Lamers et al., 2008; Nikas et al., 2022).

The biofuel industry is also seen as an important element of the nation's growing bioeconomy, and the private sector and regional organisations continue to promote agricultural intensification initiatives. Although biofuels are considered a tool for Argentina to meet its climate commitments, the lack of specific environmental criteria, such as a full life-cycle emissions threshold, is a gap in current policy (Joseph, 2024).

Looking ahead, we estimate Argentina's biofuel production – for domestic and export markets – in 2030 following an IEA projection for total liquid fuel consumption (International Energy Agency, 2023, Figure 3). We assume that Argentina maintains a consistent 12% blend for ethanol, and reaches the mandated 7.5% biodiesel blend, with stable average export shares. This leads in 2030 to about 1.1 billion litres of corn-and-molasses-based ethanol (with the split following the past mix) and 1.5 billion litres of soy biodiesel.

### *4.1.8. Canada*

The Canadian Federal Government sets minimum biofuel blending rates for gasoline and diesel: in 2023 these were E5 and B2. However, many Canadian provinces mandate higher rates; for example, in 2023 the province of Quebec mandated E10 and B3, and this is expected to rise to E15 and B10 by 2030. The province of British Columbia has adopted a blending quota for jet fuel of 3% in 2030 (Government of British Colombia, 2023b). British Columbia has also operated a Low Carbon Fuel Standard (BC-LCFS) since 2010, and by 2030, will require fuel suppliers to reduce the average lifecycle GHG emissions intensity of their fuels by 30% below a

[53] EU imports are subject to quotas and minimum prices, reflecting concerns about sustainability and trade balances (Staricco & Buraschi, 2022).

standard baseline for road fuels, and by 10% for jet fuel[54] (Government of British Colombia, 2022). The combination of state blending mandates and the BC-LCFS has resulted in a gradually growing share of biofuels in the transport pool, as seen in Figure 24.

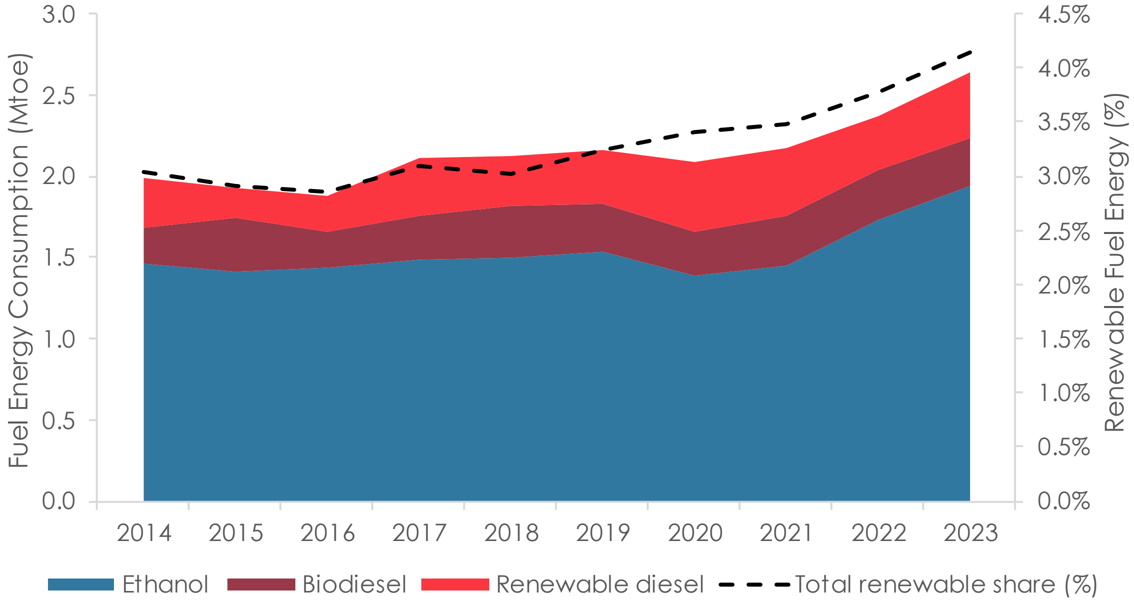


**Figure 24 Consumption of biofuels in Canada, indicating the share of overall road transport energy**

*Source: Danielson (2023)*

In 2022, the Federal Government introduced a nation-wide road LCFS, under the Clean Fuel Regulation (CFR) (Government of Canada, 2024). The schedule for lifecycle emissions reduction reaches 81.0 and 79.0 $gCO_2e/MJ$ in 2030 for gasoline and diesel pools respectively. While more modest than the BC-LCFS, these targets will still stimulate production and import of biofuels. Estimates from Environment and Climate Change Canada (ECCC) suggest that by 2030 about 4.5 billion litres per year of ethanol and 3.0 billion litres per year of biodiesel will be consumed in Canada (Danielson, 2023), representing a significant acceleration of the historical trends seen in Figure 24. We shall assume that feedstock shares will remain similar, though in reality competition with other markets may end up restricting the availability of residual oils.

Canada currently imports about 50% of its ethanol from the USA (Danielson, 2023); and, in a peculiarity of policy incentives, it exports the majority of its biodiesel to the USA while importing a similar amount back from the USA. This is because fuel made from domestically-produced rapeseed (canola) and residue feedstocks boast a relatively low emissions intensity, thus commanding a better price than USA Midwestern soy biodiesel in the state LCFS markets (principally California). Prior to the introduction of the CFR, Canada's provincial blending quotas, except for British Columbia, did not incentivise lower-emissions biofuels and were therefore met with soy-based biodiesel from the USA. This situation may change under the new

[54] The baselines are 93.67 $gCO_2e/MJ$ for gasoline-type fuels, 94.38 $gCO_2e/MJ$ for diesel-type fuels, and 88.83 $gCO_2e/MJ$ for jet-type fuels (Government of British Colombia, 2022).

federal CFR, and after updates to provincial biofuel quotas seek to favour lower-emissions fuels (e.g. in Quebec (Thomson, 2021)).

The BC-LCFS covers all aviation fuel used on domestic and international flights (Government of British Colombia, 2022, 2023a), meaning that suppliers of fossil jet fuel must supply alternative fuel or buy credits from another operator. The new federal standard, by contrast, allows alternative aviation fuels like biojet to generate credits but doesn't place an obligation on fossil jet suppliers[55]. Other governmental support for alternative aviation fuel comes in the form of a federal procurement programme (Allan et al., 2023); but aside from this, support is scant. Researchers have identified options for facilitating national adoption and scale-up of production, including differentiated taxation (Zheng, 2024), and production incentives (Allan et al., 2023). Consumption could reach 1 billion litres in 2030 (about 10% of projected demand), with the necessary feedstock well within the scope of Canada's domestic resources. This being said, an established policy signal is still absent, as so we ignore biojet fuel in our 2030 demand assessment[56].

