Cerulogy

Fuelling nature

How e-fuels can mitigate biodiversity risk in EU aviation and maritime policy

Dr Josie Phillips, Dr Cato Sandford, Sia Kebbie, Dr Chris Malins

November 2024

Acknowledgements

This work was funded by Opportunity Green. We would like to thank Graham Tucker of Nature Conservation Consulting for sharing valuable contributions (including photos) and for reviewing the report. We would also like to thank Efi Alexopoulou of the Centre for Renewable Energy Sources and Saving in Greece for speaking with us about miscanthus, and Transport & Environment and the International Council on Clean Transportation for their support in reviewing the report. Graphic design by Jane Robertson Design.

Contents

Executive summary

The challenge

The European Union (EU) is at the forefront of global efforts to address the twin crises of climate change and biodiversity loss. Central to this ambition are the targets outlined in the European Green Deal, which include cutting greenhouse gas (GHG) emissions by at least 55% by 2030 and achieving climate neutrality by 2050, as stipulated in the EU Climate Law. However, these targets come with significant challenges, especially in hard-to-abate sectors like aviation and maritime transport, which are major sources of GHG emissions.

As demand for energy in these sectors grows, the need to develop sustainable alternative fuels becomes increasingly urgent. The transition to bioenergy and renewable fuels, while critical for reducing emissions, risks leading to substantial land use changes and intensification, which can contribute to habitat destruction, loss of biodiversity, and degradation of ecosystems. This report delves into the complex intersection of these issues, assessing biodiversity risks linked to various energy production pathways, and evaluating the feasibility of aligning bioenergy development with the EU's biodiversity and climate goals.

The policy/legal environment

The regulatory environment for decarbonising the EU's aviation and maritime sectors is set under ReFuelEU Aviation and FuelEU Maritime, which establishes sector specific targets for addressing GHG emissions, through increasing the use of sustainable aviation fuels (SAFs) in aviation and sustainable maritime fuels in maritime transport. ReFuelEU Aviation mandates a minimum share of SAFs that must be supplied at EU airports, starting with 2% in 2025, with the goal of gradually increasing this share to 70% by 2050. ReFuelEU Aviation also sets a sub-target for Renewable Fuels of Non-Biological Origin (RFNBOs, also referred to as e-fuels) which progresses from an average of 1.2% in 2030 to 35% by 2050. Meanwhile, FuelEU Maritime starts in 2025 with a 2% GHG emissions intensity reduction compared to the standard comparator (91.16 gCO_2e/MJ), reaching 80% by 2050.

Both the ReFuelEU Aviation and the FuelEU Maritime regulations place restrictions on which types of fuels are eligible to contribute. They exclude food-and-feed-based biofuels, the use of which is already controversial in the on-road sector. They adopt the biofuel sustainability rules of the third and most recent iteration of the Renewable Energy Directive (RED), called RED III. These rules are intended to manage the risk that alternative fuel production in the name of climate action could impede biodiversity goals, but the protections are not comprehensive, and a rapid expansion of alternative fuel production to meet ReFuelEU Aviation and FuelEU Maritime targets could put further stress on biodiversity stabilisation and recovery. The RED III defines when it is allowable to treat the electricity used to produce RFNBOs as renewable and introduces the concept of 'renewable acceleration areas' in which renewable electricity facilities can be deployed without undue environmental impact.

These policies are also shaped by the sustainability rules of the Renewable Energy Directive (RED), which sets sustainability requirements intended to mitigate the potential for negative impacts of renewable energy generation on ecosystems and biodiversity. These rules include no-go areas for biomass sourcing (such as primary forests, protected areas and other high-biodiversity areas), and setting forest biomass sustainability criteria and limits on the use of biofuels considered to have high risk of indirect land-use change (ILUC), but do not include biodiversity requirements for many feedstock production systems.

Biodiversity protection in the EU is instead primarily shaped by the Birds and Habitats Directives. These two policies form the backbone of the EU's biodiversity protection policy framework and are supported more broadly by targets and actions set out in the EU Biodiversity Strategy for 2030 and the recently adopted Nature Restoration Regulation. The former establishes a series of targets and goals deemed necessary to halt biodiversity loss and 'put nature on the path to recovery by 2030', including targets to: protect 30% of land and sea in the EU by 2030; bring one-third of protected areas under strict protection; reduce the use of chemical pesticides by 50%; place at least 10% of agricultural land area under high-diversity landscape features (such as buffer strips, hedgerows and ponds); reduce nutrient losses from fertilisers by 50%, resulting in reduction of the use of fertilisers by at least 20%; increase organic farming to cover 25% of agricultural lands; reverse the decline in pollinators; and reduce IUCN Red list species threatened by invasive alien species by 50%.

Additionally, the Nature Restoration Regulation bolsters the legal basis for achieving the objectives of the Habitats Directive relating to the restoration of degraded habitat types and encourages practices that support wider habitat and species restoration across ecosystems and economic settings (including agriculture and forestry). The Nature Restoration Regulation mandates the restoration of 20% of the EU's land and sea areas by 2030, and all ecosystems in need of restoration by 2050. It also requires Member States to develop National Nature Restoration Plans and submit them to the Commission by mid-2026, detailing specific restoration measures to be taken to meet the legally binding targets and obligations, as well as identifying areas that will be selected for streamlined planning and development of renewable energy, emphasising that "the restoration of biodiversity should consider the deployment of renewable energy and vice versa".

Meanwhile, international frameworks such as the International Maritime Organisation (IMO) and the International Civil Aviation Organisation's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) contribute to shaping the regulatory landscape on emissions reduction and carbon offsetting for the aviation and maritime sectors at an international level. The IMO has adopted voluntary targets which aim to reach net zero "by or around" 2050 for international shipping, with interim goals of a 20-30% reduction in lifecycle emissions compared to 2008 levels in 2030 and a 70-80% reduction in 2040. Meanwhile, ICAO's CORSIA, is a global market-based measure requiring airlines to offset the growth in CO_2 emissions from international flights above 2020 levels through the purchase of eligible carbon credits, thus encouraging the use of SAFs and other practices to limit emissions from aviation.

Alternative fuels

Alternative fuels are energy sources that can replace conventional fossil fuels in the aviation and maritime sectors. In this report, we consider a range of alternative fuels including advanced biofuels produced from purpose-grown cellulosic and ligno-cellulosic energy crops (including annual and perennial biomass crops, and short-rotation forestry)and from cellulosic and ligno-cellulosic residues and wastes from existing activities in agricultural and forestry, lipid-based biofuels produced from waste and low-value oils (such as used cooking oil and rendered animal fats) and oilseeds grown as intermediate crops on existing agricultural land. We also consider Renewable Fuels of Non-Biological Origin (RFNBOs) such as green hydrogen and e-fuels, and briefly we consider liquified natural gas (LNG) and ammonia.

Risks

This report evaluates key risks to biodiversity associated with the production and use of alternative fuels, including land use change and intensification, habitat loss, soil health, pollution, the risk of invasive species, and demand for inputs such as fertiliser, pesticide, and water. The report also acknowledges additional environmental impacts not covered in detail, such as the risks of ammonia leakage on environmental acidification and eutrophication. The biodiversity risk assessment considers both the direct and indirect effects of energy production pathways, and highlights the importance of integrated, cross-sectoral policy approaches to mitigate these risks effectively.

While this report examines the biodiversity risks associated with meeting the decarbonisation targets for aviation and maritime by producing additional feedstock in Europe, it also gives some consideration to the global consequences of displacement of resources from alternative uses. For instance, increased demand for rendered animal fats within the EU may outcompete existing uses, creating a supply gap that is met through the import of materials such as palm oil, which carry significant ILUC risks and broader climate, ecosystems, and biodiversity impacts.

Within the EU, the type of land that is selected within to support the deployment of additional bioenergy or renewable energy generation is of particular concern. A common narrative that marginal lands are widely available and can be used to support renewable energy warrants critical discussion, as these lands are often of high biodiversity importance, and therefore overlap considerably with Natura 2000 sites (the EU’s network of protected areas) and wider areas holding habitat types and species protected by the Birds and Habitats Directives. Indiscriminately converting significant areas of marginal land would therefore pose biodiversity risks. A multi-criteria evaluation framework is employed to assess risk levels in several categories, drawing on data from EU reports, scientific literature, and expert consultation to rank the severity of these risks across different energy pathways.

Policy options

The scenarios explored in this report assume that the EU will maintain its current regulatory and policy ambition on climate and biodiversity. A quantitative model is developed to explore pathways delivering on the overall targets and sub-targets set by ReFuelEU Aviation and FuelEU Maritime in the period 2025 to 2050. Each scenario presents different pathways for meeting the regulatory targets, with varying implications for biodiversity. The model scenarios are based on different levels of deployment of the key alternative fuel types and are accordingly called ‘High RFNBO’, ‘High Lipid’, ‘High Biomass Crop’, and ‘High Residue’.[1] Each scenario models a different pathway for meeting projected fuel demands[2], with emphasis on a key fuel type for meeting the policy targets:

1 Other fuel types are represented in the model but are kept constant across model scenarios.

2 We follow the European Commission’s projections of segment energy demand to 2050, which do

Table 1. The compliance scenarios used in the energy modelling

Scenario	Description
High RFNBO	Emphasis on the deployment of liquid and gaseous RFNBOs leads to increased demand for renewable electricity
High Lipid	Emphasis on first-generation lipid-based fuels leads to increased demand for waste and residual oils and development of intermediate oilseed crops
High Biomass Crop	Emphasis on the use of ligno-cellulosic material from energy crops relies on development of biomass-based fuel production technology, and leads to expansion of agricultural land
High Residue	Emphasis on the harvesting of ligno-cellulosic residues and wastes from agriculture, forestry, and industry for biomass-based fuel production

Results

Our analysis reveals that the risks to biodiversity and land use posed by the different policy options vary significantly. Scenarios that rely heavily on biofuels, particularly those sourced from dedicated biomass crops, pose high risks to biodiversity due to their extensive land use demands. For instance, the use of biomass crops such as short-rotation forestry, annual energy crops and perennial grasses such as miscanthus relies on the development of biomass-based fuel production technology and requires additional agricultural or forestry land, and/or land intensification, to support the increase in cultivation, which poses significant risks to semi-natural habitats and species that occur on marginal lands. In contrast, the scenario that prioritises RFNBOs shifts the focus towards renewable electricity generation and associated infrastructure, which has a much lower impact on land use relative to any of the bioenergy pathways. This pathway carries significantly reduced risk for soil health and pollution, for introducing invasive alien species and for increasing the demand for agricultural inputs such as fertilisers and pesticides.

Our findings highlight the critical need for balancing the EU's decarbonisation objectives for aviation and maritime with its biodiversity goals. The High RFNBO scenario is in the least tension with the EU's Biodiversity Strategy and the Nature Restoration Regulation's targets, given its lower land demand and reduced pressure on habitats. It should be noted however that this scenario also requires a very large commitment of renewable electricity resources to support aviation and maritime, which could present its own tensions with aspects of the decarbonisation agenda other than biodiversity. The High Biomass Crops scenario presents substantial challenges due its requirements for new land, potentially leading to significant habitat conversion and biodiversity loss. The High Lipid scenario, while somewhat less demanding of new land, still poses considerable risks to biodiversity due to agricultural intensification, habitat degradation and potential pollution from increased use of fertilisers and pesticides. The High Residue scenario, while leveraging existing agricultural and forestry residues, raises concerns about soil health and long-term sustainability, particularly if residue removal is not carefully managed to maintain soil fertility and forest biodiversity.

not envisage any large-scale policy-mediated reductions in demand. The scenario results therefore founded on assumptions of continued growth in aviation and maritime transport activity; relaxing this assumption would in turn relax the pressure on future deployment of alternative fuel technologies.

In 2030 the EU's fuel mandates will still be in their early stages of ramping up, and feedstock demand and biodiversity impacts are relatively moderate for all scenarios. It will be important for the EU to continuously appraise the biodiversity and other environmental consequences as the fuel production systems to deliver these policies develop, and that the EU takes a high-level view on where each trajectory will eventually lead, so that short-term solutions which cannot be scaled sustainably do not get cemented into the EU's decarbonisation approach.

Recommendations

To support the EU's dual objectives of decarbonising the aviation and maritime sectors while preserving and enriching biodiversity, we make the following recommendations:

- **Develop RFNBOs technologies**: Renewable Fuels of Non-Biological Origin (RFNBOs) present the most compatible pathway for meeting existing biodiversity targets due to their lower pressures on land compared to bioenergy pathways. However, a significant portion of the necessary infrastructure, such as electrolysers and renewable electricity generation, is currently lacking, and the associated costs of scaling up are high. Delaying investment in RFNBO infrastructure risks increasing future costs significantly, akin to other climate mitigation challenges where delays lead to higher costs and stranded assets.
- **Reduce the overall demand in the aviation and maritime sectors:** The pressures on land, sea and biodiversity are already immense due to existing demands for agriculture, urban development, and conservation needs. As the most recent UN SDGs report highlighted, EU lifestyles are characterised by high energy consumption, and the EU's aviation and maritime sectors are poised for continued expansion under current energy scenarios. Delaying demand reduction measures will only exacerbate constraints on land and marine ecosystems, making it costlier and more challenging to achieve climate and biodiversity goals in the future. Implementing overall demand reduction strategies, such as enhancing energy efficiency, incentivising shifts towards lower-impact travel, and reducing frequent flying, business travel, and the use of private jets, can collectively reduce energy demand and help align the EU's biodiversity and climate goals.
- **Identify and protect marginal land of high biodiversity value:** Marginal lands presents both opportunities and challenges for bioenergy production. These lands, sometimes characterised as being unsuitable for productive and profitable conventional agriculture, have been promoted as an opportunity for producing bioenergy crops without reducing food production. However, these lands are often significant for biodiversity, overlapping with semi-natural habitats. Development and implementation of ecological assessments would help stakeholders to understand the biodiversity values and ecological functions of these lands before conversion. Additional strategies, such as guidelines for biodiversity-friendly mixed energy cropping, agroforestry, and adaptive management, could also help mitigate negative impacts and enhance positive outcomes.
- **Incorporate soil carbon monitoring**: Soil carbon remains a blind spot in EU greenhouse gas emissions accounting policies, such as the Land Use, Land Use Change and

Forestry (LULUCF) Regulation. Current policies do not mandate the inclusion of soil carbon unless it is a net source of emissions, resulting in insufficient monitoring and reporting. Without proper oversight, practices like residue harvesting may continue to degrade soil carbon stocks, undermining climate mitigation efforts. The EU's proposed soil monitoring law should strive to align with renewable energy targets by encouraging Member States to adopt forest and agricultural residue removal thresholds for key soil types. Effective monitoring and management of soil carbon is crucial since soils are the largest terrestrial carbon store, support 25% of biodiversity, and play a vital role in the sustainability of energy and food production.

- **Protect and expand habitats and other landscape features that support biodiversity in productive forestry and agricultural systems**: including remaining patches of semi-natural habitat, fallow land, native trees, hedgerows, ponds, ditches etc, some of which may be maintained as Ecological Focus Areas (EFAs) or under other agri-environmental measures of the Common Agricultural Policy (CAP). Such areas and features are essential for supporting biodiversity within agricultural landscapes, serving as refuges for wildlife, enhancing habitat connectivity, and providing ecosystem services such as pollination, natural pest control and water purification.

Glossary

Units and currency

$ / USD	United States dollars
£ / GBP	Great British pounds
€ / EUR	Euro
gCO_2e	Grams of CO_2-equivalent
GJ	Gigajoule (10^9 joules)
GWh	Gigawatt-hour (10^9 watt-hours)
ha	Hectare
kg	Kilogram
kha	Kilohectare (10^3 hectares)
kt	Kilotonne (10^3 tonnes)
kWh	Kilowatt-hour (10^3 watt-hours)
Mha	Megahectare (10^6 hectares)
MJ	Megajoule (10^6 joules)
Mm^3	Million cubic metres
Mt	Megatonne (10^6 tonnes)
MWh	Megawatt-hour (10^6 watt-hours)
PJ	Petajoule (10^{15} joules)
t	Metric tonne (10^3 kg)
tCO_2	Tonnes of CO_2
tCO_2e	Tonnes of CO_2-equivalent
TWh	Terawatt-hour (10^{12} watt-hours)

Chemical formulae

$C_{15}H_{24}$	Farnesene
CH_4	Methane
CO_2	Carbon dioxide
H_2	Molecular hydrogen
HFC	Hydrofluorocarbon
N_2O	Nitrous oxide
NF_3	Nitrogen trifluoride
NH_3	Ammonia
NO_x	Nitrogen oxides
PFC	Perfluorocarbon
SF_6	Sulphur hexafluoride
SO_x	Sulphur oxides

Organisations, projects, programmes, and policies

ASTM	American Society for Testing and Materials (former name)
BD	EU Birds Directive
BIKE	Biofuels production at low ILUC risk for European sustainable bioeconomy (EU Horizon 2020 project)
CAP	EU Common Agricultural Policy
CBD	UN Convention on Biodiversity
CII	IMO Carbon Intensity Indicator
CORSIA	ICAO Carbon Offsetting and Reduction Scheme for International Aviation
DfT	UK Department for Transport
DNV	Det Norske Veritas
EAFRD	European Agricultural Fund for Rural Development
EAGF	European Agricultural Guarantee Fund
EASA	European Union Aviation Safety Agency
EASAC	European Academies' Science Advisory Council
ECJ	Court of Justice of the European Union
EEA	European Economic Area
EEA[3]	European Environment Agency
EEB	European Environmental Bureau
EEDI	IMO Energy Efficiency Design
EEXI	IMO Energy Efficiency Existing Ship Index
EFSA	European Food Safety Authority
EMSA	European Maritime Safety Agency
ENSPRESO	EU Energy Systems Potential Renewable Energy Sources database
ETD	EU Energy Taxation Directive
ETS	EU Emissions Trading Scheme
EU	European Union
F2F	EU Farm to Fork Strategy
HD	EU Habitats Directive
FAO	UN Food and Agriculture Organisation
FISE	EEA Forest Information System for Europe
IATA	International Air Transport Association
ICAO	UN International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis

3 It will usually be obvious from context which EEA is more relevant. Typically, citations will be referring to studies and publications by the European Environment Agency, while the European Economic Area is relevant in the context of geographical groupings.

IMO	UN International Maritime Organisation
INCA	Integrated Systems of Natural Capital and Ecosystem Services Accounting
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification
ISO	International Organization for Standardisation
IUCN	International Union for the Conservation of Nature
JRC	EU Joint Research Centre
LIFE	EU L'Instrument Financier pour l'Environnement
LUCAS	EU land use and coverage area frame survey
MAGIC	An EU Horizon 2020 project
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MSFD	EU Marine Strategy Framework Directive
NABU	The Nature And Biodiversity Conservation Union
OECD	Organisation for Economic Cooperation and Development
PoMS	EU Pollinators Monitoring Scheme
RGI	Renewables Grid Initiative
RSB	Roundtable for Sustainable Biomaterials
RSPO	Roundtable for Sustainable Palm Oil
RTFO	UK Renewable Transport Fuel Obligation
SDG	UN Sustainable Development Goal
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
WFD	EU Water Framework Directive
WWF	World Wide Fund for Nature (formerly the World Wildlife Fund)

Other acronyms

1G	First generation
2G	Second generation
AECM	Agri-environment-climate measure
AES	Agri-environmental scheme
AEZ	Agri-ecological zone
ANC	Area of natural constraints
AtL	Alcohol-to-liquid hydrocarbon
BEV	Battery electric vehicle
BtG	Biomass-to-gaseous hydrocarbon
BtL	Biomass-to-liquid hydrocarbon
CCS	Carbon capture and sequestration
CCU	Carbon capture and use

CI	Carbon intensity
CNG	Compressed natural gas
DAC	Direct air capture
DLUC	Direct land-use change
EER	Energy efficiency ratio
EFA	Ecological focus area
EIA	Environmental Impact Assessment
EV	Electric vehicle
FAME	Fatty acid methyl ester
FRL	Forest reference level
FT	Fischer-Tropsch
GAEC	Good agri-ecological condition
GHG	Greenhouse gas
GIS	Geographic information system
GLOBIOM	IIASA Global Biosphere Management Model
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
HCS	High carbon stock
HEFA	Hydroprocessed esters and fatty acids
HFO	Heavy fuel oil
HNV	High nature value
HtL	Hydrothermal liquefaction
HVO	Hydrotreated vegetable oil
IAS	Invasive alien species
ICE	Internal combustion engine
ICV	Internal combustion vehicle
ILUC	Indirect land-use change
IPM	Integrated pest management
LCA	Lifecycle analysis
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LUC	Land-use change
LULUCF	Land use, land use change, and forestry
MGO	Marine gas oil
MPA	Marine protected area
MSW	Municipal solid waste
NECP	National energy and climate plan
NGO	Non-governmental organisation
NGV	Natural gas vehicle

PAC	Paris Agreement compatible
PFA	Planted forest area
PFAD	Palm fatty acid distillate
PHEV	Plug-in hybrid electric vehicle
POME	Palm oil mill effluent
PtL	Power-to-liquid hydrocarbon
PV	Photovoltaic
RAA	Renewable acceleration area
RBMP	River basin management plan
RCF	Recycled carbon fuel
RED	EU Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
RGI	Strategic Environmental Assessment
SAC	Special area of conservation
SAF	Sustainable aviation fuel
SIP	Sugar-to-iso-paraffin
SMR	Steam methane reforming
SOC	Soil organic carbon
SOM	Soil organic matter
SPA	Special protection area
SRC	Short rotation coppice
SRF	Short rotation forestry
SWD	Staff working document
TTW	Tank-to-wheel/wing/wake
UAA	Utilised agricultural area
UCO	Used cooking oil
VAT	Value added tax
VLSFO	Very low sulphur fuel oil
WTT	Well-to-tank
WTW	Well-to-wheel/wing/wake
ZEV	Zero-emissions vehicle

1. Introduction

The European Union (EU) is at the forefront of global policy efforts to combat climate change and biodiversity loss. Since 2019, it has set ambitious climate targets under the EU Green Deal, with the 'Fit for 55' legislative package at its core aiming to reduce greenhouse gas (GHG) emissions by 55% by 2030 and achieve carbon neutrality by 2050. Within this framework, the ReFuelEU Aviation and FuelEU Maritime regulations are central to decarbonising aviation and maritime transport, which together represent 10-13% of the EU's overall energy demand. These sectors are expected to grow significantly between 2025-2050, presenting substantial challenges for emissions reductions.

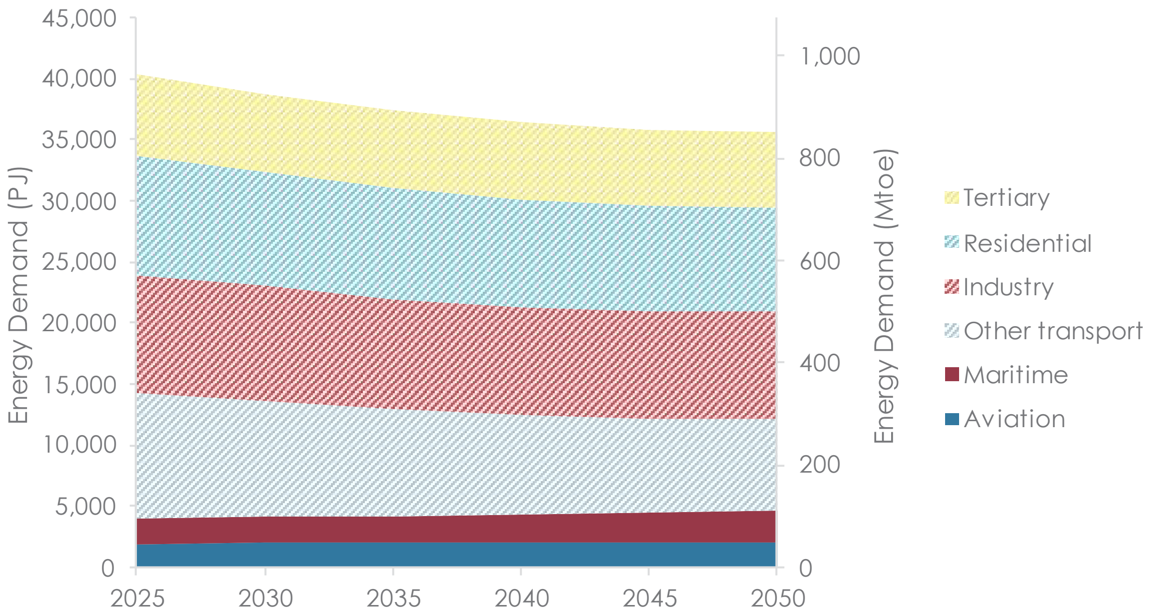


Figure 1. Projected total EU energy demand by sector to 2050, with aviation and maritime at the bottom of the stack

Note: The Aviation and Maritime components include both domestic and international transport. Tertiary energy consumption includes non-industrial commercial, services, and agriculture.

Source: Adapted from the European Commission's 'Reference 2020' scenario (European Commission, 2020e)

ReFuelEU Aviation and FuelEU Maritime set targets to replace 70% of fossil jet fuel with lower GHG-intensity alternatives and to reduce the GHG intensity of maritime energy use by 80%, both by 2050. These are the first such binding and long-term targets to be introduced anywhere in the world and meeting these targets will necessitate a rapid increase in the production and use of biofuels and 'renewable fuels of non-biological origin' (RFNBOs, also known as electrofuels or e-fuels). At present, the availability of these alternative fuels in the aviation and maritime sectors is extremely limited; meaning that compliance will require a major expansion in fuel production infrastructure and additional mobilisation of biomass and renewable electricity resources. However, this expansion is likely to bring biodiversity impacts, a concern that remains underexplored in the current literature. Balancing the EU's climate targets with biodiversity protection will be critical, particularly as energy infrastructure and biomass feedstock production could affect ecosystems within and beyond the EU.

Europe's biodiversity is both rich and fragile, with numerous ecosystems, habitats, and species that are under threat (many of which are found nowhere else on Earth). In response the EU has introduced several policies aimed at halting and reversing biodiversity loss, including the Biodiversity Strategy for 2030 the Birds and Habitats Directives; and the Nature Restoration Regulation, which mandates that Member States restore at least 20% of their land and sea by 2030, and ultimately all ecosystems in need of restoration by 2050. These policies underscore the role that healthy ecosystems play in providing essential services such as carbon sequestration, water purification, and soil fertility, which are also crucial for climate resilience and adaptation. Addressing biodiversity loss and climate change together is essential because these crises are interlinked: healthy ecosystems help mitigate climate change, and climate action can support biodiversity conservation when managed carefully.

Bioenergy feedstock production presents specific risks to biodiversity, particularly where intensive agricultural lead to habitat loss, soil degradation, and pollution from the use of fertilisers and pesticides. The conversion of natural or semi-natural habitats to monoculture plantations reduces habitat complexity and increases vulnerability to pests and disease. Well-managed agricultural landscapes, however, can maintain or even enhance biodiversity. Policies such as the EU's Common Agricultural Policy (CAP) promote biodiversity-supporting practices, including the preservation of Ecological Focus Areas (EFAs), pollinator strips, ponds, hedgerows, and other natural features which contribute to habitat connectivity and ecological balance.

In the early stages of renewable energy policy development, such as with the original Renewable Energy Directive (RED I), biodiversity was a secondary concern. While RED I prohibited biofuel production from high-biodiversity areas, it did not adequately manage biodiversity risks on existing agricultural or forest lands, nor did it fully consider the impacts of converting land areas that fell outside the defined high-biodiversity categories. RED III, the latest iteration, has expanded sustainability criteria, aimed at improving these shortcomings, though the effectiveness of these measures remains to be fully evaluated. A key challenge that persists is the risk of Indirect land use change (ILUC), where bioenergy crop production displaces other land uses, potentially driving habitat loss and biodiversity decline elsewhere, beyond the scope of the RED III sustainability requirements. Furthermore, there is a tendency to treat the CO_2 from biomass combustion as having zero climate impact at the point of combustion - a simplification that assumes the carbon was absorbed during the crop's growth. While this assumption underpins the notion of biomass renewability, it can obscure changes in carbon stock, although in principle this can be accounted for within GHG emissions frameworks such as those governed by Land Use, Land Use Change, and Forestry (LULUCF) Regulation.

In EU's 2030 Biodiversity Strategy the European Commission states that "Biodiversity loss and the climate crisis are interdependent, and they exacerbate each other" (European Commission, 2020b). The European Environment Agency reports that "despite some progress, most protected habitats and species have either poor or bad conservation status" (EEA, 2024a). Meanwhile, the 2030 Biodiversity Strategy (European Commission, 2020d), is explicit that action on biodiversity makes important contributions to economic growth and to climate change mitigation and adaptation. However, climate and biodiversity goals can sometimes conflict, particularly in the context of expanding renewable energy production, including biofuels and biomass (Bowyer et al., 2020; Dauber et al., 2010; Wiesenthal et al., 2006); yet the EU's major new policies for reducing the climate impact of the aviation and shipping sectors, ReFuelEU Aviation and FuelEU Maritime, are sure to stimulate huge growth in demand for these energy sources.

ReFuelEU Aviation creates a mandate for the use of alternative fuels in aviation, while FuelEU Maritime introduces a mandate to reduce the lifecycle carbon intensity of the energy used in shipping through increased use of shore power, wind-assisted propulsion, and lower-emissions fuels. Both regulations operate over the period 2025 to 2050, and together they will require tens of millions of tonnes of biomass resources and hundreds of terawatt-hours of electricity. Delivering those resources would have implications for land use, land management, and biodiversity in Europe and beyond.

In this report, we explore the ways in which targets under ReFuelEU Aviation and FuelEU Maritime could affect the EU's targets to reduce and reverse the decline of biodiversity. We assume that the EU's compliance targets are met and that the energy resources required (biomass, renewable power) are predominantly delivered from within the EU itself. Nevertheless, potentially significant biodiversity impacts outside the EU would still be expected because of indirect land use changes (e.g. where the use of land for bioenergy displaces food or forage crop production to countries outside the EU). A different, import-led, compliance strategy would still imply biodiversity impacts but would shift some of the burden outside the EU, and out of the scope of the EU's internal biodiversity goals.

The report is structured as follows:

- Chapter 2, 'Decarbonising aviation and maritime', reviews the policy framework for reducing greenhouse gas emissions from the aviation and maritime sectors.
- Chapter 3, 'Fuel technologies', introduces key technologies for supplying energy in the aviation and maritime sectors.
- Chapter 4, 'EU Biodiversity Policy', presents the EU's commitments on biodiversity and the portfolio of policies intended to reverse biodiversity decline.
- Chapter 5, 'Biomass-based feedstock', introduces the feedstocks needed to expand the use of renewable energy in the aviation and maritime sectors, and discusses their biodiversity impacts.
- Chapter 6, 'Biodiversity impacts of other fuels', reviews and discusses evidence on the biodiversity impacts of other production systems which will contribute to energy for the aviation and maritime sectors, and their biodiversity impacts.
- Chapter 7, 'Compliance model and decarbonisation scenarios', presents four scenarios for the resource requirements of meeting aviation and maritime decarbonisation targets.
- Chapter 8, 'Connecting demand to risk', connects the resource consumption scenarios to the expected biodiversity impacts of mobilising those resources.
- Chapter 9, 'Conclusions and recommendations', discusses the results and presents conclusions on the tensions between aviation and maritime decarbonisation policy and the delivery of EU biodiversity goals.

2. Decarbonising aviation and maritime

Aviation and maritime transport contribute a little under 10% of the EU's energy consumption (Eurostat, 2024g). As shown in Figure 2, energy demand from both sectors has risen in the past few decades, despite a decline following the 2008 global financial crisis and the 2020 coronavirus pandemic. The European Commission projects continued growth to 2050 (European Commission, 2020e).

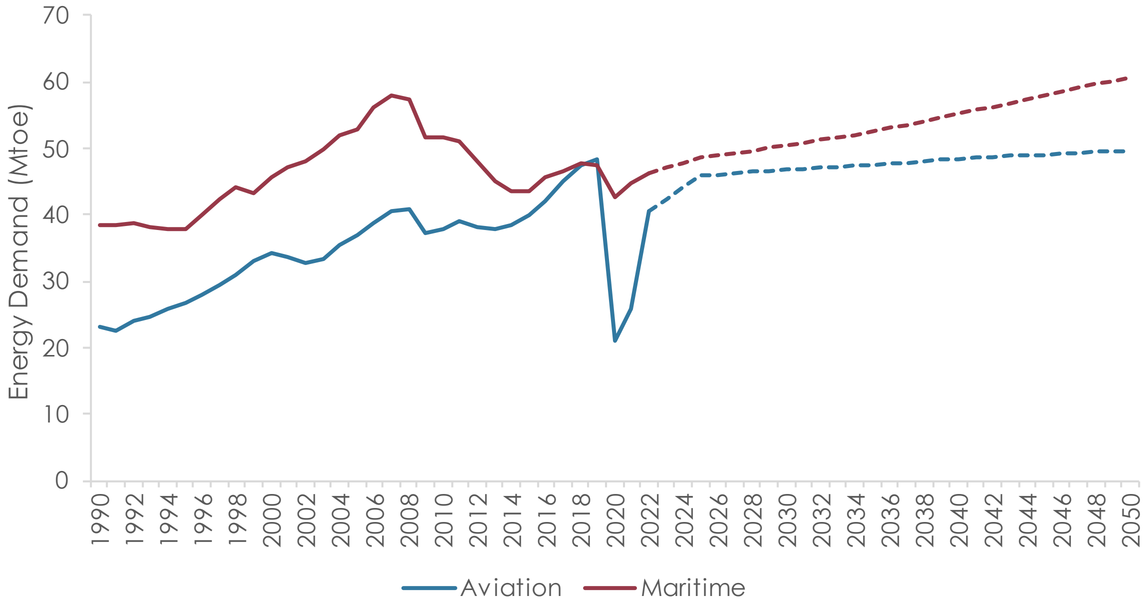


Figure 2. Historical (solid) and projected (dashed) energy demand from aviation and maritime transport in the EU

Source: Historical data from Eurostat (2024g); projection from European Commission (2020e)

This energy usage translates into considerable greenhouse gas emissions: based on Eurostat data, we find the EU's combined domestic and international aviation accounted for 123 $MtCO_2e$ of fuel combustion emission in 2022, or about 12% of transport emissions[4] (Eurostat, 2024d). In the same year, the EU's domestic and international maritime transport accounted for 149 $MtCO_2e$, or about 14% of transport emissions (Eurostat, 2024d). These figures cover in-sector emissions of common greenhouse gases[5], but not the effects of contrails, nitrogen oxides, and black carbon, which raise the climate impact of the two sectors on average. Together, they equal the annual domestic greenhouse gas emissions of the Philippines (European Commission, 2023e).