### *4.1.9. Thailand*

Thailand aims to substitute 20-25% of fossil fuels with domestically produced biofuels by 2037 under the Alternative Energy Development Plan (AEDP) (Permpool et al., 2020). In recent years, ethanol made from sugarcane, molasses, and cassava has been blended into petrol at a rate of 11-14%, and palm oil biodiesel into diesel at 5-8%; this gives 1.3 billion litres of ethanol and 1.7 billion litres of biodiesel consumed in 2024, with minimal import/export (Prasertsri, 2024).

[55] This kind of unbalanced situation where motorists end up subsidising emissions reductions for the aviation sector, is familiar from other LCFSs in the USA.

[56] The expected biojet consumption expected from British Columbia's quota (66 million litres in 2030 according to Simpliflying (2024)) is negligible compared to the Canada-wide road demand.

 

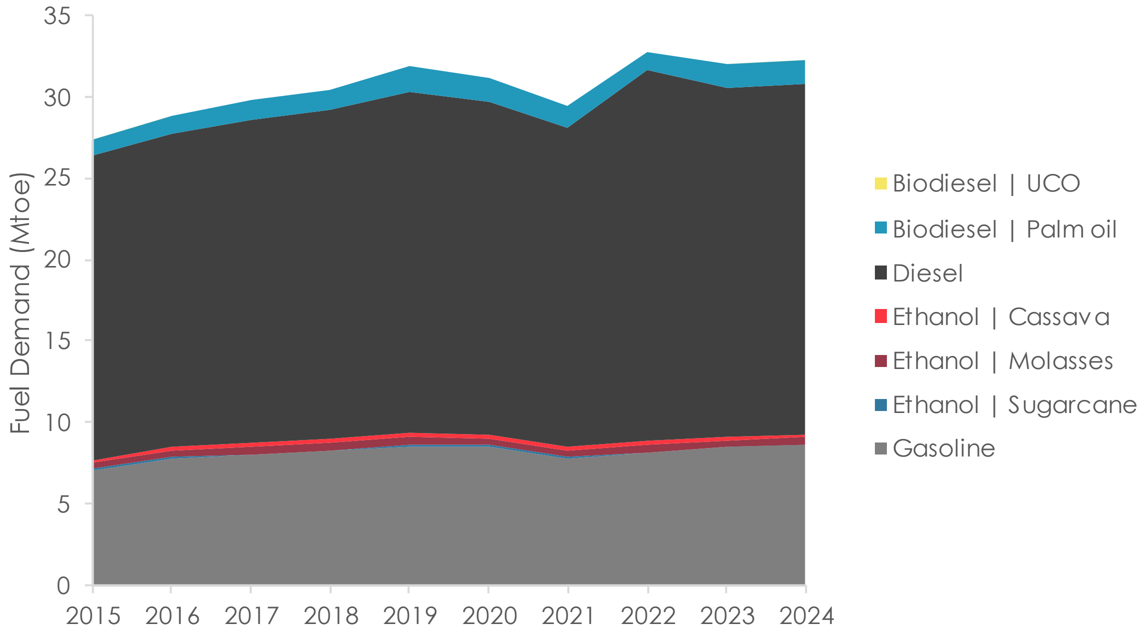


**Figure 25 Road energy demand by fuel and feedstock in Thailand**

*Note: Some feedstocks' contributions may not be visible at default zoom levels.*
*Source: Adapted from Prasertsri (2024)*

The newly proposed National Energy Plan (NEP) for 2024 signals a shift towards electric vehicles and rail transport, reducing the emphasis on biofuels for road transport. The government also plans to phase out E85 by the end of 2024 (most ethanol is already consumed as E10), and has downgraded the B10 blending mandate to B7 (Prasertsri, 2024). With these shifts, the AEDP sets 2037 consumption targets at 1.2 billion litres of ethanol and 900 million litres of biodiesel, representing a gradual scale-down. It is reasonable to assume that the mix of feedstocks will remain the same in 2030.

As the world's third largest palm oil producer, Thailand's plantations currently occupy around 1 Mha (or 5% of arable land) and are set to expand to 1.63 Mha by 2037 (Prasertsri, 2024). While the link between plantation expansion and deforestation in Thailand is weaker than in other Southeast Asian countries like Indonesia and Malaysia, the expansion still raises concerns about potential impacts on species, habitats, water and soil in ecologically sensitive areas (Saswattecha et al., 2016; Wattana et al., 2022). The planned reduction in demand palm-based biodiesel may therefore be welcomed as a step in the right direction by the environmental community.

Thailand is also developing biojet as part of its decarbonisation strategy. Starting in 2026, the government aims to introduce a 1% blend for domestic flights, rising to 8% by 2036 and hitting 675 million litres of biojet in 2037. Initially, this will be HEFA produced from UCO, though molasses-based AtJ is expected to play a growing role as the technology develops (Prasertsri, 2024). By 2030 we estimate that the reduction in palm oil demand from the road biodiesel industry will be roughly matched by an increase in UCO demand for aviation fuel. Put another way, the net biofuel production may be close to zero, but the changing feedstock slate will have positive implications for the overall climate and environmental footprint.

## 4.2. International policy drivers

The international nature of aviation and shipping means that no single country or group of countries can effectively regulate their emissions. Coordinating global frameworks for decarbonisation in these sectors remains a critical challenge. In this section we briefly introduce the measures established by the two key UN agencies: the International Civil Aviation Organisation (ICAO) and the International Maritime Organisation (IMO).

### *4.2.1. UN ICAO*

The Carbon Offsetting and Reduction for Sustainable International Aviation scheme (CORSIA) was agreed upon in 2016, with the primary goal of achieving 'carbon neutral growth' in the aviation sector. Airlines must offset their emissions above a set baseline (85% of their 2019 emissions) by either: (i) purchasing eligible carbon offsets; and/or (ii) reducing the reportable lifecycle emissions from their fuel use (IATA, 2024). Participation in CORSIA will become mandatory for UN Member States from 2025-2035 (when the scheme is due to end). Notably, the scheme does not cover the climate effects of contrails and nitrogen oxides emitted at altitude.

Fuels with reportable emissions savings of 10% or more compared to fossil jet fuel are eligible for compliance. However, the value of CORSIA credits is essentially capped by the cost of carbon offsets (the alternative compliance option), which remains too low to cover the additional costs of alternative fuels. As a result, CORSIA alone provides little incentive for investment in biofuel production; but airlines that purchase biojet fuel supported under local incentives may count it towards CORSIA compliance.

### *4.2.2. UN IMO*

The IMO's 2023 Strategy (UN International Maritime Organisation, 2023) adopted a series of aspirational decarbonisation targets, including an aspiration to reach net-zero greenhouse gas emission "by or around 2050", with interim goals of a 20-30% reduction in lifecycle emissions compared to 2008 levels by 2030 and a 70-80% reduction in 2040[57]. The Strategy does not cover black carbon emissions from ship exhausts.