4 This is on an inventory basis rather than a lifecycle basis, i.e. it does not consider the emissions associated with fossil fuel extraction and production.

5 Specifically, CO_2, N_2O, CH_4, HFCs, PFCs, SF_6, and NF_3.

Considering the whole EU economy, prospects for mitigating future emissions vary by sector. The power sector, for instance, has already achieved reductions through the introduction of renewables and phasing down of coal – facilitated by falling costs of renewable electricity technologies. In road transport, adoption of clean electric vehicles offers the prospect of simultaneously advancing environmental goals while reducing the overall cost of driving for both light- and heavy-duty vehicles (Basma & Rodríguez, 2023; Link et al., 2024). Conversely, aviation and maritime are considered 'hard-to-abate' sectors, because there is a shortage of low-cost decarbonisation options (see e.g. ICCT, 2023). Rising historical emissions from EU international aviation and maritime transport are shown in Figure 3.

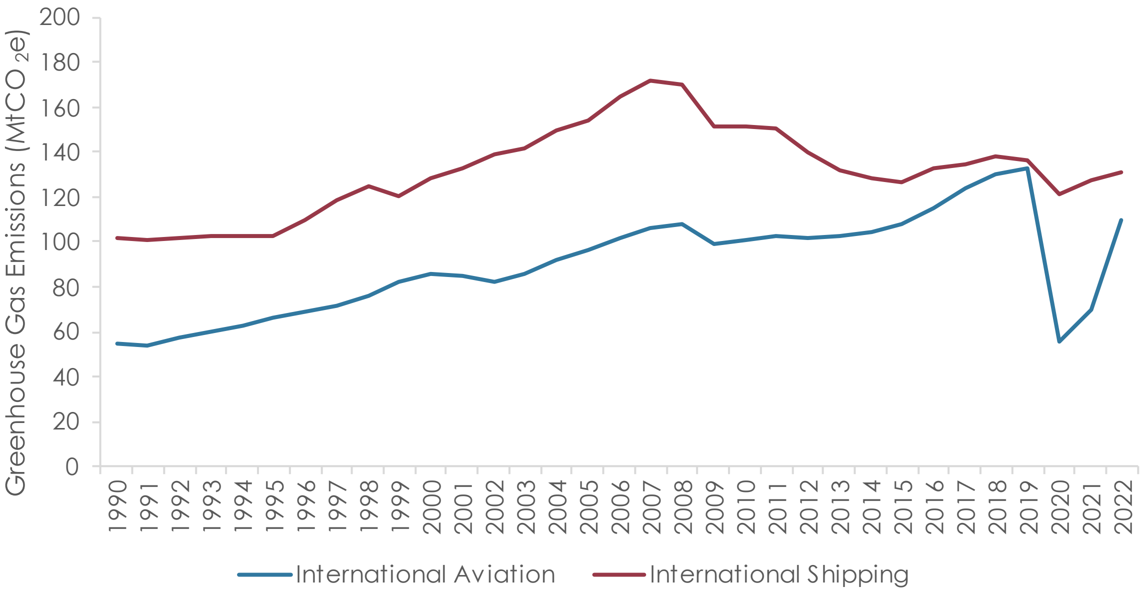


Figure 3. Historical EU fuel combustion emissions from international aviation and maritime transport

Source: EEA (2024b)

Note: International maritime emissions fell from 2007 to 2015 following the financial crash and since then have been relatively stable at around 130 $MtCO_2e$ per year.

At present, both aviation and maritime are heavily dependent on liquid fossil fuels. Aeroplanes consume jet kerosene (and to a much lesser extent aviation gasoline) and shipping consumes heavy fuel oil and marine gas oil. Both modes of transport require energy-dense fuels to make long-distance transport practical, and electricity from batteries is expected to be only a niche option for both modes in the period to 2050. Still, decarbonising aviation and maritime has been identified by the EU as a priority: the EU's 'Sustainable and Smart Mobility Strategy' (European Commission, 2021e) states that,

> *"Air and waterborne transport have greater decarbonisation challenges in the next decades, due to current lack of market ready zero-emission technologies, long development and life cycles of aircraft and vessels, the required significant investments in refuelling equipment and infrastructure, and international competition in these sectors. … Action in these sectors is urgently needed."*

While decarbonisation efforts in both modes include technological and operational options to increase efficiency, neither mode can be brought anywhere close to net zero emissions without a fundamental transition to energy sources that have lower lifecycle emissions intensity[6]. This requires rapidly increasing the production of alternative fuels that can displace fossil fuels and may in the longer-term mean transitioning to new engines or propulsion systems. For example, hydrogen could have a role as an aviation fuel but only with new plane designs that incorporate hydrogen fuel systems, and which use fuel cells and/or specialised combustion engines for propulsion. Similarly, ammonia could have a role as a maritime fuel but would require the installation of ammonia tanks and either the modification of existing engines for ammonia combustion or the introduction of ships with fuel cells. Modern sails can reduce fossil fuel demand for shipping but must be retrofitted to existing ships or designed into new ships. Even a relatively simple measure like switching ships to the use of on-shore power when moored requires installing electrical infrastructure at ports.

The production of alternative fuels and the change in propulsion systems can have biodiversity implications. Biomass and renewable energy production require land, and therefore are associated with the risk of disturbing the ecosystems where they are produced. Changing to alternative or more efficient propulsion systems in the maritime environment, or reducing ship speeds, could deliver biodiversity benefits by reducing underwater noise from engines and propellors.

The remainder of this section outlines recent EU and international policies which stimulate emissions savings and fuel decarbonisation in these sectors. We note up front that demand reduction – especially for aviation – has been identified as crucial for advanced economies to maintain a realistic chance of meeting climate goals (Element Energy, 2022); but at the time of writing, no direct policy interventions are on the table to achieve this.

2.1. Aviation

The climate impact of a long-haul flight easily outweighs the impact of most other single activities a person could undertake. The climate impact of aviation is amplified by so-called 'non-CO_2' effects, in particular where clouds formed in the wake of aircraft trap heat. The warming impact of these 'contrails' varies depending on the conditions for a given flight, but on average can be estimated as about double again the climate impact of the CO_2 from fuel combustion (Arrowsmith et al., 2000; D. S. Lee et al., 2021)[7]. Non-CO_2 effects may be reduced by a transition to alternative fuels but would not be eliminated. Because their climate impacts are not regulated at present, this report does not consider non-CO_2 effects in the model scenarios presented in Section 7.

The period since the EU's first biofuel targets were introduced through the 2003 Biofuel

6 The term 'lifecycle emissions intensity' refers to the lifecycle greenhouse gas emissions per unit of energy used in transport – typically in units of gCO_2e/MJ (grams of carbon dioxide equivalent per megajoule of energy). Lifecycle emissions factor in various stages of fuel production, transport, and use, and may include indirect 'knock-on' effects in the wider economy such as displacement of other uses and opportunity costs. Lifecycle emissions are estimated according to a set methodology deemed appropriate to the context at hand; the EU's Renewable Energy Directive establishes the lifecycle analysis requirements for regulatory characterisation of alternative fuels under EU policy.

7 See also the emission avoidance calculation methodology for the Innovation Fund (EU Innovation Fund, 2024) which recognises the outsize climate impact of non-CO2 effects from aeroplanes.

Directive has seen a legislative focus on alternative fuels for on-road applications rather than for aviation. During the 2010s, most EU Member States had no mechanism to count renewable fuel use in aviation towards targets under the EU's Renewable Energy Directive (RED)[8], and therefore aviation could not access the value of national renewable fuel incentives under the RED. While there are high aspirations for aviation biofuel use in parts of industry and government, very little biofuel was actually supplied between 2010 and 2020. For example, the EU's 'Biofuels Flight Path' set a target for 2 million tonnes of biofuel use in EU aviation by 2020 (ICAO, 2016), about four per cent of total jet fuel consumption. The actual supply was less than 0.05% (EASA, 2022).

This picture shifted somewhat with the transition to the RED II (European Union, 2018a), where the Directive was amended to explicitly favour the supply of renewable fuels to the aviation and maritime sectors. Member States were allowed to count each unit of renewable fuel supplied to aviation and maritime sectors as 1.2 units, making it easier to satisfy their renewable energy targets. In response to this and other developments, several alternative fuel plants capable of producing aviation-grade fuel have been built in Europe, and more are on their way (EASA, 2022, Figure 4.6).

The next three sections highlight specific policies which will influence the rollout of alternative aviation fuel in the EU over the coming years.

2.1.1. ReFuelEU Aviation

ReFuelEU Aviation (European Union, 2023a) is the centrepiece EU regulation for decarbonising the aviation sector; it is, along with FuelEU Maritime (Section 2.1.1), one of the two major policy pillars considered in this report. ReFuelEU Aviation affects EU airlines, airports, and aviation fuel suppliers; the latter in particular are subject to a mandate for the uptake of alternative fuels – specifically 'drop-in' fuels that are chemically similar to and can be mixed with conventional petroleum-based fuels used in existing aircraft engines. These may include RED-compliant liquid biofuels, 'RFNBOs'[9] made from electrolytic hydrogen, and recycled carbon fuels (RCFs).

Between 2025 and 2050, fuel suppliers serving airports in EU Member States must include a legislated minimum share of these alternatives in their fuel mix, as well as a minimum share of RFNBOs. As it currently stands, 2050 will see a 70% blend of alternative fuel, with 35% coming from RFNBOs (European Union, 2023a, Annex I). The quinquennial targets are shown in Table 2.

8 Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

9 RFNBO stands for 'renewable fuel of non-biological origin' and covers renewables-powered electrolytic hydrogen and other electrofuels made from this hydrogen. The ReFuelEU Aviation regulation refers to these as 'synthetic' fuels, but for clarity we use the term RFNBO.

Table 2. ReFuelEU Aviation targets, applying to aviation fuel suppliers

ReFuelEU Aviation Target	Unit	2025	2030	2035	2040	2045	2050
Share of alternative fuel	%	2%	6%	20%	34%	42%	70%
	ktoe	914	2,755	9,193	15,752	19,641	31,936
Share of RFNBOs	%	0%	1.2%[10]	5%	10%	15%	35%
	ktoe	0	468	2,298	4,633	7,015	15,968

Note: Mandated fuel supply (in energy units has been estimated following energy demand projections from the ReFuelEU Aviation impact assessment study, Giannelos et al., 2021).

Suppliers failing to meet these targets are subject to a penalty of at least twice the price difference between alternative and conventional aviation fuel. Exactly how this cost difference should be assessed by Member States has not yet been specified. Importantly, payment of the penalty fee does not clear the alternative fuel deficit, which is carried over to the following year. This means that the incentive for compliance is very high and EU aviation fuel suppliers should be willing to pay high prices on the global market.

To be eligible to count towards ReFuelEU Aviation targets, fuels must comply with RED III's sustainability criteria. These include, among other things, proscriptions on sourcing biofuel feedstock from forests, wetland, and highly biodiverse areas (described in further detail in Section 5.1); restrictions on what types of electricity can be used to produce RFNBOs (European Commission, 2023b); and maximum greenhouse gas intensity thresholds for each fuel batch. Aviation fuels supplied to satisfy ReFuelEU Aviation targets will – with one potential exception related to RED's Annex IX Part B which we'll come to later – also be able to count towards cross-transport RED III targets and therefore to stack the incentives from both. These 'doubly-compliant' fuel production processes will have a competitive advantage over fuels which can only be counted towards one of the obligations.

Certain biofuel feedstocks which are eligible for RED III, but which have been identified as having higher sustainability risks are prohibited altogether in ReFuelEU Aviation. The contribution of food and feed crops – that is, main crops rich in oil, starch, or sugar[11] – is capped in RED III at a level which varies by Member State up to a maximum of 7% of all transport energy. But in ReFuelEU Aviation, they are completely excluded. Also excluded are soap stock[12], and all palm- and soy-derived feedstocks except for oil recovered from palm oil mill effluent and empty palm fruit bunches. Intermediate crops, such as cover crops grown between main harvests, are also excluded unless they satisfy the criteria to be included in the recent update to RED's Annex IX Part A (see European Commission, 2024a). This creates a new category of crop-based fuels which are eligible to count towards ReFuelEU Aviation on

10 Specifically, the average share is not to be less than 1.2% in the period 2030-31, with a minimum of 0.7% in each year. The average in the period 2032-34 is to be not less than 2.0%, with a minimum of 1.2% in 2032-33 and 2.0% in 2034.

11 The technical definition can be found in RED III Article 2.

12 A by-product of vegetable oil refining traditionally used in soap manufacture.

top of receiving the benefits accorded to 'advanced' biofuels under the RED. The potential role of intermediate crops in aviation biofuels is further discussed in Section 5.4.

The RED identifies certain feedstocks as eligible for extra support: these include things like industrial wastes, straw, manure, and ligno-cellulosic material, and are listed in Annex IX of the Directive (reproduced in Section 5.1.1, Table 10). The RED confers special advantages on these feedstocks in order to incentivise uptake; but ReFuelEU Aviation goes further by restricting the use of any feedstocks not listed in Annex IX, capping them at 3% of total fuel. Hitting this maximum supply cap would meet half of the alternative fuel obligation in 2030 (see Table 2); the relative contribution of non-Annex IX fuel would fall quickly thereafter.

The aforementioned exception where ReFuelEU Aviation supports biofuels that would be excluded from support under RED III relates to RED's Annex IX Part B. This lists feedstocks for which fuel conversion processes are mature; originally this meant used cooking oil (UCO) and residual animal fats from the rendering industry[13], though there have been recent additions. In RED III, there is a nominal cap on the use of these fuels at 1.7% of transport energy[14]. The imposition of a cap on these fuels is intended to motivate the development of next-generation 'advanced' biofuels, and to manage risks associated with high levels of demand for the listed feedstocks, such as mis-labelling fraud. In contrast to RED III, ReFuelEU Aviation places no cap on the volumes of Annex IX Part B fuels that can contribute to targets. ReFuelEU Aviation is therefore expected to drive a redeployment of UCO and animal fats out of road biofuels and into aviation biofuels. Indeed, it will be very difficult to meet near-term ReFuelEU Aviation targets without significant volumes of HEFA[15] made from these feedstocks, as the HEFA technology is the only alternative aviation fuel currently produced at anything like commercial scale. This could lead to volumes of residual oils being consumed in aviation that exceed the RED III capped level – these batches of lipid-based aviation fuel would receive support only from ReFuelEU Aviation and not from RED III[16]. There is a broader question about whether there is a net benefit from shifting fuels currently consumed in the road sector into aviation instead, but that is outside the scope of this report (cf. EWABA, 2021).

Turning from biofuels to RFNBOs, we note that the latter offer considerable decarbonisation potential if produced from additional renewable electricity. As will be discussed in later sections, RFNBOs are one of the more scalable solutions for liquid fuel production. But the technology is expensive (largely due the cost of electricity) and under-utilised (Malins, 2017; Soubly & Riefer, 2020), with negligible production at present. ReFuelEU Aviation could jump-start this industry, as it provides a strong regulatory value signal for RFNBOs through the dedicated binding sub-target (Table 2). Actually meeting this target would, however, necessitate a very high degree of ambition for the scale-up of both renewable electricity generation availability and RFNBO production capacity.

13 Specifically, category 1 and category 2 fats which are somehow contaminated and not fit for use in food and feed chains (Malins, 2023).

14 Member States can request to exceed the cap, and many do so (Soquet-Boissy et al., 2024).

15 HEFA stands for 'hydroprocessed esters and fatty acids'. It is a type of drop-in renewable jet fuel made from lipid feedstocks.

16 With reference to Footnote 14, it is plausible that Member States will use the leeway for raising their domestic cap on Annex IX part B feedstocks to make sure that the volumes supplied are always eligible for the double credit.

2.1.2. Other EU legislation

Two EU policy developments unconnected to the RED or ReFuelEU Aviation have important implications for the cost difference between conventional (fossil) and alternative aviation fuels: the Emissions Trading Scheme (ETS) and the Energy Taxation Directive (ETD). The ETS is a cap-and-trade market covering high-emitting sectors in the European Economic Area (EEA). Under the ETS, a limited number of emissions allowances are made available to trade among obligated parties who must pay for the right to pollute (European Commission, 2023l). Flights within the EEA are covered by the ETS, meaning that airlines must buy emissions allowances equal to their combustion emissions. There is a contrast here with the ReFuelEU Aviation blending mandate, where the regulated party is the fuel supplier rather than the airline. Because alternative fuels are treated as zero-emission under the ETS, they are exempt from the extra costs from buying allowances: this strengthens the incentives for airlines to procure alternative fuels in aviation, and hence creates a value signal for fuel suppliers and producers. In future, the ETS may be expanded to cover many international flights as well, depending on the EU's assessment of the performance of CORSIA (which is discussed in Section 2.1.4) (Wissner & Graichen, 2024).

The second EU policy discussed in this section is the ETD, which sets minimum levels of fuel duty within the EU, but which currently exempts aviation and certain maritime fuels. An amendment put forward by the European Commission as part of the 'Fit for 55' package proposed a minimum tax for fossil fuels used in aeroplanes, but not for alternative fuels (European Commission, 2021d, Article 14). This tax would be mandatory for intra-EU flights, and Member States would have discretion over extra-EU flights. The minimum rate was proposed to be the same as for petrol and diesel, namely 10.75 €/GJ (European Commission, 2021d, Annex I), which translates to around 0.38 €/litre for jet kerosene. At the time of writing, it seems that the proposal is still being negotiated in the EU trilogue (cf. Gavin, 2024).

2.1.3. UK SAF Mandate

In parallel with the EU's introduction of ReFuelEU Aviation the UK is in the process of introducing a Sustainable Aviation Fuel Mandate (the 'SAF Mandate'), which was announced in 2022 as part of the Government's Jet Zero Strategy (UK Department for Transport, 2022). Like ReFuelEU Aviation, this requires a gradual increase in alternative share of aviation fuels supplied in the UK and includes a sub-target for RFNBOs (in this context called power-to-liquid, or PtL fuels; these exclude the direct use of hydrogen). Rules for the Mandate have been provisionally finalised by the UK Department for Transport[17]; the alternative fuel quota starts at 2% in 2025 and rises to 22% in 2040 (UK Department for Transport, 2024a). The PtL target is set to reach 3.5% in 2040 – relatively modest next to ReFuelEU Aviation's 10%. The quinquennial points set by the UK Government are shown in Table 3; quotas for intervening years are to be linearly interpolated.

17 At the time of writing these have been approved by the lower house of the UK Parliament (Hussain, 2024), but have not yet become law.

Table 3. Regulatory fuel volumes required by the UK SAF Mandate, in % 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	230	1,238	1,918	2,918
PtL obligation	%	0.0%	0.5%	1.5%	3.5%
	ktoe	0	58	166	360

Note: The regulatory percentages in this table are translated into estimated fuel volumes using DfT's jet fuel demand projection (UK Department for Transport, 2024b). The SAF Mandate includes a weighting factor which scales with fuels' lifecycle emissions intensity; this means that a given physical ktoe of fuel may count as more or less than 1 ktoe for regulatory purposes.

The biofuel feedstocks that can contribute to SAF Mandate compliance are restricted to wastes and residues, and PtL fuel must be based on low-carbon electricity. The contribution of lipid-based HEFA is allowed to be significant in early years of the Mandate but is capped at a maximum 7.8% of total aviation fuel consumption from 2035 onwards. Among other things, this signals to investors that there will be increasing demand for non-HEFA fuels like ligno-cellulosic biofuels in the UK market.

Fuel suppliers have the option of paying a fixed 'buy-out' fee (expressed in units of £/litre) instead of supplying alternative fuel. This acts as a cost-containment mechanism, as obligated parties will never have to spend more than the buy-out to maintain compliance, even if alternative fuel prices should rise due to limited market supply. However, the buy-out price has been set rather high – 4.75 £/litre (or 5.00 £/litre for PtL): for context, petroleum-based jet fuel costs around 0.60 £/litre. Since fuel suppliers should be willing to pay anything up to the buy-out plus the cost of fossil jet in pursuit of compliance, this gives an indication to prospective fuel producers and investors of the revenue they can expect from a unit of fuel.

For the EU, the UK's SAF Mandate is both a competitor and an ally. If there is short supply of compliant fuel volumes on the market, then both systems will vie for the same limited fuel pool. At the same time, the existence of two independent regulatory markets with commonalities in their sustainability criteria should provide confidence to fuel producers and their investors to invest in fuel plants and scale up operations. In particular, the UK market will provide a clearer value signal for cellulosic fuels than ReFuelEU Aviation in the near term and could therefore support the deployment of technologies that the EU market will urgently need after 2030.

2.1.4. CORSIA

The Carbon Offsetting and Reduction for Sustainable International Aviation scheme (CORSIA) was established in 2016 by the UN's International Civil Aviation Organisation (ICAO) in pursuit of 'carbon neutral growth'. This goal intends to balance rising airline activity and CO_2 emissions with an obligation to buy carbon offsets, and/or reduce fuel lifecycle emissions. CORSIA is currently in its first phase of implementation, and the scheme is scheduled to end in 2035. As of September 2024, 128 states have agreed to participate from 2025 onwards (phase 1 is 2024-2026) (IATA, 2024). For now, participation remains voluntary.

The programme is impressive in its global coverage and provides a foundational framework of methodologies and standards that can be adapted to suit national contexts. For markets such as the EU and UK, which already have a sufficiently strong value signal to motivate alternative fuel supply anyway, CORSIA credits can be stacked and value passed through to fuel producers to improve returns. However, weaknesses in conception and implementation have been identified in the environmental literature (Schneider & Wissner, 2022). The reliance on offsets rather than direct emissions reductions means that the scheme's effectiveness is dependent on the availability and integrity of these offsets, which can vary widely in quality and impact. Furthermore, the price of carbon offsets – even those which have been vetted under the CORSIA methodology – has generally been lower than what is needed to incentivise airlines to make significant operational changes or invest heavily in alternative fuels and efficiency technologies. The value signal to promote alternative fuel production and uptake is therefore weak.

2.2. Maritime

2.2.1. FuelEU Maritime

The FuelEU Maritime Regulation (European Union, 2023c) establishes a quinquennial schedule of greenhouse gas intensity reduction targets for the energy used by maritime ships calling at EU and neighbouring ports. The use of a greenhouse gas intensity target (per unit of energy), rather than mandating a share of energy to be met with alternative fuel is an important structural difference with ReFuelEU Aviation. Another is that compliance with FuelEU Maritime is the responsibility of vessel operators (akin to the ETS) rather than on fuel suppliers. This allows FuelEU Maritime to incentivise practises that are beyond the control of fuel suppliers, such as the use of shore power when docked and the use of wind power with modern sails.

The emissions intensity schedule starts in 2025 with a 2% reduction compared to the standard comparator (91.16 gCO_2e/MJ) and tightens to 80% in 2050 as shown in Table 4. Fuels' emission intensities are calculated using the RED methodology, and the average emissions intensity for ship operators is calculated according to a formula which accounts for the amount of each fuel consumed, the calorific value of the fuel, the capacity to use wind propulsion, the use of direct connections to on-shore electrical power, methane slip from LNG engines, and a regulatory bonus for using RFNBOs (see Annex C.3.1 below)[18]. There is a separate nominal obligation to use a 2% RFNBO blend that is triggered if the use of RFNBOs falls below 1% in 2031; but this requirement may be waived if certain conditions are met – like if RFNBOs being deemed too expensive.

Table 4. FuelEU Maritime targets, applying to shipping operators

FuelEU Maritime Target	Unit	2025	2030	2035	2040	2045	2050
Emissions Intensity Reduction	%	2%	6.0%	14.5%	31.0%	62.0%	80.0%
Emissions Intensity Standard	gCO_2e/MJ	89.3	85.7	77.9	62.9	34.6	18.2

Note: Percentage reductions are with reference to a standard comparator of 91.16 gCO_2e/MJ.

18 The formula for calculating an operator's overall emissions intensity does not differentiate the relative efficiencies of different engine types.

In terms of eligibility criteria, fuels must adhere to the sustainability criteria in RED III's Article 29. Food-and-feed biofuels are excluded from contributing, but otherwise the set of compliance options is wider than under ReFuelEU Aviation and even RED III. Thus, batches of fossil-based LNG, ammonia, methanol could be supplied, provided they meet the Regulation's other eligibility criteria (cf. Springer et al., 2023).

Not all maritime fuel consumption is covered by the FuelEU Maritime Regulation. Ships below 5,000 t are exempt, as are fishing boats, military vessels, and inland vessels. Obligations apply to all fuel used on voyages between Member State ports (unless the voyage is to an 'outermost region'[19]), but only apply to half of the fuel used on voyages between Member States and third countries. To minimise the risk that long-haul shipping would be re-routed via nearby non-EU ports in order to cut the obligation, major neighbouring ports within 300 nautical miles are considered to be within scope (European Union, 2023c, Recital 13).

A ship or fleet operator with a compliance surplus in one year may bank it for the following year. An operator with a deficit may make up the shortfall (with interest) in the following year – provided the deficit is sufficiently small and such a claim has not been made two years running. Failing this, the operator faces a penalty which grows with the emissions above the target[20], and which ratchets up for each consecutive year of non-compliance.

2.2.2. Other EU legislation

Aside from FuelEU Maritime, two other pieces of EU legislation contain measures to drive decarbonisation of maritime fuel. The first is RED III, which includes an indicative sub-target for Member States to ensure that, from 2030, at least 1.2% of fuel supplied at their maritime ports be RFNBOs (European Union, 2023b, Article 25.1). This aligns with the FuelEU Maritime obligation on individual ship operators to source at least 1% RFNBOs.

The second is the ETS, which by 2026 will cover 100% of emissions on voyages between EU Member States, 50% of emissions on voyages between an EU Member State and another country, and 100% of at-berth emissions at EU ports. As with aviation, use of alternative fuels will reduce the burden of buying ETS credits, and so alternative fuel suppliers can benefit from stacking the value of FuelEU Maritime and the ETS[21].

2.2.3. IMO targets

In addition to the EU-specific regulations, the International Maritime Organisation (IMO) plays a role in the regulation of greenhouse gas emissions from maritime transport. Its 2023 Strategy (UN International Maritime Organisation, 2023), agreed a series of aspirational targets,

19 The EU has nine outermost regions located in remote places, including: Guadeloupe, French Guiana, Martinique, Mayotte, Réunion, and Saint Martin (France), the Azores and Maderia (Portugal), and the Canary Islands (Spain).

20 The relationship between the penalty level and the emissions overshoot is not trivial, with the fee in € per excess tCO_2e varying inversely with operators' achieved CI.

21 It should be noted that by promoting the use of alternative fuel, ReFuelEU Aviation and FuelEU Maritime would ceteris paribus increase the availability of ETS credits in other sectors of the economy, perversely allowing them to increase their greenhouse gas emissions. This 'waterbed effect', which is common to cap-and-trade systems, can be avoided if the overall emissions cap is adjusted down to reflect the extra decarbonisation impetus from the new regulations.

including to reach net zero "by or around" 2050, with interim goals of a 20-30% reduction in lifecycle emissions compared to 2008 levels in 2030 and a 70-80% reduction in 2040[22]. This is complemented by a target to reduce the average lifecycle emissions intensity by at least 40% in 2030, and a sub-target to use 5-10% zero-or-near-zero-emissions sources in the energy mix, also in 2030. The Strategy does not recognise black carbon (from ship exhausts) as a climate pollutant, even though this has a significant warming effect, particularly when emitted in at high latitudes.

In contrast with the EU regulations, the IMO's targets are at present voluntary for IMO Member States – there are no binding provisions to ensure the targets are met. Regulatory levers which have been identified for driving down emissions on existing and new ships in pursuit of the above targets are the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII). In their current form they are not expected to drive high rates of efficiency improvements or alternative energy adoption; avenues for strengthening them have been identified (Abbasov, 2024; Comer & Carvalho, 2023; Faber et al., 2016).

22 According to Figure 3 (EEA, 2024b), emissions from international shipping in 2008 were 170 $MtCO_2e$, so achieving the IMO targets would amount to emitting 119-136 $MtCO_2e$ in the year 2030 and 34-51 $MtCO_2e$ in 2040.

3. Fuel technologies

A given fuel used in the transport sector can be categorised according to several characteristics, including:

- The type of molecule (e.g. hydrocarbon, alcohol);
- The type of engine it is used in (e.g. combustion, fuel cell);
- The type of feedstock used to produce it (e.g. vegetable oil, cellulosic biomass); and
- The production technology (e.g. gasification plus Fischer-Tropsch synthesis, electrolysis).

The next section gives a preliminary introduction to types of engine technologies; those that follow itemise the fuel production technologies of greatest relevance to this report. This will cover some key points about fuel production and use, the major feedstock and input requirements, and some climate impacts. Ecological and biodiversity impacts will be discussed in depth in Chapters 5 and 6. A pre-emptive summary of the fuels considered is provided in Table 5 below. We return to discuss fuel and engine types in more depth in Chapter 7 which presents modelled scenarios of future fuel demand.

Table 5. Summary of fuels expected to contribute to the maritime and aviation sectors under ReFuelEU Aviation and FuelEU Maritime, organised by fuel production technology

Fuel Production Technology	Major Process	Main Output	Modes	Feedstocks
FOSSIL-BASED FUELS				
Fossil liquids	Drilling, cracking, fractionation	Liquid hydrocarbons	Maritime (HFO, MGO) and aviation (kerosene)	Petroleum
LNG	Liquefaction	Liquefied hydrocarbon	Maritime	Fossil methane
Industrial gas fermentation	Fermentation and catalytic upgrading	Liquid hydrocarbons	Maritime and aviation	Carbon monoxide
Pyrolysis	Thermochemistry and catalytic upgrading	Liquid hydrocarbons	Maritime and aviation	Waste plastics, rubbers, etc.
FIRST-GENERATION BIOFUELS				
HVO/HEFA	Hydrogenation	Liquid hydrocarbons (distillate range)	Maritime (HVO) and aviation (HEFA)	Lipids, including vegetable oil and residual oils
Biodiesel	Trans-esterification	Liquid oxygenate fuel	Maritime	Lipids, including vegetable oil and residual oils
Bio-methane	Anaerobic digestion	Gaseous hydrocarbon	Maritime	Biogas from biological wastes

Fuel Production Technology	Major Process	Main Output	Modes	Feedstocks
BIOMASS-BASED FUELS				
Gasification	Thermochemistry and Fischer-Tropsch synthesis	Liquid hydrocarbons	Maritime and aviation	Cellulosic biomass
Pyrolysis	Thermochemistry and catalytic upgrading	Liquid hydrocarbons	Maritime and aviation	Cellulosic biomass
SIP	Fermentation and catalytic upgrading	Liquid hydrocarbons	Aviation	Cellulosic biomass
AtL	Fermentation and catalytic upgrading	Liquid hydrocarbons	Maritime and aviation	Cellulosic biomass
HtL	Aqueous thermochemistry and catalytic upgrading	Liquid hydrocarbons	Maritime and aviation	Cellulosic biomass slurry, municipal waste, sewage
ELECTROFUELS				
e-Hydrogen	Electrolysis	Hydrogen	Maritime and aviation	Electricity
e-Ammonia	Electrolysis and thermochemical processing	Ammonia	Maritime	Electricity
PtL	Electrolysis and Fischer-Tropsch synthesis	Liquid hydrocarbons	Maritime and aviation	Electricity and captured carbon dioxide
ELECTRICITY				
Battery storage	Electro-chemical recharging	Electric potential energy	Maritime and aviation	Renewable and fossil electricity
WIND				
Modern sails and rotors	Energy capture	Direct propulsion	Maritime	NA

3.1. Engine types

3.1.1. Combustion engines

Essentially all planes and ships today run on fossil liquid hydrocarbons fed into internal combustion engines. In these, explosive ignition of a fuel-air mixture is converted into propulsion: in ships, combustion drives rotation of a propellor, while in jet aeroplanes it creates thrust by heating and driving air through a compression chamber. In addition to carbon dioxide and water, combustion engines tend to produce pollutants such as nitrogen oxides (NO_x), which are formed when atmospheric nitrogen is heated in the presence of oxygen, and particulate matter (PM) and sulphur oxides (SO_x) which arise from fuel impurities.

At present, jet engines have relatively uniform design principles and fuel specifications. Alternative fuels must match these specifications, and the ASTM standards body has at the time of writing approved 11 production pathways, with a further seven under evaluation

(ICAO, 2024). For each of these there is a cap on the maximum contribution of alternative fuel in the fuel blend, with the corollary that no commercial flight running entirely on alternative fuel is possible under current regulations.[23]

Ships typically have more space and load capacity than aeroplanes for engines and fuel, and a greater diversity of engine types are used: from conventional heavy fuel oil (HFO)[24] and marine gas oil (MGO) engines, to engines capable of burning LNG. Given the long service lifetimes of both aeroplanes and ships, many of the vehicles which are being built today will still be operational in 2050, and barring engine retrofits, will still be reliant on fossil or renewable hydrocarbons.

3.1.2. Fuel cells

Alternative propulsion systems use electric motors powered by fuel cells or rechargeable batteries. Fuel cells generate electricity by reacting hydrogen and oxygen: the oxygen is taken from the surrounding air, and the hydrogen must be either be supplied from a pressurised storage tank, or from a reformer that converts a hydrogen-containing energy carrier like ammonia (NH_3) or methane (CH_4) into molecular hydrogen. Some high-temperature configurations are able to perform this reaction in the fuel cell itself (Van Veldhuizen et al., 2023). Avoiding any combustion means that pollutant emissions and engine noise are much reduced.