These IMO targets are not legally binding, and such voluntary measures have historically had limited success in driving investment in alternative fuel production. Even more so than with CORSIA, which at least introduces some price signals, the IMO goals are likely to serve more as a complement to local policy incentives than as drivers in their own right (Abbasov, 2024; Comer & Carvalho, 2023; Faber et al., 2016).

[57] Emissions from international shipping in 2008 were 170 $MtCO_2e$ (EEA, 2024). Achieving the IMO's targets would reduce emissions to 119-136 $MtCO_2e$ in the year 2030 and 34-51 $MtCO_2e$ in 2040.

## 4.3. Growing demand to 2030

### *4.3.1. Biofuels and feedstocks*

Table 9 collates our calculations of the case studies' 2030 demand for ethanol and lipid-based biofuels, split by feedstock[58]. This, combined with geography-dependent fuel and agricultural yield data[59], allows us to estimate feedstock demand and the implied demand for cropland. A brief discussion of trends in other countries and regions of the world is provided in Annex B.

**Table 9 Reported biofuel, feedstock, and land demand in 2023 and estimated demand in 2030 for the case study countries**

| Country | Fuel Production (Mtoe) | | | Feedstock Demand (Mt) | | | Cropland (Mha) | |
|---|---|---|---|---|---|---|---|---|
| | Type | 2023 | 2030 | Type | 2023 | 2030 | 2023 | 2030 |
| USA | Ethanol | 29 | 28 | Corn | 135 | 134 | 7 | 7 |
| | | | | Other grain crops | 1 | 1 | 0.1 | 0.1 |
| | Biodiesel & HVO | 13 | 25 | Soybean oil | 6 | 17 | 3 | 8 |
| | | | | Rapeseed oil | 2 | 4 | 1 | 4 |
| | | | | Residual oil | 7 | 8 | -- | -- |
| Brazil | Ethanol | 16 | 23 | Sugarcane | 102 | 154 | 4 | 7 |
| | | | | Corn | 13 | 20 | 1 | 2 |
| | Biodiesel & HVO | 6 | 10 | Soybean oil | 5 | 8 | 2 | 4 |
| | | | | Other vegetable oil | 1 | 2 | 0.5 | 1 |
| | | | | Residual oil | 1 | 1 | -- | -- |
| EU+UK | Ethanol | 3 | 3 | Grain crops | 14 | 14 | 1 | 1 |
| | | | | Sugar crops | 3 | 3 | 0.1 | 0.1 |
| | Biodiesel & HVO | 14 | 17 | Vegetable oil | 10 | 13 | 4 | 6 |
| | | | | Residual oil | 6 | 7 | -- | -- |
| | Cellulosic | 0.0 | 3 | Cellulosic crops | 0.0 | 16 | 0.0 | 1.1 |
| Indonesia | Ethanol | 0.0 | 0.2 | Molasses | 0.0 | 2 | 0.0 | 0.1 |
| | Biodiesel & HVO | 11 | 14 | Palm oil | 13 | 16 | 4 | 5 |
| China | Ethanol | 2 | 3 | Starch crops | 10 | 14 | 1 | 1 |
| | Biodiesel & HVO | 2 | 5 | Residual oil | 3 | 6 | -- | -- |
| India | Ethanol | 3 | 5 | Grain crops | 2 | 3 | 0.3 | 1 |
| | | | | Damaged crops | 2 | 4 | -- | -- |

[58] This table considers 1G feedstocks and, for the EU+UK, feedstocks from ligno-cellulosic crops. The other cellulosic material expected to be consumed in the EU+UK tends to be highly heterogeneous – things like manure, straw, municipal waste, sawdust – and we don't estimate a total feedstock mass demand. They also have a low or zero direct land demand, and are therefore excluded here.

[59] The 2030 land demand is based on the same FAOstat average yields as 2023.

| Country | Fuel Production (Mtoe) | | | Feedstock Demand (Mt) | | | Cropland (Mha) | |
|---|---|---|---|---|---|---|---|---|
| | Type | 2023 | 2030 | Type | 2023 | 2030 | 2023 | 2030 |
| | | | | Sugar crops | 18 | 30 | 1 | 1 |
| | Biodiesel & HVO | 0.2 | 4 | Palm oil | 0.1 | 3 | 0.0 | 1 |
| | | | | Residual oil | 0.1 | 2 | -- | -- |
| Argentina | Ethanol | 1 | 1 | Corn | 2 | 2 | 0.1 | 0.2 |
| | | | | Molasses | 2 | 2 | 0.1 | 0.1 |
| | Biodiesel & HVO | 1 | 2 | Soybean oil | 1 | 2 | 1 | 1 |
| Canada | Ethanol | 1 | 2 | Corn | 4 | 10 | 0.2 | 1 |
| | | | | Other grain crops | 1 | 1 | 0.1 | 0.2 |
| | Biodiesel & HVO | 0.4 | 3 | Rapeseed oil | 0.2 | 2 | 0.2 | 1 |
| | | | | Soybean oil | 0.0 | 0.2 | 0.0 | 0.1 |
| | | | | Residual oil | 0.2 | 1 | -- | -- |
| Thailand | Ethanol | 1 | 1 | Sugar crops | 4 | 4 | 0.2 | 0.2 |
| | | | | Cassava | 1 | 1 | 0.1 | 0.1 |
| | Biodiesel & HVO | 1 | 1 | Palm oil | 2 | 1 | 0.5 | 0.4 |
| | | | | Residual oil | 0.0 | 0.3 | -- | -- |
| Total | Ethanol | 55 | 66 | Starch crops | 184 | 206 | 11 | 13 |
| | | | | Sugar crops | 127 | 193 | 6 | 8 |
| | Biodiesel & HVO | 49 | 80 | Crop oils | 39 | 67 | 15 | 30 |
| | | | | Residual oils | 17 | 26 | -- | -- |
| | Cellulosic | 0.0 | 3 | Cellulosic crops | 0.0 | 16 | 0.0 | 1.1 |
| | **Total** | **104** | **150** | **All** | **368** | **508** | **32** | **52** |

*Note: Most values are given to zero decimal places, but we have expanded to one decimal place in cases where there is a small but non-zero value. A '—' indicates a truly zero value.*
*Note: The cropland area columns consider the 'net' area required to produce the biofuel feedstock – that is, neglecting the area allocated to co-products. See Section 3.2.1 for a discussion.*
*Note: 'Residual oil' covers UCO, residual animal fats, and corn oil; these are treated as having no direct land requirement (though it is possible that their diversion from other uses will cause indirect land use change). 'Sugar crops' includes sugar cane, sugar beet, and molasses.*
*Note: Feedstock demand for sugar crops refers to the dry mass (DM).*

Modelling by the IEA provides some useful context for these results: its 'NZE' scenario maps a possible pathway for the world to reach net-zero emissions by 2050 (IEA, 2021a). Under NZE, energy demand in the transport sector must peak around 2025 and then decline. This is primarily driven by electrification of light-duty passenger vehicles[60]; but the IEA envisions in parallel a rapid scale-up of biofuels, reaching 310 Mtoe per year in 2035 and holding steady thereafter. Consulting Table 9, we see that without a substantial step up in biofuel policy targets, this will remain well out of reach.