Use of fuel cells in aeroplanes is limited to experimental and pilot projects, and the weight of the hydrogen fuel system limits future applicability to short-haul flights (Mukhopadhaya & Rutherford, 2022). Breakthroughs in low-weight hydrogen storage and fuel delivery systems on board aircraft, efficient cooling for fuel cells, and jet engines tailored for hydrogen combustion, could bring hydrogen propulsion to a broader range of aircraft and routes (Barker et al., 2022). But the consensus for now is that even under optimistic scenarios, hydrogen will not be able to displace liquid kerosene-like fuels.

System weight, volume, and compact cooling are less of a concern for maritime transport, and hydrogen propulsion has already been demonstrated in ferries and shipping applications.

3.1.3. Batteries

Battery-powered electric motors also eliminate exhaust pollutants and reduce noise. In the EU road sector, sales of passenger battery electric vehicles (BEVs) have grown rapidly (IEA, 2024; Transport and Environment, 2024), and the share of electric heavy-duty freight vehicles and buses is also increasing (Chu & Cui, 2023; IEA, 2024). The superior efficiency of electric motors, which convert around 90% of electrical energy to mechanical work, combined with increasing share of renewable electricity generation in national grids, means that lifecycle greenhouse gas emissions from BEV usage are comparatively low (Bieker, 2021).

Due to the weight considerations, purely battery-powered civil aviation is likely to remain

23 At the end of 2023, a Virgin Atlantic flight demonstrated the technological feasibility of crossing the Atlantic running entirely on non-petroleum-based aviation fuel. However, it required special authorisation from the UK Civil Aviation Authority and passengers did not pay for their tickets.

24 In this report, we treat the terms heavy fuel oil and very low sulphur fuel oil (VLSFO) interchangeably.

restricted to short flights taken by small 'turboprop' planes (e.g. for island-hopping routes). Another drawback of batteries in the context of aviation is that unlike liquid fuel tanks, their mass doesn't diminish as energy is consumed. Considering the existing distribution of flight distances, it is estimated that lithium-ion batteries could displace at most 5% of the fossil fuel demand of the aviation sector in a hypothetical scenario where the entire global stock of the smallest aircraft were to be replaced (Barker et al., 2022). However, future advances in batteries' specific energy, durability, and charging rates may enable the construction of larger planes to use the technology.

In the maritime sector, a number of vessel types are suited to using batteries, either as the sole energy source or in a hybrid configuration with a combustion engine. Electric ferries and harbour support vessels – which travel relatively short distances and are never far from recharging facilities – are important commercial use cases. However, liquid fuels and fuel cells will almost certainly be needed for long-haul shipping even in the long term.

3.1.4. Wind

It is standard practice to plan aeroplanes' flight paths to take advantage of favourable wind currents, as this can speed up flight times and reduce fuel consumption. Similar planning of ocean routes based on winds and ocean currents happens in the commercial maritime sector, but more active harnessing of wind for propulsion is in a second infancy. The major wind propulsion technologies under development are rotor (Flettner) sails, hard and soft sails, suction wings, and kites: each of these have different cost implications and domains of applicability (Laursen et al., 2023).

3.2. Fossil-based fuels

The remainder of this chapter introduces the types of fuels of greatest relevance to future aviation and maritime applications, starting with fossil fuels made from petroleum and natural gas,

3.2.1. Fossil liquids

Fossil liquids are hydrocarbons including kerosene used in jet engines, and heavy fuel oil (HFO) and marine gas oil (MGO) used in ship engines. They are derived from petroleum via fractional distillation – a process where petroleum is heated, and its components are separated according to boiling point. Depending on the desired output, heavier, long-chain hydrocarbons may be 'cracked' – i.e. broken into shorter, lighter molecules through a chemical reaction with hydrogen. For example, excess HFO could be cracked to produce more kerosene.

Technical specifications on fuel properties are imposed by international regulations from the ICAO and the IMO. These include physical characteristics like viscosity and chemical characteristics like sulphur content.

3.2.2. Liquefied natural gas (LNG)

LNG is fossil methane that has been liquefied under high-pressure cryogenic conditions, reaching an energy density about 6,000 times greater than gaseous methane at standard conditions. Prior to liquefaction, the methane must usually be treated to remove impurities like hydrogen sulphide and heavier gaseous hydrocarbons. Due to the weight and complexity of the LNG fuel system, it is suitable for use in heavy maritime transport but not aviation.

Commercial LNG-capable combustion engines are a relatively new technology, and refuelling infrastructure at ports is not yet widespread. Nevertheless, use of LNG in shipping is growing, with an EU-27 consumption of around 2 Mt in 2021 (European Commission, 2023c). A study which pre-dates the adoption of the FuelEU Maritime Regulation estimated that by 2030 there would be 2,500-4,000 LNG-fuelled ships in the EU, consuming between 1 and 5 Mt of LNG per year (Faber et al., 2017). More recently, Comer et al. (2022) put the number at 7.4 Mt.

Burning LNG generally produces fewer air pollutants than conventional liquid fuels, and carbon dioxide emissions per unit of energy delivered are estimated to be around 20-30% lower, so fossil LNG is regarded by some as a transitional lower-carbon fuel. However, full lifecycle analyses which account for methane leakage throughout the whole supply chain and methane slip from engines have found that the climate advantages of LNG may be much reduced or even reversed (Lowell et al., 2013), and so the environmental community is by and large sceptical of fossil LNG as a genuine decarbonisation option.

3.2.3. Recycled carbon fuels (RCFs)

RCFs are fuels which harness unspent chemical energy from fossil by-products. They are not expected to be a major component of the EU's energy mix for maritime and aviation, but it is nonetheless useful to briefly consider two main production pathways: gas fermentation and pyrolysis. In gas fermentation, modified micro-organisms process industrial off-gases which contain carbon monoxide into alcohols; these alcohols can then be upgraded into hydrocarbon fuel (see Section 3.4.4). Steel mills are one industry that produces suitable off-gas mixes. Pyrolysis starts with wastes containing fossil carbon such as unrecyclable plastics or rubbers (e.g. car tyres). These wastes are heated to produce pyrolysis oil, which can then be catalytically upgraded to hydrocarbons (see Section 3.4.2).

The lifecycle emissions for both fuel production routes are sensitive to the alternative fate of the fossil carbon feedstock. For example, if standard procedure would be to burn waste carbon monoxide to produce useful heat, then substitution emissions (e.g. from extra natural gas consumption) must be accounted for.

3.3. First-generation biofuels

We use the term 'first-generation biofuels' to refer to fuels made from biogenic feedstocks using mature and commercialised technologies. 'First generation' is sometimes abbreviated to '1G'.

3.3.1. HVO and HEFA

HVO stands for hydro-treated vegetable oil and HEFA stands for hydro-processed esters and fatty acids. Their production pathways are virtually the same, but it is customary to refer to fuel meeting road and maritime specifications (i.e. diesel analogues) as HVO, and fuel meeting aviation specifications (i.e. jet kerosene analogues) as HEFA. Hence, they are sometimes referred to as 'renewable diesel' and 'renewable jet fuel' respectively.

HVO/HEFA are liquid hydrocarbon biofuels produced from lipids – that is, virgin vegetable oils like soy oil or palm oil, or wastes and residues like used cooking oil (UCO). These feedstocks are first cleaned and then reacted with hydrogen to saturate double bonds and remove oxygen atoms, resulting ultimately in a straight (paraffinic) or branched (iso-paraffinic) hydrocarbon. As with all hydrocarbon-producing pathways, these cover a range of molecular weights and chain lengths, so fractional distillation must be used to extract the different fuel grades (i.e. kerosene-like fraction for aviation, and the diesel- or heavy-fuel-oil-like fraction for maritime).

The use of virgin vegetable oils for biofuel production is often associated with agricultural expansion into formerly unfarmed areas, with commensurate climate and environmental impacts (described in Annex B.1). UCO and low-grade animal fats, on the other hand, are considered waste resources, and by convention their production emissions are set to zero. However, the supply of both is limited, and they are already widely used to make fuel for the road sector (and beyond – cf. Malins, 2023). Since scope for sustainable expansion of the lipid feedstock base is limited, it is possible that future HVO used in ships and HEFA used in planes will have been diverted from road transport, and hence offer little direct climate benefit. Moreover, the high value placed on waste oils has in the past led to fraudulent labelling of virgin vegetable oil (Suzan, 2023).

3.3.2. Biodiesel

FAME biodiesel[25] (henceforth just 'biodiesel') can be blended with diesel-like fuels up to a limit determined by the fuel specification[26]. Biodiesel is made by reacting a lipid base with methanol and removing the glycerol by-product; on a molecular level, this leaves an oxygenated fuel rather than a pure hydrocarbon – hence the need for the blend specification. Since the underlying feedstocks are the same as for HVO/HEFA, the same comments apply.

3.3.3. Bio-LNG

Bio-methane can be liquefied in the same way as natural gas (Section 3.2.2) to produce bio-LNG. Bio-methane itself is produced when biogenic wastes and residues such as animal manure, sewage sludge, household food waste, or the biogenic fraction of landfills, rot in a low-oxygen ('anaerobic') environment. The resulting biogas consists mostly of carbon dioxide and methane; this can be directly used as a fuel, or it may be purified, pressurised, and injected into the natural gas grid. 'Book-and-claim' systems allow bio-methane producers to earn some form of certificate for injecting the bio-methane; certificates can then be sold to a down-stream user of natural gas from the grid who can claim to be using a low-carbon fuel regardless of where the molecules of gas actually come from.

25 FAME stands for fatty acid methyl ester.

26 For example, B5 denotes a 5% biodiesel blend by volume, but standards exist for mixes up to and including B100.

3.4. Biomass-based fuels

Biomass-based fuels are sometimes known as 'second-generation biofuels' ('2G biofuels'). They are produced from cellulosic and ligno-cellulosic feedstocks – for example, wood residues from forestry activities, crop residues like wheat straw, sawdust from wood mills, waste cardboard, or purpose-grown perennial grasses. More dispersed feedstocks are naturally more challenging to collect, and all may have existing uses or limits to the amounts that can be sustainably harvested for biofuels.

The biomass-to-liquid (BtL) and biomass-to-gas (BtG) fuels considered here showcase a range of methods for producing hydrocarbons (Maniatis et al., 2017), but it is worth noting that at the time of writing, few if any commercial-scale plants have demonstrated viability.

3.4.1. Gasification

Gasification is a thermo-chemical process where biomass at high temperature emits a mix of hydrogen, carbon monoxide, and carbon dioxide (Landälv et al., 2018). The bio-hydrogen component can be separated out and purified, or the mix of gases can be used as a 'syngas' for Fischer-Tropsch synthesis of liquid hydrocarbons (this would produce a form of BtL fuel).

For the latter process, it is typically necessary to enrich the hydrogen content of the syngas, either from an external source or by using a 'water-gas shift' reaction, after which the Fischer-Tropsch and hydrocracking steps convert the gas into a mix of hydrocarbons (Yugo & Soler, 2019). The relative abundance of hydrocarbons with different chain lengths can be tuned through the optimisation of the refinery and the level of hydrocracking used – thus a refinery can be optimised to produce jet fuel, road gasoline, road diesel, or marine fuels. As with other technologies whose main output is a hydrocarbon mix (such as the fossil liquids discussed in Section 3.2.1), fractional distillation is used to isolate the different fuel grades.

3.4.2. Pyrolysis

Pyrolysis generically refers to a process where feedstock is heated to around 500 °C in the absence of oxygen. For biomass, this produces a liquid mixture of organic compounds (the 'pyrolysis oil'), as well as solid biochar and volatile gases. Pyrolysis oil is a complex mixture of compounds, from which impurities and oxygen can be removed through reactions with hydrogen to obtain a hydrocarbon mixture.

An advantage of pyrolysis over gasification is that the pyrolysis oil production facilities can be smaller, which reduces the up-front cost and the required catchment area for feedstock. Multiple facilities may then feed a centralised oil-upgrading facility, as the liquid is less cumbersome to transport than bulky and potentially heterogeneous ligno-cellulosic feedstocks. Depending on quality and the presence of contaminants, the solid biochar co-product may be used as a soil amendment and / or a medium-term store of carbon.

3.4.3. Synthetic iso-paraffin (SIP)

The synthetic iso-paraffin (SIP) technology pathway converts simple sugars into a hydrocarbon molecule farnesene[27] through direct fermentation by specialised micro-organisms. Hydro-processing converts this into 'farnesane', which can be blended with conventional aviation fuel up to a limit set by the ASTM (van Dyk & Saddler, 2021, Section 5.4.1). For first-generation SIP biofuel, the basic feedstock would come from sugar- or starch-rich crops, but these may not contribute to either ReFuelEU Aviation or FuelEU Maritime targets, so we do not consider them in this report. For second-generation SIP, simple sugars are obtained from cellulose via enzymatic hydrolysis. Since the microbes used for fermentation will perform differently depending on the mix of sugars available, the biochemical composition of the cellulosic input feedstock is of more consequence for SIP than for the purely thermo-chemical pathways introduced above.

3.4.4. Alcohol-to-liquid (AtL)

Alcohol-to-liquid technologies use a microbial agent like yeast to ferment sugars into alcohol (e.g. methanol, ethanol, or butanol), which may in turn be chemically 'oligomerised' into hydrocarbons (van Dyk & Saddler, 2021). Compared with SIP, the extra step adds some complexity, but this process has the advantage of the mature biological and bio-engineering understanding of alcohol-producing yeasts, and the higher degree of control that can be exercised over AtL's second thermo-chemical stage. Similar considerations about feedstock composition apply as in Section 3.4.3.

3.4.5. Hydrothermal liquefaction (HtL)

Hydrothermal liquefaction is a comparatively robust technology where heterogeneous feedstocks from municipal waste to sewage sludge to algae are subjected to high pressures and temperatures in an aqueous environment. This causes the break-down of complex molecules. Following a series of chemical reactions, a water-insoluble 'bio-oil' can, like pyrolysis oil, be upgraded through hydrogenation into a mix of hydrocarbons.

3.5. Electrofuels

Electrofuels are made using electricity to 'electrolyse' water into hydrogen and oxygen. In the EU context, electrofuels are termed 'renewable fuels of non-biological origin' (RFNBOs), and the electricity used must meet criteria set by the European Commission to show that it is both renewable and 'additional' (European Commission, 2023b). RFNBOs may not be produced using biomass power. To qualify as additional, it must be arguable that the renewable power source would not have been built without the demand for power due to the EU's alternative fuels policy: this is intended to ensure that renewable electricity (and its associated emissions savings) is not simply being diverted from one economic sector into another.

For the analysis in this report, we assume that the Commission's rules are effective and therefore that production of electrofuels is accompanied by an expansion of renewable power generation. We assume that wind and solar power are the sources most likely to meet this additional demand, and therefore assess the potential biodiversity impacts based on the deployment of new wind farms and solar farms (see Section 6.1). Hydropower generation in the EU is relatively stable and is considered unlikely to grow significantly given goals to remove

27 Farnesene is a long chain hydrocarbon molecule ($C_{15}H_{24}$) with alternating single and double bonds.

obstructions from waterways, and therefore we do not consider additional hydropower deployment to meet demand from electrofuel production.

3.5.1. Hydrogen

'Green' hydrogen produced through renewables-powered electrolysis can either be combusted in specialised engines or, more efficiently, undergo a reverse electrolysis in a fuel cell to produce electricity. Either way, the chemical end product is water vapour (though high temperatures in a combustion chamber may also result in NO_x production).

A drawback of using hydrogen as a fuel is that its storage and transport is challenging. As with LNG (Section 3.2.2), high pressures and cryogenic temperatures are needed to achieve a reasonable energy density, but this adds to the cost, complexity, and size of fuel systems. Hydrogen is also a very small molecule prone to escape containment and to degrade the structure of its containers (Arrigoni & Bravo Diaz, 2022), hence creating fire and explosion risks.

Hydrogen acts as a short-lived indirect greenhouse gas by extending the residence time of methane in the atmosphere, which warms the planet directly. Sand et al. (2023) studied the climate impacts of emitted hydrogen using a suite of five atmospheric and terrestrial chemistry models; they concluded that a kilogram of hydrogen has a warming effect equivalent to 11.6 kg of CO_2 over a 100-year time horizon, and 37.3 kg over a 20-year time horizon. Any leaks along the hydrogen supply chain will diminish or even reverse the climate advantages of hydrogen and hydrogen-based fuels, including electrofuels (Ocko & Hamburg, 2022; Sun et al., 2024). Analyses in the literature report that supply chain leaks of up to 20% for liquefied hydrogen are plausible (Arrigoni & Bravo Diaz, 2022; Esquivel-Elizondo et al., 2023); while containment and transport technologies continue to improve, the lack of tested monitoring technologies and strategies, and indeed of monitoring obligations, means that there is little visibility of the scale of the problem.

3.5.2. Ammonia

'Green' ammonia can be synthesised from green hydrogen and is significantly easier to store and transport. The Haber-Bosch process for making ammonia is well-established in industrial chemistry (ammonia is a key component of chemical fertiliser), and there is already a global infrastructure for production, storage, and transport.

As a fuel, ammonia is considered to be viable for maritime transport but not for aviation. Like hydrogen, ammonia can be burned directly or reformed to use in a fuel cell; and like hydrogen, ammonia is sometimes referred to as a 'zero-carbon fuel' in the sense that its use in combustion engines and fuel cells does not produce CO_2. However, on a full lifecycle perspective, the production of ammonia incurs the same climate impacts as the hydrogen feedstock, amplified by inefficiencies in chemical conversion, and supplemented by the energy demands of the extra processing requirements. The production of nitrous oxide (N_2O) during fuel transport, handling, and use can have warming effects (Laursen et al., 2022, Section 2.2.1). Wong et al. (2024) used assessments on existing ships to calculate that switching to a global ammonia-powered fleet would result in N_2O climate impacts equivalent to 5.8% of current shipping CO_2 emissions. Further ecological implications are discussed in Section 6.3.

3.5.3. Power-to-liquid (PtL)

Section 3.4.1 described the Fischer-Tropsch process for synthesising hydrocarbons from bio-hydrogen and carbon monoxide. The same can be done using electrolysis-derived hydrogen, if combined with a source of carbon – typically carbon dioxide, which can be reacted with hydrogen in a water-gas shift reaction to produce carbon monoxide. PtL is therefore an example of 'carbon capture and utilisation' (CCU). This carbon dioxide could be captured from an industrial point source or from the atmosphere via direct air capture (DAC). We discuss the implications of the CO_2 source in Section 6.1.8.

Electrolysis can be done with any type of electricity, but in the context of EU regulations, only renewable electricity (excluding biomass) is eligible to count towards targets (European Commission, 2023b)[28]. Given the potential scalability of renewable electricity generation compared to the limited availability of and/or the sustainability concerns around biofuel feedstocks, PtL is considered to be the most robust long-term technology pathway for production of drop-in hydrocarbon fuels that can be used in existing infrastructure and vehicle engines.

3.6. Electricity stored in batteries

Electricity from the grid or from isolated power plants could in principle be used to charge on-board batteries for both aeroplanes and ships. Electricity is generated from several sources: renewables like solar, wind, geothermal, hydroelectric and biomass; nuclear power; and the fossil fuels natural gas and coal. There is a small amount of petroleum-based power from standalone generators, but this is not included in our modelling. The evolving share of installed generation capacity and actual energy supply from each source will determine the overall impacts of electricity consumption. From a greenhouse gas perspective, renewables and nuclear are considered 'low emissions', and some sources may be treated as having zero lifecycle emissions for the purposes of regulation.

28 For the context of this report, we further refine contributing electricity generation sources to solar and wind.

4. EU Biodiversity Policy

The growing recognition that healthy ecosystems are vital for human well-being, economic prosperity and resilience to climate change has positioned biodiversity as a cornerstone of EU environmental policy (Tucker et al., 2023). Its relatively complete biodiversity policy framework enabled EU Member States to commit to halting biodiversity loss; but neither the initial target of 2010 nor the updated target of 2020 from the EU's Biodiversity Strategy to 2020 was achieved. Despite these failures, and the clear need for more ambitious actions, political commitment to the target has strengthened, due to rising public concern, international obligations under the Convention on Biological Diversity (CBD) and the realisation that the climate and biodiversity crisis are interrelated. As further discussed in Section 4.2.2, the EU Biodiversity Strategy for 2030 therefore forms a key part of the broader European Green Deal that integrates biodiversity conservation with climate action and sustainable development. The overarching 2030 target is intended to "ensure that Europe's biodiversity will be on the path to recovery by 2030 for the benefit of people, the planet, the climate and our economy". Although this target has some ambiguity, this implies that biodiversity losses are at least halted to enable recovery.

This report takes these commitments at face value – that is, we assume that the EU is serious about meeting its political commitments and its binding legal targets. As the EU strives to transition to a climate-neutral economy, balancing renewable energy expansion (and increased use of biotic resources in general) with biodiversity protection is crucial. This chapter explores the significance of biodiversity and its conservation and restoration, further outlines the EU's current biodiversity commitments, and examines the interplay between biodiversity and other related EU policies.

4.1. The EU's biodiversity and its importance

Despite being less biodiverse than tropical regions (Gaston, 2000), and despite the lasting effects of the last ice age, Europe has a relatively rich biodiversity due its complex mosaic of topography, geology, and climatic zones. The CBD defines 'biodiversity' as the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems. Much of Europe's biodiversity is endemic, meaning it can be found nowhere else on Earth (Hochkirch et al., 2023): this includes more than half of Europe's amphibian species, over 40% of reptiles and nearly a fifth of terrestrial mammals (European Environment Agency, 2024).

Most of Europe's remaining terrestrial biodiversity, including endemic, rare, and threatened species, is now dependent on 'semi-natural habitats', as much of Europe's natural habitats have been destroyed or heavily modified by centuries of human activities. Semi-natural habitats, according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) definition, is an ecosystem that has been altered by human intervention, but still has most of its biodiversity and processes intact. In Europe, forest land covered nearly 160 million hectares (Mha) of the EU-27 in 2020, comprising 38.6% of the EU territory (European Parliament, 2023), with nearly 94% considered semi-natural (plantations cover around 4% and undisturbed forests, the remaining 2%) (SOEF, 2020).

Semi-natural grasslands are another crucial component of Europe's biodiversity, as these habitats support a wide range of plant and animal species that rely on traditional low-intensity farming practices (Shipley et al., 2024). These grasslands (some examples of which are shown in Figure 4), like heathlands, Mediterranean shrublands, and pastoral woodlands, are a result of complex, labour-intensive farming systems using livestock breeds, crop types, and husbandry practices adapted to local soils, vegetation, and climate. Due to their high biodiversity value, many semi-natural grasslands, along with other agricultural habitats, are protected under the Habitats Directive and Birds Directive (discussed in detail below). Despite their importance, these grasslands have rapidly declined due to agricultural intensification, land abandonment, and land-use changes (Prangel et al., 2023). Many associated species, including pollinators and wildflowers, are now classified as vulnerable or endangered, underscoring the need for stronger conservation efforts to maintain these habitats.

Figure 4. Semi-natural grasslands: fallow grassland in Spain (left) and flower-rich coastal grassland in UK (right)

Copyright Graham Tucker (personal communication)

The significant role that these farming systems can play in nature conservation, which are now widely referred to as 'High Nature Value' (HNV) farming (Baldock et al., 1993; Oppermann et al., 2012), is generally recognised and incorporated into EU policy. Although difficult to map and quantify, estimates undertaken by the European Environment Agency and the European Commission suggests that a significant portion of farmland in the EU-27 may be HNV farmland (Keenleyside et al., 2014, Table 3.2), giving a minimum area of 513,147 km^2 and maximum of 748,690 km^2. This would equate to between 33% and 48% of the utilised agricultural area respectively. Other studies have reported HNV farmland to be around 30% of agricultural area (Beaufoy & Marsden, 2010; Pardo et al., 2024). However, given the documented ongoing intensification of agriculture, and agricultural abandonment (EEA, 2020), these areas are likely to have continued to decline since and are therefore increasingly the focus of nature conservation measures (including under the Common Agricultural Policy) aimed at maintaining them.

In contrast, agriculturally improved grasslands and intensively managed arable land in Europe has a highly impoverished biodiversity (e.g. see Poláková et al, 2011; Stoate et al, 2009). This is because the key determinant of the richness and abundance of biodiversity associated with agricultural habitats is the degree to which they have been modified from their natural state (e.g. as a result of grazing, one-off or occasional agricultural improvements, ploughing and conversion from grasslands to crops) and the intensification or modernisation of management (e.g. cultivations, the use of fertilisers, irrigation and pesticides) and specialisation in particular intensive systems.

Biodiverse ecosystems have intrinsic worth simply because they exist and support life forms and ecological processes (Naeem et al., 2012, 2016). When species and habitats are lost, replacing them is not a simple matter (Cardinale et al., 2012). This is because the complex interactions that take place between different organisms and their environments, mean that the loss of a single species can have cascading impacts and potentially disrupt entire ecosystems (Cardinale et al., 2012; Díaz et al., 2019; Hooper et al., 2012). Semi-natural habitats, play a vital role in maintaining ecological networks and preventing these disruptions. Their conservation is therefore central to preserving the overall resilience and sustainability of Europe's biodiversity.

Biodiversity also plays a critical role in 'ecosystem functions' (Tilman et al., 2014), which can be understood as the mechanisms through which ecosystems operate. For example, productivity refers to the amount of biomass an ecosystem can generate (Tilman et al., 2012), which is directly relevant to the bioenergy production pathways considered later in this report. Invasibility indicates an ecosystem's vulnerability to invasive species (Essl et al., 2020), which is pertinent to evaluating the risks associated with the introduction of bioenergy crops. Nutrient cycling involves the transfer of energy and matter between the living and non-living parts of an ecosystem (de Vries & Wallenstein, 2017), directly influencing soil health and productivity, both key concerns for sustainable land management. This list is not exhaustive, but highlights why biodiversity is crucial to ecosystem function, as it supports a wide range of processes which sustain life. Maintaining biodiversity is essential for these processes to function optimally (Cardinale et al., 2012), thereby ensuring the resilience and sustainability of ecosystems in the face of environmental changes (Hautier et al. 2015).

Ecosystem functions provide the foundation for 'ecosystem services.' These can be thought of as the various benefits that humans get from ecosystems, which includes food provision, air and water filtration, pollination, pest and disease control, climate regulation, and protection against extreme weather like heat waves and flooding (Vysna et al., 2021). These services are essential for supporting life itself (Balvanera et al., 2017), and if biodiversity declines to such an extent that these processes, functions, and services collapse entirely, the consequences for humanity will be devastating (Díaz, Settele, Brondízio, Ngo, Agard, et al., 2019).

The IPBES regional assessment report for Europe and Central Asia presents compelling evidence that human activities are driving the decline of biodiversity and ecosystem services (IPBES, 2018b). The report identifies land-use change as the major direct driver of the loss of both biodiversity and ecosystem services, caused by production-based subsidies which have led to the intensification of agriculture and forestry, together with the impacts of urban development. Additionally, the report highlights that increased land use intensity has impeded traditional land use and reduced semi-natural habitats of high conservation value, as well as eroding indigenous knowledge and culture across the region (IPBES, 2018b).

Similarly, the EEA's State of Nature report for Europe shows that intensifying management practices, and/or the abandonment of extensive management are the most common overall pressures for habitats and species (cf. IPBES, 2018a, p.13; Naumann et al., 2020). A recent assessment from the International Union of the Conservation of Nature (IUCN) of its Red List of Threatened Species, found nearly one fifth of all species assessed in Europe to be threatened with extinction. The IUCN attributed the decline of European biodiversity to intensified agriculture and forestry practices, as well as expanding urban areas, transport networks, and other anthropogenic activities (Hochkirch et al., 2023).

4.2. Nature Conservation Policy Framework

4.2.1. The Birds and Habitats Directives

Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds, and Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, henceforth referred to as the Birds Directive and the Habitats Directive respectively, are the main EU policy instruments contributing to the protection and conservation of biodiversity. Both directives have a similar framework of two pillars of measures: 1) site protection and conservation management measures that are targeted to areas of particular importance; 2) species protection measures that apply wherever a protected/designated species occurs.

The Birds Directive aims to conserve all naturally occurring wild bird species present in the EU. The Directive includes general provisions that apply to species wherever they occur that requires Member States to maintain and manage bird populations by protecting their eggs, nests, and habitats, and regulating activities which may harm them. It also requires Member States to classify Special Protection Areas (SPAs) for the conservation of bird species listed in Annex I of the directive (hereafter referred to as BD Annex I species) and migratory species, giving special attention to wetland species.

The Habitats Directive complements the provisions of the Birds Directive and aims to ensure the conservation of specified natural/semi-natural habitat types of Community interest listed under Annex I of the Directive (hereafter referred to as HD Annex I habitats), as well as rare, threatened, and/or endemic animal and plant species of community interest listed under Annexes II and/or IV and V (hereafter referred to as HD species). Table 7 summarises the annexes of the Birds and Habitats Directives. The main objectives of the Habitats Directive are to:

- "*Contribute towards ensuring biodiversity through the conservation of natural habitats and of wild fauna and flora*" in Member States' European territory (Article 2.1); and
- "*Maintain or restore, at favourable conservation status, natural habitats and species of wild fauna and flora of Community interest*" (Article 2.2) (Table 6).

It is important to note that the achievement of favourable conservation status is required across the entire area of each habitat and species range within each Member State. Whilst the term 'favourable conservation status' is not mentioned in the Birds Directive, it is implied. Therefore, the aims of the two directives are broadly analogous according to the European Commission's legal services (Tucker et al., 2023).

Table 6. Definitions provided for 'favourable' conservation status of natural habitats and species

Theme	Habitats	Species
Distribution	The natural range, or area covered with the habitat's range is stable or increasing	The species' natural range should not be getting smaller, nor expected to shrink in the future
Structure and function	The specific structure and functions the habitat needs to stay healthy are present and will continue to be in the future	The species must have enough suitable habitat available now and, in the future, to support its population in the long term
Condition of species	The typical species living in the habitat are also in good condition	Population dynamics must indicate that it is maintaining itself over the long term in its natural environment

Source: Habitats Directive, Article 1(e) and 1(i); European Union (2013)

The Habitats Directive makes provisions for the designation of protected sites that form a coherent EU-wide network of protected sites, known as the Natura 2000 network. Specifically, for:

- SPAs designated under the Birds Directive (which thereby gain strengthened protection under the provisions of the Habitats Directive).
- Special Areas of Conservation (SACs): designated for the protection of Annex I habitats and Annex II species (hereafter HD Annex I species).

The Habitats Directive also has special protection provisions for the species listed on Annexes IV and management provision for those listed on Annex V, which apply wherever the species is found. Table 7 below provides a summary of what is covered under the annexes of the Birds and Habitats Directives.

Table 7. Summary table of contents of each Annex of the Birds and Habitats Directives

Directive	Annex	Content
Birds (2009/147/EC)	I	Lists bird species that are particularly threatened, requiring the designation of Special Protection Areas (SPAs) for their conservation.
	II	Lists bird species that may be hunted according to national legislation within the EU, with the condition that hunting does not jeopardize the conservation efforts.
	III	Lists bird species that may be sold provided that the birds have been legally killed or captured or otherwise legally acquired.
	IV	Specifies prohibited methods and means of hunting birds, including traps, nets, poisons, and other non-selective methods.
Habitats (92/43/EEC)	I	Lists the types of natural habitats that are of community interest, requiring the establishment of Special Areas of Conservation (SACs).
	II	Lists animal and plant species of community interest that require the designation of SACs for their protection.
	III	Outlines criteria for selecting sites that will become part of the Natura 2000 network, based on the species and habitats they support.
	IV	Lists species of community interest in need of strict protection, prohibiting their capture, killing, disturbance, and destruction of habitats.
	V	Lists species of community interest whose exploitation is subject to management measures to ensure they are used sustainably.
	VI	Specifies prohibited methods of capturing and killing species listed in Annexes IV and V to prevent non-selective and destructive practices.

As it stands, Natura 2000 represents the largest coordinated network of protected areas anywhere in the world (EEA, 2022). In 2022, the network covered 27,193 sites and over 1.2 million square kilometres, representing 18.6% of European land and 9% of European seas (EEA, 2022a). A break-down by Member State is shown in Figure 5.

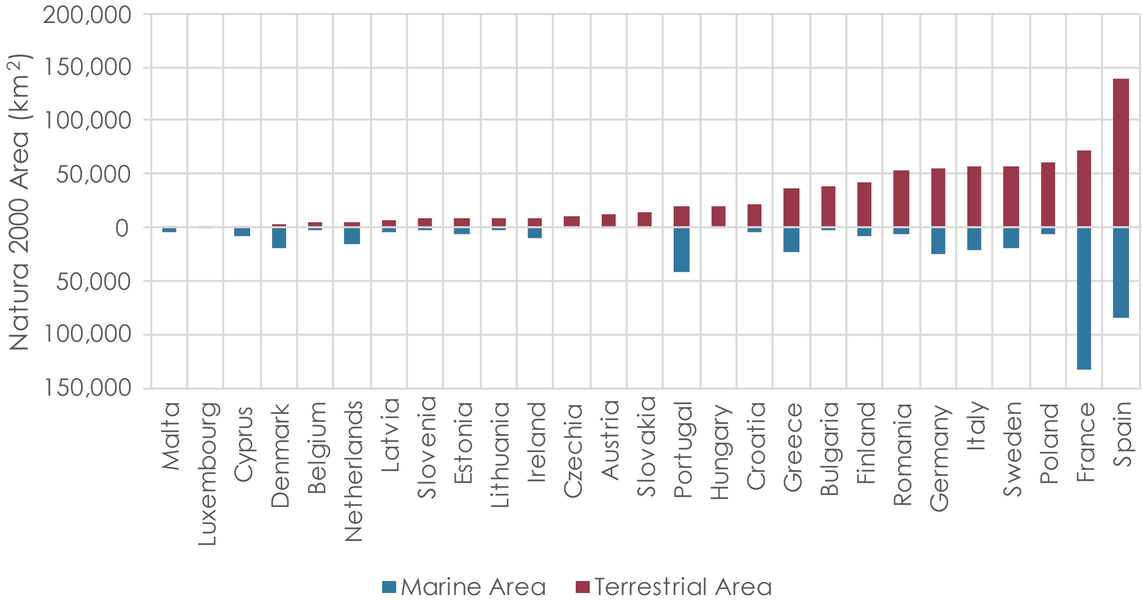


Figure 5. Natura 2000 land and marine areas for EU-27 by the end of 2022, with countries sorted by total protected land area

Note: For the smallest countries, protected area may not be visible on the graph without zooming.
Source: Adapted from EEA (2022a)

Natura 2000 is critical for protecting unique and threatened species and habitats in Europe (Kokkoris et al., 2023). For example, over 80% of the HD Annex I species are endemic to Europe, and 60% are narrow endemics (i.e. meaning they only occur in a small geographical area) (EEA, 2012). However, some HD Annex I habitats and HD species and birds are widely dispersed and occur widely outside the Natura 2000 network. Indeed, many rely on semi-natural habitats and landscape features, HNV farmland, and even some cropland and managed forest land as feeding and breeding habitats and to move between protected areas. For example, several species of globally threated birds, such as Great Bustard (Otis tarda) are highly reliant on increasingly rare areas of dry low-intensity cereal land in the Iberian Peninsula and eastern Europe. Protection and management measures that apply beyond the Natura 2000 network are therefore often required to achieve the objective of favourable conservation status.