[60] Recall from Section 3.2.1 (Footnote 15) that each unit of electricity delivered to run a BEV electric motor does multiple times the amount of work as liquid fuel.

Moreover, given the well-known concerns around the sustainability of the current biofuel industry, a profound shift in feedstock supply models would be needed to deliver ecologically sustainable expansion under current biofuel policy, let alone under the NZE scale-up. The majority of growth in the NZE comes from biofuels made from organic wastes and residues, for which production would have to rise by a factor of 15 between 2022 and 2030 (Frankl & Moorhouse, 2023)[61]. Yet among the case study countries – which represent the vast majority of global biofuel production and consumption – only the EU was identified as having stringent policy safeguards to limit (though not halt) the expansion of biofuels made from food and feed crops. Other national and sub-national policy regimes do favour the use of wastes and residues, particularly used cooking oil and low-grade animal fats; but supply of these resources is limited and their growth in the biofuel industry is unfortunately eclipsed by the rise in use of virgin vegetable oils, as seen in Table 9.

While the NZE envisages low additional land requirements, the results of our analysis paint a less optimistic picture. Table 10 sums the total land dedicated to producing biofuel feedstocks for the case study countries: all except Thailand exhibit growth in land requirements, with some showing a significant increase[62]. This will have commensurate implications for biodiversity and ecosystem service.

**Table 10 Total land use (Mha) for biofuel crops by the case study countries (excluding and including co-product land demand)**

| Land Use Change | | Argentina | Brazil | Canada | China | EU+UK | India | Indonesia | Thailand | USA | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Net | 2023 | 1.0 | 8.4 | 0.5 | 0.9 | 4.8 | 1.1 | 3.5 | 0.7 | 11.0 | 32.0 |
| | 2030 | 1.3 | 13.2 | 2.2 | 1.3 | 7.8 | 2.6 | 4.6 | 0.7 | 18.4 | 52.1 |
| | Change | +0.3 | +4.8 | +1.7 | +0.3 | +3.1 | +1.6 | +1.1 | -0.1 | +7.4 | +20.1 |
| | Change % | +25% | +57% | +352% | +36% | +65% | +149% | +31% | -9% | +67% | +63% |
| Gross | 2023 | 3.2 | 15.7 | 0.9 | 1.6 | 9.0 | 1.3 | 3.7 | 0.8 | 25.2 | 61.3 |
| | 2030 | 4.0 | 25.4 | 4.0 | 2.2 | 15.2 | 3.0 | 4.9 | 0.7 | 47.7 | 107.1 |
| | Change | +0.8 | +9.7 | +3.1 | +0.6 | +6.3 | +1.8 | +1.1 | -0.1 | +22.6 | +45.8 |
| | Change % | +26% | +62% | +353% | +36% | +71% | +140% | +31% | -8% | +90% | +75% |

*Note: 'Net' denotes the cropland area required to produce the biofuel feedstock, not including the area allocated to co-products. 'Gross' indicates the full cropland area, including that dedicated to co-products.*

[61] The IEA anticipates some increase in the use of conventional crop-based biofuels to contribute to the NZE, this extra feedstock is presumed to derive from improvements in crop productivity (so that in IEA's modelling it doesn't require the use of extra land). The plausibility of this assumption is questionable, and the indirect impacts of diverting large crop volumes into the biofuel sector are likely to be large.

[62] Note that the table shows both net and gross calculated land areas (see Section 3.2.1). Countries for which the difference between net and gross is large are those whose biofuel feedstocks are associated with more co-products, such as corn (DGS) and soybean (soy meal).

### 4.3.2. *Indirect land impacts and emissions*

The analysis in the previous section presented the land requirement to produce biofuel feedstocks. Following the earlier discussion of ILUC, we also consider the net land use change that may arise in response to evolving demand patterns. The GLOBIOM model presented in Section 3.2.3 was developed for the context of a demand spike for feedstock in the EU, and will not therefore capture the regional subtleties of markets and agricultural practices in each country-feedstock combination. Nevertheless, with the slight adjustments noted above, the GLOBIOM results can give an indicative picture of how the biofuel policies of the case study countries may impact land use around the world.

Table 11 shows our projected changes in biofuel demand in each country between 2023 and 2030. This results in changes in land demand (a little lower than the 'direct' cropland requirement, due to factors like demand reduction and agricultural intensification in the GLOBIOM modelling). It also results in ILUC emissions and in emissions savings from substituting fossil fuels with biofuels; the 'net emissions change' column in Table 11 sums these two emissions terms to indicate whether the case study countries' biofuel policies may be expected to increase or decrease net GHG emissions in the period 2023 to 2030[63].

**Table 11 Impacts from changing biofuel production in 2030 compared with 2023**

| Country | Δ Biofuel Energy (Mtoe/year) | Δ ILUC Land Area (Mha) | Δ Emissions ($MtCO_2e$/year) | | |
|---|---|---|---|---|---|
| | | | ILUC Emissions | Fossil Fuel Displacement | Net Emissions Change |
| Argentina | +0.4 | +0.2 | +2.2 | -1.0 | +1.3 |
| Brazil | +10.7 | +3.8 | +25.6 | -28.3 | -2.6 |
| Canada | +3.7 | +1.3 | +5.3 | -8.6 | -3.2 |
| China | +3.4 | +0.3 | +0.7 | -9.6 | -8.8 |
| EU+UK | +6.5 | +2.9 | -3.6 | -18.6 | -22.2 |
| India | +5.5 | +1.3 | +22.3 | -11.9 | +10.3 |
| Indonesia | +3.5 | +1.2 | +31.7 | -5.0 | +26.8 |
| Thailand | +0.0 | -0.1 | -1.8 | -0.4 | -2.2 |
| USA | +12.5 | +7.5 | +66.4 | -32.0 | +34.4 |
| **Total** | **+46.2** | **+18.6** | **+148.9** | **-115.2** | **+33.7** |

*Note: The 'Δ biofuel energy demand' column shows the annual energy demand in the year 2030 minus the demand in the year 2023, using the Greek letter delta (Δ) to signify a change. The 'Δ ILUC land area' column shows the increase in cropland area to meet this change in demand that would be consistent with the GLOBIOM results. Similarly for the three 'Δ emissions' columns: these are the annual emissions in 2030 minus the annual emissions in 2023. This can be thought of as the absolute change by 2030 due to policy and economic trends.*
*Note: Negative, green-coloured values signify 'beneficial' outcomes: net gains in semi-natural land areas and reductions in GHG emissions. Positive, red-coloured values are 'detrimental' outcomes.*

[63] Adding the two terms combines indirect and direct emissions factors which have been calculated under very different frameworks. While this operation is not always fully appropriate (cf. Malins & Sandford (2023)), in this context it provides a useful illustration.

 

In Table 11 we see some beneficial outcomes, where emissions decrease in compared to 2023, and some detrimental outcomes. These are graphed in Figure 1 (Executive Summary), and Table 15 in Annex C gives a more detailed break-down of Table 11 by fuel and feedstock type. Narratively:

- For Argentina, there is little change in ethanol consumption but relatively large increases in soybean oil consumption, which gives a high ILUC factor and hence high net emissions increase.
- Brazil witnesses decreased net emissions from its sugarcane-based ethanol industry, but this is counterbalanced by simultaneous growth in oilseed-based (and in particular soybean-based) biodiesel.
- In Canada, increased consumption of corn ethanol – which GLOBIOM models as having relatively low ILUC impacts – is responsible for a decline in emissions, as is an increasing use of residual oil in the lipid mix.
- China, similarly to Canada, sees growth in ethanol from corn and other grains, and almost exclusive reliance on residual oils which are assumed in this analysis to be genuine and to have no ILUC impacts. Both of these factors lead to net emission reductions.
- The EU+UK can be highlighted for its significant emissions savings (despite increased land demand), both in absolute terms and compared to the fossil-only baseline. This arises from a combination of two main factors: the mandated shift away from palm oil, and growth in the use of bioenergy crops associated with negative ILUC impacts.
- India's expected reliance on palm oil for its burgeoning biodiesel industry gives it a high net emissions score, despite promising moves to source more feedstock from residual oil and surplus / damaged crops.
- Indonesia is another country which is targeting rapid expansion of palm-based biofuel. Its emissions are expected to rise accordingly.
- Thailand's policy targets declining road biofuel demand, with a shift towards aviation fuel based on residual oils. This results in reductions both in cropped area for biofuels and in ILUC emissions.
- The USA – the world's largest biofuel market – is predicted to expand lipid-based biofuel production considerably. The major feedstock will likely be soybean oil, whose large ILUC factor gives it a negative emissions balance. Our analysis predicts that the USA will be a major driver of global biofuel-related emissions increases.

For reference, estimates of the total biofuel lifecycle emissions for each country are shown in Annex C.

#### *4.3.3. Biofuel mix carbon intensity*

The previous section estimates changes in net annual emissions associated with the case study countries' biofuel policies. As a complementary calculation, we present the average carbon intensity of the consumed biofuels in Table 12. These are calculated as a demand-weighted sum over the feedstocks used in each country, where the carbon intensity of each feedstock is the sum of direct and ILUC components. Since we have not assumed any change in the pathway-specific carbon intensities in the period 2023-30, any observed shift in average carbon intensity owes to shifts in the fuel and feedstock mix.

**Table 12 Projected carbon intensity of biofuels in 2023 and 2030 for each case study, in absolute units and compared to fossil fuels**

| Year | Unit | Argentina | Brazil | Canada | China | EU+UK | India | Indonesia | Thailand | USA | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2023 | $gCO_2e/MJ$ | 152.0 | 85.1 | 67.8 | 46.1 | 90.9 | 68.4 | 293.2 | 218.9 | 79.3 | 109.2 |
| | % | +62% | -10% | -28% | -51% | -3% | -27% | +212% | +133% | -16% | +16% |
| 2030 | $gCO_2e/MJ$ | 153.6 | 88.6 | 76.5 | 39.7 | 72.7 | 115.1 | 289.6 | 185.6 | 101.7 | 111.7 |
| | % | +63% | -6% | -19% | -58% | -23% | +22% | +208% | +97% | +8% | +19% |

*Note: Percentage rows are relative to the fossil fuel benchmark of 94 $gCO_2e/MJ$. Positive, red-coloured values indicate biofuel emissions are higher than fossil fuels; negative, green-coloured values indicate biofuel emissions are lower than fossil fuels. The final 'average' column shows the total biofuel emissions from the nine case study countries divided by the total biofuel energy.*

These estimated average carbon intensities are also shown in Figure 26. For some countries like Argentina, Brazil, and Indonesia, we have estimated only modest changes to the feedstock portfolio, and so the average carbon intensities are roughly the same between 2023 and 2030. China, the EU+UK, and Thailand register beneficial shifts – for instance, Thailand intends to substitute some palm oil consumption for used cooking oil, the EU+UK will eliminate palm oil altogether. Finally, Canada, India, and the USA all see worsening climate emissions per unit of fuel between 2023 and 2030 due to increasing consumption of food-type crop feedstocks.

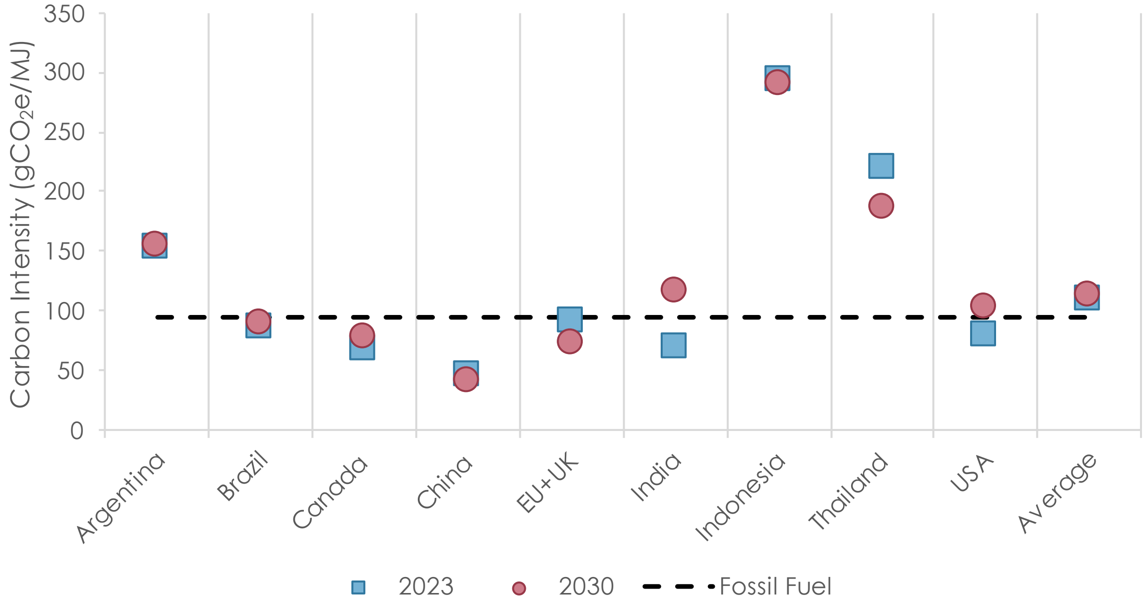


**Figure 26** **Projected carbon intensity of biofuels in 2023 and 2030 for each case study**

*Note: As in Table 12, the fossil fuel benchmark is set at 94 $gCO_2e/MJ$.*

It should be noted that even for the regions in which we estimate a net benefit from biofuel use in 2030, the contribution to the overall goal of transport decarbonisation is modest (because the biofuels' impact is diluted by a larger quantity fossil fuels in the overall pool). In Brazil, for example, the 6% average GHG benefit estimated in Table 12 translates into a reduction of about 2% in emissions from road fuels.