As with all EU directives, Member States are required to implement national legislation to achieve directive goals. Regular reporting and assessment mechanisms are in place to evaluate whether conservation targets are being met, and the EU Commission can act against Member States which fail to meet their obligations. This includes bringing cases before the Court of Justice of the European Union (ECJ). For instance, the ECJ ruled that Spain failed to prevent significant water extraction and pollution which degraded the natural habitats and species in Doñana Wetlands National Park (a protected Natura 2000 site) in Andalucia (ECJ, 2016). The Spanish Government was required to implement stricter regulations on water use and improve management practices to prevent further degradation of the protected areas (ECJ, 2021).

4.2.2. The Biodiversity Strategy for 2030

The EU's Biodiversity strategy for 2030, a central component of the European Green Deal, aims to "bring nature back into our lives" and "put Europe's biodiversity on the path to recovery by 2030" (European Commission, 2020b). Building on the foundations of the Birds and Habitats Directives, the EU's four Biodiversity Strategies since 1998 have developed a broader policy framework to halt biodiversity, restore degraded ecosystems, and promote the sustainable use of natural resources across the EU. These cross-cutting Strategies have integrated provisions for key economic sectors (Tucker et al., 2023).

The most recent Biodiversity Strategy provides a framework for advancing towards a key target to protect 30% of the land and sea in the EU by 2030. Data from the EU database of nationally designated and protected areas (see Figure 6) show that by the end of 2021, 26% of EU land had been protected, with 18.6% designated as part of the Natura 2000 network (EEA, 2023e). The remaining 7.4% of EU land is protected under national schemes. By the end of 2021, 12.1% of EU seas were classed as protected, with 8% designated within Natura 2000 and 3% under national protection (EEA, 2023c). Figure 6 and Figure 7 show that, to achieve the Biodiversity Strategy target of protecting at least 30% of EU land and seas by 2030, an additional 4% of land and 19% of sea areas will need to be designated. Further context of progress towards these targets by individual Member States is provided in Annex A.1.

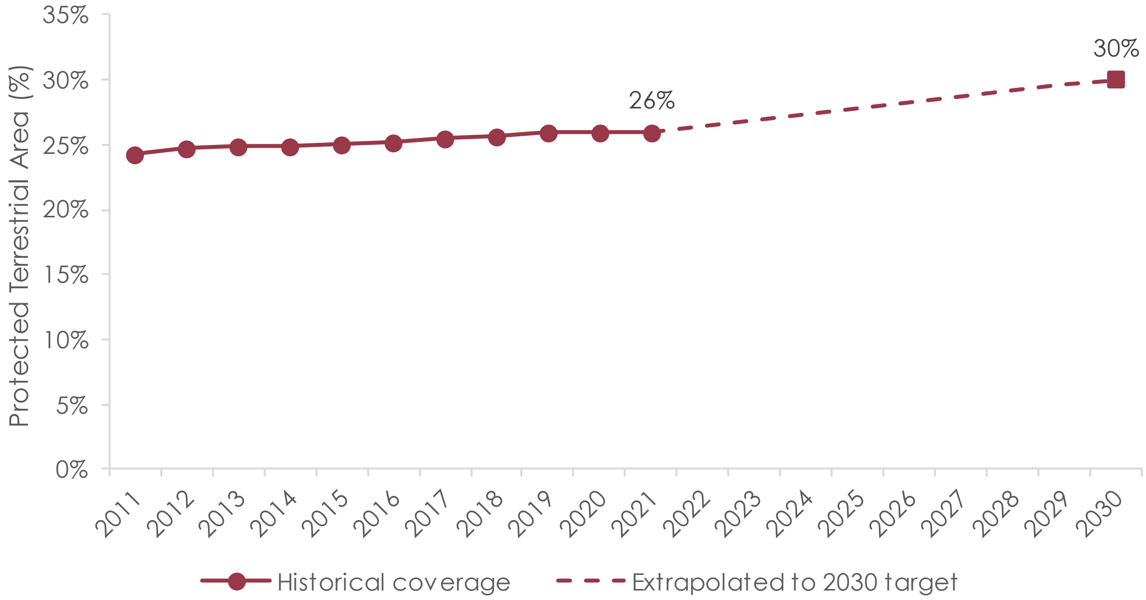


Figure 6. Coverage of protected areas in the EU-27 land area in 2011-2021

Source: Adapted from EEA (2023d)

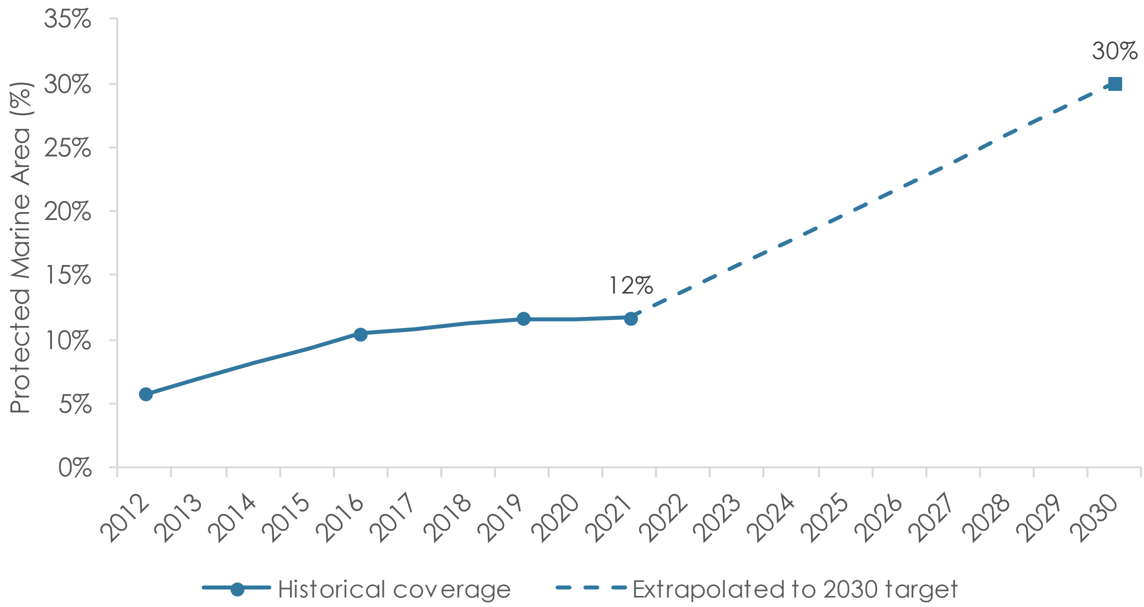


Figure 7. Marine protected area coverage in the EU, 2012-2021

Source: Adapted from EEA (2023b)

Similarly, not all protected areas provide the same level of protection. The figures above show areas that are protected to some degree; but the Biodiversity Strategy states that just 3% of land and less than 1% of marine areas in the EU are under 'strict protection'. Strictly protected areas are those that are (Cheilari, 2023):

> *"Fully and legally protected areas designated to conserve and/or restore the integrity of biodiversity-rich natural areas with their underlying ecological structure and processes and supporting natural environmental processes. This means that 'natural processes are therefore left essentially undisturbed from human pressures and threats to the area's overall ecological structure and functioning, independently of whether those pressures and threats are located inside or outside the strictly protected area."*

This doesn't mean that strictly protected areas are incompatible with human activity, but any activities taking place within them should be compatible with the conservation objectives of those areas. As such the Biodiversity Strategy includes a sub-target to bring at least one-third of protected areas (10% of EU land and 10% of EU sea) under strict protection. This should include all remaining primary and old-growth forests, which make up 3% of the EU forest area and around 1.2% of total EU land (Barredo et al., 2021). To support Member States in this endeavour the Commission has released criteria and guidance for the designation of additional protected areas (European Commission, 2022) as well as guidelines for defining, mapping, monitoring and strictly protecting EU primary and old-growth forests (European Commission, 2023f).

With the exception of a footnote signposting to the CBD definitions for primary and old growth forests, no definitions are provided in the EU's Biodiversity Strategy for 2030. Considering that much of the Strategy focusses on the restoration of degraded ecosystems, the lack of a clear definition on what is meant by 'degraded' may create challenges further down the line. The Strategy does however, set commitments to ensure that habitats and species show "no deterioration in conservation trends and status; and that at least 30% reach favourable conservation status or at least show a positive trend by 2030".

Further discussion on key thematic areas related to the Biodiversity Strategy for 2030 (energy, agriculture, soils, etc.) are provided in Annex A, which offers a deeper dive into these thematic areas and how they interact with and are influenced by the other biodiversity-relevant EU policies covered in the next section. These sections in the Annex explore the specific challenges and opportunities each sector faces in aligning with the EU's biodiversity goals and provides further context for understanding the broader implications of these policies for biodiversity conservation. Table 8 provides a summary of the key commitments of the Biodiversity Strategy, and their thematic target areas (some of which are discussed in further detail in Annex A).

Table 8. Summary of key commitments made under the EU's Biodiversity Strategy for 2030, and thematic target areas

Key commitments for 2030	Target areas
Protect 30% of land and sea in the EU by 2030	Species and Habitat Protection
Bring one-third of protected areas under strict protection	Species and Habitat Protection
Introduce legally binding nature restoration targets	Species and Habitat Restoration
Reduce the use of chemical pesticides by 50%	Agriculture, Soils, Pollution
Place at least 10% of agricultural land area under high-diversity landscape features (such as buffer strips, hedgerows, and ponds)	Agriculture
Reducing nutrient losses from fertilisers by 50%, resulting in reduction of the use of fertilisers by at least 20%	Agriculture, Pollution, Soils
Increase organic farming to cover 25% of agricultural lands	Agriculture, Soils
Reverse the decline in pollinators	Species and Habitat Protection, Restoration, Agriculture
Make significant progress on the remediation of contaminated soil sites	Agriculture, Pollution, Soils
Plant at least three billion additional trees across the EU	Forests, Agriculture
Restore at least 25,000 km of free-flowing rivers	Inland waters
Reduce IUCN Red list species threatened by invasive alien species by 50%	Species and Habitat Protection

4.2.3. Nature Restoration Regulation

One commitment of the Biodiversity Strategy was to introduce legally binding nature restoration targets (see Table 8). These were adopted in June 2024 under the Nature Restoration Regulation. At the EU level, the Regulation aims to provide the cohesion and consistency needed to halt and reverse biodiversity loss (European Union, 2024). It mandates the restoration of 20% of the EU's land and sea areas by 2030 and, ultimately, all ecosystems in need of restoration by 2050. This commitment differs slightly to the Biodiversity Strategy's goal to legally protect a minimum of 30% of the land and sea, including one third under strict protection. Criteria and guidance for the designation of additional protected areas by Member States highlight that if restored areas comply, or are expected to comply with these criteria, these should also contribute towards the EU targets for protected areas.

The impact of the Nature Restoration Regulation extends beyond designated protected areas, covering a broader range of environmental contexts and objectives. It integrates many of the EU's biodiversity-related policies and requires Member States to implement various strands of the Biodiversity Strategy. Critically, the regulation imposes deadlines to achieve the objectives of the Birds and Habitats Directives (described in Section 4.2.1) and address previous shortcomings in voluntary compliance. This includes supporting the restoration of habitats to achieve favourable conservation status (see Table 6). The regulation also reinforces commitments to Natura 2000 and states that, until 2030, Member States should prioritise Natura 2000 sites when implementing restoration measures.

The Regulation requires Member States to develop and submit National Nature Restoration Plans to the Commission by mid-2026. These plans must detail the specific restoration measures to be taken to meet the legally binding ecosystem-specific targets and obligations, including:

- Outlining strategies for restoring various ecosystems;
- Assessing and addressing pressures on biodiversity;
- Implementing restoration measures with clear timelines, responsible authorities, and necessary resources;
- Ensuring these measures are integrated into broader national land-use and environmental policies.

The National Nature Restoration Plans will ensure a coordinated approach across Member States, with progress-reporting obligations designed to overcome previous shortcomings due to the lack of legally binding targets and cohesive strategies. This addresses the challenges seen in other areas of EU climate and environmental policy, where non-binding targets, such as those for advanced biofuels under the original RED, and earlier aspirational targets for alternative aviation fuels, have failed to deliver meaningful outcomes.

The Regulation further includes specific obligations to improve biodiversity in agricultural ecosystems, measured by indicators such as the grassland butterfly index and the stock of organic carbon in cropland mineral soils. Member States are also required to restore farmland bird populations (based on the established farmland bird index), and drained peatlands used for agriculture. Both are very relevant here, as growing bioenergy crops is likely to conflict with the bird target, while rewetting organic soils may be compatible with growing short rotation trees or perennial grasses,[29] as discussed in Chapter 5.

Additionally, the Regulation recognises the absence of a common method for assessing the condition of forest ecosystems. Instead of specific forest restoration targets, the Regulation requires Member States to enhance biodiversity in forest ecosystems and measure the fulfilment based on increases in the common forest bird index. Member States must also achieve an increasing trend at national level of at least six out of seven indicators for forest ecosystems, including standing deadwood, lying deadwood, the share of forests with uneven-aged structure, forest connectivity, stock of organic carbon, the share of forests dominated by native tree species, and tree species diversity. As we will see in Section 5.3.6, this is particularly relevant when considering forest residue harvesting, as many of these forest health 'indicative features', especially, deadwood and organic carbon stock, are likely to be impacted by increased residue harvesting.

The Regulation emphasises that "the restoration of biodiversity should consider the deployment of renewable energy and vice versa". It encourages the combination of these activities wherever possible, including in the development of Renewables Acceleration Areas (RAAs) and dedicated grid and storage areas. Designating RAAs involves coordinated mapping activities as outlined in the Renewable Energy Directive (2018/2001), where Member States identify areas to upscale renewable energy infrastructure. This is especially relevant for RFNBOs, the electricity for which must be delivered from additional renewable energy capacity rather than competing with existing uses. For the establishment of RAAs, priority is to be given to artificial and built surfaces, such as rooftops and facades of buildings, transport infrastructure and their direct surroundings, parking areas, farms, waste sites, industrial sites, mines, artificial inland water bodies, lakes or reservoirs, and, where appropriate, urban waste-water treatment sites, as well as degraded land not usable for agriculture. These land types will tend to be of low biodiversity value.

4.3. Other biodiversity-relevant policies

Aligning various environmental policies together under a coherent strategy like the Biodiversity Strategy creates opportunity for different interests to work together towards halting biodiversity loss and restoring degraded ecosystems. This section outlines other EU policy instruments which carry implications for biodiversity goals.

4.3.1. Soil strategy for 2030 and proposed Soil Monitoring Directive

Healthy soils are foundational to ecosystem resilience, supporting biodiversity by maintaining habitats and ecosystem services that mitigate impacts from land-use changes. In 2021, the EU adopted its Soil Strategy for 2030, which aims to ensure that all EU soil ecosystems are in a 'healthy condition' by 2050. The Strategy aims to protect soil fertility, reduce erosion and enhance soil organic content through sustainable practices such as crop rotation, cover cropping, and reduced tillage (i.e. less mechanical turning, stirring, and mixing soil when preparing to plant crops). Building on these commitments, the European Commission also adopted a proposal for a Soil Monitoring Directive (European Commission, 2023i); this would

29 Biomass cultivation in wetlands is referred to as 'paludiculture'.

aim to standardise soil monitoring across Member States, ensuring comprehensive and consistent data for effective soil management policymaking.

4.3.2. Common Agricultural Policy (CAP)

The CAP is the primary instrument through which the EU supports agriculture and rural development. First implemented in 1962, CAP has undergone several reforms to address changing priorities, including environment and biodiversity-related goals. The CAP 2023-2027 promotes sustainable farming through measures such as Agri-Environment-Climate Measures (AECMs) and Greening Measures, which encourage practices like crop diversification, maintaining permanent grassland, and creating Ecological Focus Areas (EFAs), including fallow land, landscape features like buffer strips, and agroforestry areas. Additionally, Annex III of the CAP Strategic Plan Regulation (European Union, 2021) includes rules and standards for good agricultural and environmental condition of land (GAEC). GAEC 8 requires CAP beneficiaries to maintain and protect landscape features such as hedges, ditches, trees, ponds, and fallow land on at least 4% of arable land. Under GAEC 9, environmentally sensitive permanent grasslands are covered by a ban on conversion or ploughing in Natura 2000 zones.