# 5. Conclusion

Energy, climate, and environment policies share many common goals; nevertheless, certain actions taken in pursuit of one may inadvertently weaken or undermine the other. Ambitious targets for including biofuels in the fuel mix will fail to deliver net climate benefits if the biofuels' lifecycle greenhouse gas emissions, including emissions from ILUC and other indirect effects, exceed those of fossil fuels. Governance of biofuel sustainability is mixed across producing countries, and the evidence suggests that biofuel policies have been less effective in mitigating climate change than had perhaps been hoped. At the same time, they have played a role in exacerbating social and environmental problems, as production of biofuel feedstock requires valuable resources such as land which could be put to alternative economic and/or ecological uses.

A failure to recognise the indirect knock-on effects of biofuel production – whether the resource is wheat, used cooking oil (UCO), land, or water – leads to an underestimation of biofuels' broader negative impacts. Using food crops as biofuel feedstock reduces food market supply and increases long-term demand for cropland. Similarly, diverting residual oils like rendered animal fats from other supply chains can lead the affected markets to resort to potentially less sustainable feedstocks.

Currently, large areas of agricultural land worldwide are dedicated to biofuel feedstocks. Our analysis of policy regimes in nine major producing countries suggests significant growth in biofuel production between now and 2030, and this is likely to be predicated on the use of food commodities as feedstock. This expansion is expected to drive further land use change, impact biodiversity, and continue to inflate food prices. Furthermore, while using land for biofuel feedstock can displace fossil fuels and offer net gains for the climate, restoring forest and natural habitats on that land would deliver greater climate and biodiversity benefits at a lower ecological cost. This highlights the 'carbon opportunity cost' of land use. While there is some scope to rely on residues and wastes such as UCO, growth in biofuel demand will easily outpace growth in the availability of these feedstocks.

The Global Biofuels Alliance (GBA) aims to further the goals of biofuel-producing nations by promoting investment in production facilities, facilitating trade, and working towards a more uniform global system of standards. However, it remains to be seen whether this focus will lead to better sustainability performance, or simply lock in inadequate sustainability governance. Historically, global biofuel forums have often treated the sustainability of biofuels as a given rather than a matter for rigorous assessment and certification; ultimately, this approach is short-sighted, both for the planet and for the industry itself. Governmental responses to the ILUC debate and the 2007-2012 food price crises demonstrate that support for biofuels is not guaranteed if their environmental and social impacts spiral out of control.

A more productive role for groups like the GBA would be to commit resources to the persistently difficult commercialisation of cellulosic biofuel technologies, and to support the development of genuinely stringent and effective minimum environmental standards for the global biofuel industry.

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# Annex A Glossary

## A.1 Units

| | |
|---|---|
| **Energy** | |
| MJ | Megajoule ($10^6$ joules) |
| PJ | Petajoule ($10^{15}$ joules) |
| Mtoe | Million tonnes of oil equivalent |
| **Power** | |
| kWp | Kilowatt-peak |
| **Mass** | |
| t | Metric tonne ($10^3$ kg) |
| Mt | Megatonne ($10^6$ tonnes) |
| **Area** | |
| ha | Hectare |
| kha | Kilohectare ($10^3$ hectares) |
| Mha | Megahectare ($10^6$ hectares) |
| **Emissions** | |
| $gCO_2e$ | Grams of $CO_2$-equivalent |
| $tCO_2e$ | Tonnes of $CO_2$-equivalent |
| $MtCO_2e$ | Million tonnes of $CO_2$-equivalent |
| **Currency** | |
| BRL | Brazilian real |
| EUR | Euro |
| USD | USA dollar |

## A.2 Organisations, institutions, policies, and programmes

| | |
|---|---|
| AEDP | Thailand Alternative Energy Development Plan |
| CAAC | Civil Aviation Administration China |
| COP | UN Conference of Parties |
| CORSIA | ICAO Carbon Offsetting and Reduction for Sustainable International Aviation |
| ECCC | Environment and Climate Change Canada |
| EEA | European Environment Agency |
| EIA | U.S. Energy Information Administration |
| EPA | U.S. Environmental Protection Agency |

| | |
|---|---|
| ESMAP | World Bank Energy Sector Management Assistance Program |
| ESR | EU Effort Sharing Regulation |
| ETD | EU Energy Taxation Directive |
| ETS | EU Emissions Trading System |
| FAO | UN Food and Agriculture Organisation |
| FAS | USDA Foreign Agricultural Service |
| GAIN | USDA FAS Global Agricultural Information Network |
| GBA | Global Biofuels Alliance |
| GLOBIOM | Global Biosphere Management model |
| IATA | International Air Transport Association |
| ICAO | UN International Civil Aviation Authority |
| IEA | International Energy Agency |
| IFEU | Institut Für Energie- Und Umweltforschung |
| IMO | UN International Maritime Organisation |
| ISCC | International Sustainability and Carbon Certification |
| ISPO | Indonesia Sustainable Palm Oil |
| NEP | Thailand National Energy Plan |
| OECD | Organisation for Economic Co-operation and Development |
| RED | EU Renewable Energy Directive |
| RFS | U.S. Renewable Fuel Standard |
| RSPO | Roundtable for Sustainable Palm Oil |
| GFW | Global Forest Watch |
| USDA | U.S. Department of Agriculture |
| UNFCCC | UN Framework Convention on Climate Change |
| WEF | World Economic Forum |

## A.3 Other acronyms

| | |
|---|---|
| AtJ | Alcohol-to-jet |
| AtL | Alcohol-to-liquid |
| BEV | Battery electric vehicle |
| CAGR | Compound annual growth rate |
| CFS | Clean fuel standard |
| DM | Dry matter |
| FAME | Fatty acid methyl ester |
| FFV | Flex-fuel vehicle |

| | |
|---|---|
| GHG | Greenhouse gas |
| GREET | The Greenhouse gases, Regulated Emissions, and Energy use in Technologies model |
| HEFA | Hydrotreated esters and fatty acids |
| HVO | Hydroprocessed vegetable oil |
| ICV | Internal combustion engine vehicle |
| ILUC | Indirect land use change |
| LCA | Lifecycle analysis |
| LCFS | Low carbon fuel standard |
| LNG | Liquefied natural gas |
| MSW | Municipal solid waste |
| NGO | Non-governmental organisation |
| PV | Photovoltaic |
| SAF | Sustainable aviation fuel |
| SIP | Synthetic iso-paraffin |
| SOC | Soil organic carbon |
| UCO | Used cooking oil |

# Annex B Biofuel consumption trends in non-case study regions

While the case study countries covered in detail in Section 4 of the main text represent the lion's share of biofuel production and consumption (cf. Figure 7), the industry continues to grow in the rest of the world. Figure 27 shows that the historical trend has been one of sizeable growth since the mid-2000s. For years between 2024 and 2030, we do a simple linear extrapolation (based on 2015-23 data) to estimate how production might evolve if past trends are sustained. This suggests that biofuel output may surpass 7.5 Mtoe (320 PJ) in 2030.

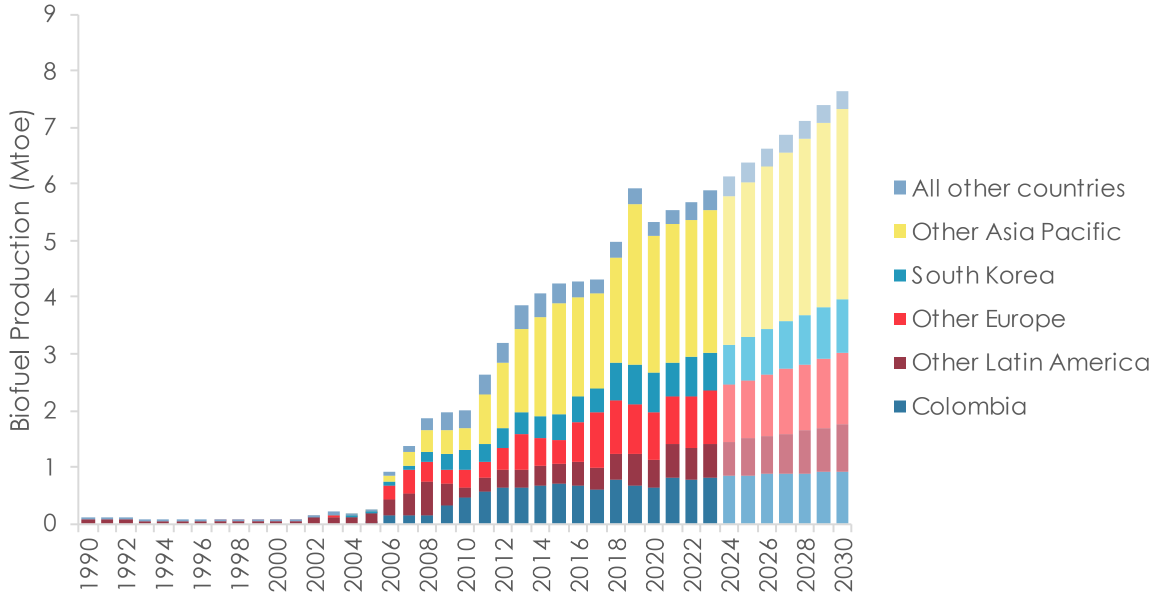


**Figure 27** **Biofuel energy production for selected countries and regions besides the case study countries, where the years 2024-30 are projections**

*Note: The regions beginning with 'other' indicate all countries not already named; so 'Other Latin America' means all of Latin America besides Argentina and Brazil (which are case study countries), and Colombia (which is represented separately on the graph).*
*Source: Historical data from Energy Institute (2024)*

This growth would of course come with associated pressures on feedstock supply. Given the infancy of 2G biofuel industry in the relatively advanced case study economies, it is safe to say that the majority of production in the rest of the world will continue to come from 1G crops, potentially complemented by any residual oils that are too difficult or too costly to export to markets where they command a higher policy value.

Splitting the biofuel production shown in Figure 27 into ethanol and biodiesel contributions for each region (following trends calculated from Energy Institute (2024) data), we calculate that 2.0 Mtoe of the estimated 2030 production would be ethanol and 4.6 Mtoe biodiesel. Based on the assumed fuel and crop yields for each region, this suggests a feedstock demand in the region of 11.2 Mt of starch and sugar crops (occupying 0.8 Mha of land), and 5.3 Mt of oil crops (occupying over 7.1 Mha of land).

# Annex C Emissions results

## C.1 Emissions savings from fuel displacement and land restoration

Figure 11 in the main text showed how greenhouse gas savings stack up for the case study countries under two land-use scenarios: biofuels are used to displace fossil fuels, and land used for biofuel production is allowed to return to its natural state. Table 13 below presents the underlying data for the graph, along with the emissions savings associated with restoring the 'gross' cropland – i.e. including the land allocated to co-products of biofuel production.

**Table 13 Greenhouse gas emissions savings (in units of $MtCO_2e$) associated with allowing land to return to a natural state versus using it to grow biofuel feedstock**

| Country | Fuel Displacement | Land Restoration | Land Restoration (Gross) |
|---|---|---|---|
| Argentina | 4 | 17 | 59 |
| Brazil | 58 | 92 | 238 |
| Canada | 3 | 6 | 10 |
| China | 11 | 10 | 18 |
| EU+UK | 43 | 64 | 143 |
| India | 8 | 12 | 16 |
| Indonesia | 15 | 73 | 76 |
| Thailand | 4 | 12 | 13 |
| USA | 89 | 143 | 359 |
| **Total** | **233** | **428** | **932** |

*Note: Calculations are based on 2023 consumption levels in each of the case study countries.*

## C.2 Lifecycle biofuel emissions

Table 14 shows the estimated total lifecycle emissions from biofuels for each of the case study countries. This includes both direct and indirect components, following the same logic as used for Table 11 in the main text.

**Table 14** **Lifecycle emissions (direct plus indirect) from biofuel use in the case study countries in units of $MtCO_2e$**

| Year | Argentina | Brazil | Canada | China | EU+UK | India | Indonesia | Thailand | USA | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 2023 | 12 | 72 | 3 | 8 | 62 | 9 | 133 | 18 | 117 | 435 |
| 2030 | 15 | 117 | 14 | 13 | 71 | 42 | 174 | 16 | 200 | 662 |
| Change | +3 | +45 | +11 | +4 | +9 | +33 | +40 | -3 | +83 | +226 |
| Change % | +25% | +63% | +344% | +53% | +14% | +363% | +30% | -14% | +71% | +52% |

As ever, the observed changes in emissions arise from two factors: the changing carbon intensity of the biofuel mix, and growth in the total consumption of biofuels. Thailand is an example of a country whose average biofuel carbon intensity declines while total consumption stays roughly constant, as discussed in the main text. Canada is an example where consumption grows significantly, accompanied by a modest increase in average carbon intensity.

## C.3 ILUC and ILUC emissions by country and feedstock type

Table 15 below is a more detailed version of Table 11 in the main text, which distinguishes land use and land-based emissions impacts by country, fuel, and feedstock type. Refer to the discussion in Section 4.3.2.

**Table 15** **Impacts from changing biofuel production in 2030 compared with 2023**

| Country | Biofuel | Feedstock | Δ Biofuel Energy Demand (Mtoe/year) | Δ ILUC Land Area (Mha) | Δ Emissions ($MtCO_2e$/year) | | |
|---|---|---|---|---|---|---|---|
| | | | | | ILUC Emissions | Fossil Fuel Displacement | Net Emissions Change |
| USA | Ethanol | Corn | -0.2 | -0.0 | -0.1 | +0.4 | +0.3 |
| | | Other grain crops | -0.0 | -0.0 | -0.0 | +0.1 | +0.0 |
| | Biodiesel & HVO | Soybean oil | +9.5 | +5.9 | +59.8 | -23.6 | +36.2 |
| | | Rapeseed oil | +2.5 | +1.6 | +6.7 | -6.5 | +0.2 |
| | | Residual oil | +0.7 | -- | -- | -2.3 | -2.3 |
| Brazil | Ethanol | Sugarcane | +5.8 | +1.2 | +4.2 | -16.2 | -11.9 |
| | | Corn | +1.3 | +0.6 | +1.1 | -3.9 | -2.8 |
| | Biodiesel & HVO | Soybean oil | +2.7 | +1.7 | +16.7 | -5.8 | +10.9 |
| | | Other vegetable oil | +0.6 | +0.4 | +3.7 | -1.3 | +2.4 |
| | | Residual oil | +0.4 | -- | -- | -1.2 | -1.2 |
| EU+UK | Ethanol | Grain crops | +0.1 | +0.0 | +0.1 | -0.2 | -0.1 |
| | | Sugar crops | +0.0 | +0.0 | +0.0 | -0.1 | -0.1 |

| Country | Biofuel | Feedstock | Δ Biofuel Energy Demand (Mtoe/year) | Δ ILUC Land Area (Mha) | Δ Emissions ($MtCO_2e$/year) | | |
|---|---|---|---|---|---|---|---|
| | | | | | ILUC Emissions | Fossil Fuel Displacement | Net Emissions Change |
| | | Other starch | +0.0 | -- | -- | -0.0 | -0.0 |
| | Biodiesel & HVO | Palm oil | -1.2 | -0.4 | -11.9 | +2.5 | -9.4 |
| | | Other vegetable oil | +3.6 | +2.3 | +9.8 | -7.3 | +2.4 |
| | | Residual oil | +0.8 | -- | -- | -2.6 | -2.6 |
| | Cellulosic | Cellulosic Crops | +3.2 | +1.0 | -1.6 | -10.8 | -12.4 |
| Indonesia | Ethanol | Molasses | +0.2 | +0.0 | +0.2 | -0.6 | -0.4 |
| | Biodiesel & HVO | Palm oil | +3.3 | +1.2 | +31.6 | -4.4 | +27.2 |
| China | Ethanol | Corn | +0.4 | +0.2 | +0.3 | -0.6 | -0.3 |
| | | Other grain crops | +0.3 | +0.2 | +0.4 | -0.6 | -0.2 |
| | Biodiesel & HVO | Residual oil | +2.7 | -- | -- | -8.3 | -8.3 |
| India | Ethanol | Grain crops | +0.3 | +0.2 | +0.4 | -0.5 | -0.1 |
| | | Damaged crops | +0.3 | -- | -- | -1.0 | -1.0 |
| | | Sugar crops | +1.4 | +0.3 | +1.0 | -3.3 | -2.3 |
| | Biodiesel & HVO | Palm oil | +2.2 | +0.8 | +20.8 | -2.8 | +18.0 |
| | | Residual oil | +1.4 | -- | -- | -4.3 | -4.3 |
| Argentina | Ethanol | Corn | +0.1 | +0.0 | +0.0 | -0.1 | -0.1 |
| | | Molasses | +0.0 | +0.0 | +0.0 | -0.1 | -0.1 |
| | Biodiesel & HVO | Soybean oil | +0.3 | +0.2 | +2.2 | -0.7 | +1.4 |
| Canada | Ethanol | Corn | +1.3 | +0.3 | +0.6 | -2.7 | -2.1 |
| | | Other grain crops | +0.2 | +0.1 | +0.2 | -0.4 | -0.2 |
| | Biodiesel & HVO | Rapeseed oil | +1.3 | +0.8 | +3.5 | -2.6 | +0.9 |
| | | Soybean oil | +0.2 | +0.1 | +1.0 | -0.3 | +0.7 |
| | | Residual oil | +0.8 | -- | -- | -2.5 | -2.5 |
| Thailand | Ethanol | Sugar crops | -0.0 | -0.0 | -0.0 | +0.0 | +0.0 |
| | | Cassava | -0.0 | -0.0 | -0.0 | +0.0 | +0.0 |
| | Biodiesel & HVO | Palm oil | -0.2 | -0.1 | -1.8 | +0.2 | -1.6 |
| | | Residual oil | +0.2 | -- | -- | -0.7 | -0.7 |
| Total | Ethanol | Starch crops | +4.2 | +1.6 | +3.3 | -10.2 | -6.9 |
| | | Sugar crops | +7.2 | +1.5 | +5.3 | -19.6 | -14.4 |
| | Biodiesel & HVO | Oilseed crops | +24.6 | +14.4 | +142.0 | -52.5 | +89.4 |
| | | Residual oil | +6.9 | -- | -- | -22.0 | -22.0 |

| Country | Biofuel | Feedstock | Δ Biofuel Energy Demand (Mtoe/year) | Δ ILUC Land Area (Mha) | Δ Emissions ($MtCO_2e$/year) | | |
|---|---|---|---|---|---|---|---|
| | | | | | ILUC Emissions | Fossil Fuel Displacement | Net Emissions Change |
| | **Cellulosic** | **Cellulosic Crops** | +3.2 | +1.0 | -1.6 | -10.8 | -12.4 |
| | **Total** | | **+46.2** | **+18.6** | **+148.9** | **-115.2** | **+33.7** |

*Note: Negative, green-coloured values signify 'beneficial' outcomes: net gains in semi-natural land areas and reductions in GHG emissions. Positive, red-coloured values are 'detrimental' outcomes.*