Biofuel feedstock could still be grown and harvested in an EFA under certain conditions – the land must not receive fertiliser treatment (except low input with solid manure) or pesticide treatment. In theory, short rotation forestry (discussed in Section 5.3.4) could be a viable compliant alternative to establishing purely nature-focused features, provided it is accepted that harvesting the wood does not compromise biodiversity levels. The potential significance of this will be discussed later. But in short, CAP policies directly impact biodiversity through promoting agricultural practices that can support or hinder species and habitat conservation. Agricultural land used for energy production, supported by CAP incentives, has direct implications for meeting the EU's renewable fuel targets.

4.3.3. Pollinators Initiative

The EU Pollinators Initiative, adopted in 2018 and revised in 2023, aims to reverse the decline in wild pollinators by 2030 (European Commission, 2023d). It sets objectives and actions to: (1) improve knowledge of pollinator decline, its causes and consequences; (2) tackle the causes of pollinator decline; and (3) promote strategic planning at all levels for pollinator protection, including new frameworks and monitoring. Protecting pollinators is crucial for maintaining ecosystem health and resilience, which can be indirectly impacted by land-use changes, as is likely to occur in meeting the demands for renewable fuel in aviation and maritime.

4.3.4. Forest Strategy for 2030 and proposed Forest Monitoring Law

Building on various prior forest-related policies, the EU's Forest Strategy for 2030 aims to sustainably manage and protect EU forests. Additionally, the Commission has put forward a proposal for a Regulation on a Forest Monitoring Framework (European Commission, 2023j). Together, these policies focus on sustainable forest management, carbon sequestration, and data collection to understand and monitor forest health, supporting biodiversity conservation and forest goals. The Strategy is highly relevant as wood-based bioenergy is a significant renewable energy source in the EU (accounting 60% of the EU's renewable energy mix).

Sustainable forest management practices will be crucial for balancing bioenergy production from forest residues and short rotation forestry with biodiversity conservation.

4.3.5. Water Framework Directive (WFD)

Adopted in 2000, the WFD (European Union, 2000) aims to achieve 'good status' for all EU water bodies by 2027, though many are currently 'poor status' (European Environment Agency, 2021) and many EU Member States have been slow to comply with their obligations (Wetlands International, 2023a).

Water bodies in this context include rivers, lakes, estuaries, coastal waters, and groundwater. Clean water bodies are essential for biodiversity. However, many of Europe's water bodies, particularly in regions with intensive agriculture and high population density, are affected by 'diffuse pollution' that comes not from point source discharges but from distributed runoff and leaching through soil during rainfall and irrigation (OECD, 2017). Excess nutrients (largely nitrogen, phosphorus, potassium) which drive eutrophication, and toxic pesticides pose particular challenges (Wiering et al., 2020).

4.3.6. Marine Strategy Framework Directive

The Marine Strategy Framework Directive (MSFD), adopted in 2008, seeks to achieve 'good environmental status' of the EU's marine waters and protect the resource base upon which marine-related economic and social activities depend (European Union, 2008b). The MSFD promotes sustainable maritime activities, provides the legal premise for establishing Marine Protected Areas (MPAs), and requires Member States to develop their own marine strategies.

Ensuring sustainable practices in marine environments aligns with renewable energy strategies that reduce the environmental impacts of shipping, in particular pollution and underwater noise (discussed in more detail in Section 6.4). Annex A.2.7 provides the list of qualitative descriptors that define good environmental status of EU marine waters under Annex I of the MSFD.

4.3.7. Invasive Alien Species Regulation

Invasive alien species are a serious and growing threat to global biodiversity (Díaz, Settele, Brondízio, Ngo, Guèze, et al., 2019). They also cause major damage to ecosystems and economies, with a recent study by Henry et al. (2023) estimating that the total cost of biological invasions across the EU from 1960 to 2020 amounted to €138.6 billion, with an average annual cost of €151.4 million. Recognising this, the Invasive Alien Species Regulation (European Union, 2014b), adopted in 2014, aims to prevent and manage the introduction and spread of invasive species in the EU. The regulation provides a list of 'invasive alien species of Union concern', restricts activities related to them, and mandates Member States to take preventive and management measures.

To date, no species which contribute to biomass production for bioenergy in the EU have been officially identified as invasive alien species of Union concern. Notwithstanding, in Chapters 5 and 6 we consider some bioenergy production systems that do pose a risk of becoming invasive (Carboneras et al., 2018; Crosti et al., 2016).

4.3.8. Land Use, Land Use Change and Forestry (LULUCF) Regulation

The LULUCF Regulation was adopted in 2018 to incorporate GHG emissions and CO_2 removals from land use into the EU's climate and energy targets (European Union, 2018b). The regulation sets the overall Union target of net GHG removals in the LULUCF sector at 310 million tonnes of CO_2 equivalent in 2030 and establishes rules for land management practices to enhance carbon stocks and mitigate emissions.

Under Article 5 (4) of the regulation, Member States must disclose changes in carbon stocks related to above-ground (living) biomass, dead wood, and harvested wood products under the land category of managed forest land. However, they do not need to disclose changes in carbon stock in litter, dead organic matter, mineral soils, and organic soils, providing that these pools have not become a source of emissions. This could pose challenges further down the line. According to Bellassen et al. (2022), EU forest area for which soil carbon is being accurately reported is at best 33%, and more likely close to 24%, highlighting that forest soil carbon is somewhat of a blind spot in EU greenhouse gas emissions accounting. This has indirect implications for practices such as forest residue harvesting (which we come to in Section 5.3.6), which may impact soil carbon levels.

This issue is illustrated to some extent by the FAO's Global Forest Resources Assessment (UN FAO, 2020b), which surveys national governments on the areas and characteristics of forest lands within their borders. The report notes the difficulties experienced by many countries in accurately assessing the mix of tree types and their biomass, let alone less visible carbon stock components such as roots and soil. Figure 8 shows the data collected for EU Member States; some estimates for carbon in dead wood, leaf litter, and soil are clearly absent.

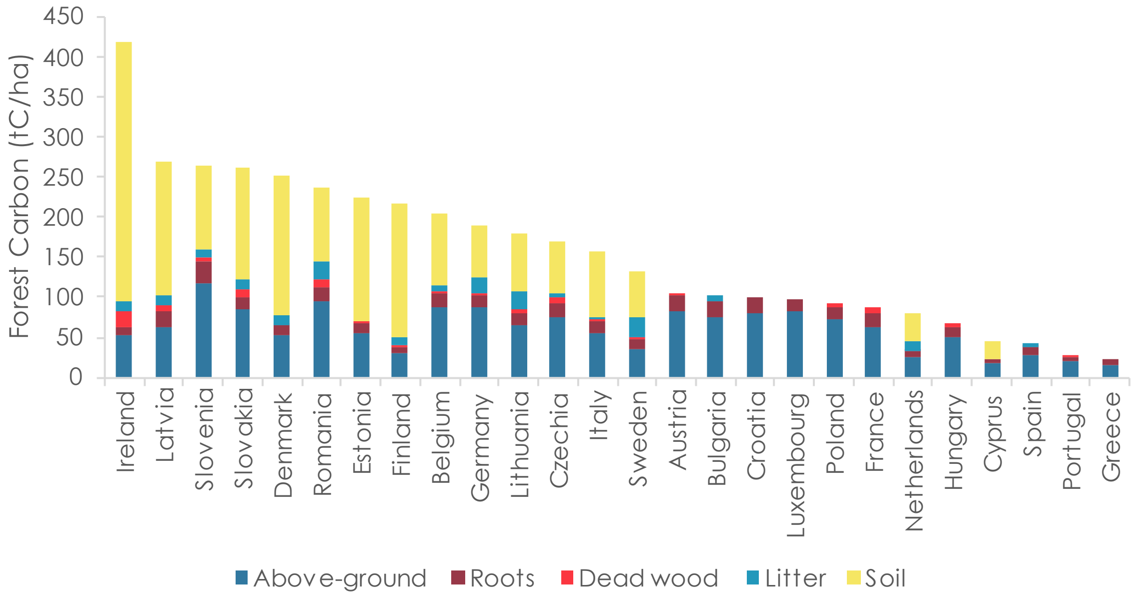


Figure 8. Carbon stock in forest lands reported by EU Member States for the year 2015

Note: The year 2015 is chosen as this has the most complete reporting record.
Source: UN FAO (2020a)

4.4. Global biodiversity commitments

The global community recognises the urgent need to protect and restore biodiversity through various international agreements and frameworks, including the Kunming-Montreal Global Biodiversity Framework under the Convention on Biological Diversity (CBD), and the United Nation's (UN) Sustainable Development Goals (SDGs) and Decade on Ecosystem Restoration.

These frameworks guide and complement the EU's own efforts to halt biodiversity loss and restore degraded ecosystems. By aligning its Biodiversity Strategy with global commitments and taking decisive action at home, the EU can lead by example and demonstrate how integrated biodiversity and climate policies can deliver broader environmental and socio-economic goals. This approach is essential for ensuring the long-term health and sustainability of both natural systems and human communities, supporting the EU's broader environment and climate goals on the global stage.

4.4.1. Aichi Targets

Adopted in 2010, the CBD's Aichi Biodiversity Targets comprised 20 ambitious targets aimed at addressing the root causes of biodiversity loss, reducing direct pressures on biodiversity, safeguarding ecosystems, species, and genetic diversity, and enhancing the benefits of biodiversity and ecosystem services by 2020. Although progress was seen in certain areas, the CBD reported that no target was fully achieved, no single country hit all the targets, and many important biodiversity indicators were still in decline, with high rates of species extinction and ecosystem destruction (Secretariat of the Convention on Biological Diversity, 2020).

The EU's track record in meeting the Targets was similarly mixed. For instance, Target 15 aimed to restore at least 15% of degraded ecosystems by 2020, but this was not achieved. While some local successes in expansion of protected areas and species protection were observed, overall progress was limited due to inadequate implementation, lack of enforcement, and insufficient funding (EEA, 2020b). This underscores the need for binding commitments and global co-operation to drive meaningful action.

4.4.2. Kunming-Montreal Global Biodiversity Framework

The Kunming-Montreal Framework, covering the period 2022-2030, was built upon the Aichi Targets' inauspicious foundations, and in its inception sought to learn from past difficulties by orientating more towards focussed and measurable outcomes without stinting on ambition – a headline objective is to protect 30% of land and marine areas by 2030 (cf. the EU's own commitments in Section 4.2). The EU adopted the Framework at the fifteenth meeting of the Conference of the Parties (COP15) to the CBD in December 2022.

The Framework includes 23 action-orientated global targets, which fall under three pillars: i) reducing threats to biodiversity, ii) meeting people's needs through sustainable use and benefit sharing, and iii) tools and solutions for implementation and mainstreaming. Several targets for 2030 align closely with those set out in the Biodiversity Strategy, most relevant in the context of this report are:

- Spatial planning and management: ensuring that all areas are under participatory, integrated and biodiversity inclusive spatial planning and/or effective management processes by 2030. This aims to bring the loss of areas of high biodiversity importance close to zero (Target 1).

- Restoration: at least 30 % of areas of degraded terrestrial, inland water, and marine and coastal ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity (Target 2).
- Conservation: at least 30% of land, waters and seas are conserved through effectively managed and well-connected systems of protected areas and other area-based conservation measures (Target 3).
- Invasive alien species: manage and control pathways for the introduction of invasive alien species, reducing rates of introduction and establishment of known or potential invasive alien species by 50% (Target 6).
- Pollution: reducing pollution from plastics, excess nutrients, pesticides, and other harmful chemicals to levels that are not detrimental to ecosystem functions and biodiversity (Target 7).
- Nature's Contributions to People: restoring, maintaining, and enhancing nature's contributions to people, including ecosystem functions and services such as the regulation of air, water, and climate, soil health, pollination, and protection from natural hazards and disasters through nature-based solutions and / or ecosystem-based approaches (Target 11).

4.4.3. The Sustainable Development Goals (SDGs)

Adopted in 2015 as part of the UN 2030 Agenda for Sustainable Development, the UN SDGs provide a comprehensive framework for a sustainable future, with 169 targets under 17 global goals. Several goals are directly relevant here:

- SDG 7 (Affordable and Clean energy): ensuring access to affordable, reliable, and sustainable energy for all. Encouraging a shift to renewable energy sources and reducing the pressure on ecosystems caused by fossil fuel extraction and mismanagement of natural resources.
- SDG 12 (Responsible consumption and production): focusses on ensuring sustainable consumption and production patterns through promoting waste reduction, resource efficiency and encouraging practices which minimise environmental and biodiversity impacts.
- SDG 14 (Life below water): focusses on sustainably managing and protecting marine and coastal ecosystems to prevent significant adverse impacts, strengthening their resilience, and ensuring healthy oceans.
- SDG 15 (Life on land): aims to protect, restore and promote the sustainable use of terrestrial ecosystems, halt deforestation, combat desertification and halt biodiversity loss.

Countries including the EU monitor their progress towards the SDGs through a set of 102 annually assessed indicators. The latest assessment indicates that the conservation status of ecosystems and biodiversity in the EU is unfavourable, and highlights that the negative impacts of EU life-style patterns on global biodiversity are considerable (EEA, 2023d). While the SDGs are not legally binding, they are crucial for guiding national and international policies towards sustainable development, and a country's failure to meet its goals could result in reputational damage and missed opportunities for economic and social benefits.

4.4.4. UN Decade on Ecosystem Restoration

The UN Decade on Ecosystem Restoration (2021-2030) aims to massively accelerate efforts to restore degraded ecosystems, recognising the critical role that this plays to addressing the climate crisis, ensuring food and water security, and protecting biodiversity. The initiative emphasises the need for international cooperation to meet existing restoration pledges, which collectively total over 1 billion hectares of land (an area larger than China). A 2021 report for the UN highlights that meeting this restoration target through reviving ecosystems and other natural solutions would contribute over one third of the global climate mitigation needed by 2030, curbing the risk of mass species extinctions and future pandemics (Dickson et al., 2021).

5. Biomass-based feedstock

Biomass-based feedstocks are expected to play a pivotal role in combatting climate change, as they can provide an alternative to fossil fuels. Biomass feedstocks encompass a wide range of sources, from cellulosic materials such as agricultural residues and woody biomass, to intermediate crops and low-grade oils and fats. Understanding the diversity of these feedstocks and their respective impacts on biodiversity is crucial for understanding whether biomass can provide "win-win solutions for energy generation" as outlined in the EU's Biodiversity Strategy for 2030.

The RED provides sustainability rules and criteria to which Member States should adhere in meeting their renewable energy goals. This chapter considers the sustainability criteria outlined in the RED (Section 5.1), some of the broad issues that arise around the use of biomass feedstocks, and limitations imposed by the eligibility criteria in ReFuelEU Aviation and FuelEU Maritime. It then introduces some overall issues surrounding land types and land use change (Section 5.2), before considering biofuel feedstock types more specifically. The use and potential impacts of cellulosic biomass crops from various sources, residual oils and fats, and industrial wastes is discussed in the sections that follow.

5.1. Sustainability rules

Ensuring the sustainability of the feedstocks used to support the energy transition is crucial to avoid unintended environmental, social, and economic consequences. As mentioned in the policy introduction in Chapter 2, the RED, alongside ReFuelEU Aviation and FuelEU Maritime, provide a framework of sustainability rules and criteria to guide the production and utilisation of biofuels.

5.1.1. RED sustainability rules

The first incarnation of the RED, introduced in 2009, set a minimum target of 20% renewable energy use in each Member State, including 10% renewable energy in transport, by 2020 (see Table 9). The key sustainability criteria for biofuels included:

- Greenhouse gas emissions savings: biofuels had to deliver at least 35% GHG emissions savings compared to fossil fuels, increasing to 50% by 2017, and 60% for installations starting after January 2017.
- Biodiversity protection: raw materials for biofuels were not to be sourced from land with high biodiversity value, such as primary forests, designated protected areas and highly biodiverse grassland[30].
- Land with High Carbon Stock (HCS): biofuels should not be produced from materials sourced from land with high carbon stock, such as wetlands and continuously forested areas[31]. There is also a proscription on using materials

30 More precise definitions for these land types can be found in the RED I, Article 17.3 (European Union, 2009).

31 Ditto Footnote , Articles 17.4 and 17.5.

from peatlands unless it can be proven that harvesting did not involve draining previously undrained soils.

- Voluntary certification schemes: the use of voluntary certification schemes, such as the Roundtable for Sustainable Biomaterials (RSB), the Roundtable on Sustainable Palm Oil (RSPO) and the International Sustainability and Carbon Certification (ISCC) to verify compliance with sustainability through independent auditing.

The EU adopted RED II in 2018, setting a more ambitious target of 32% renewable energy consumption by 2030 and a minimum of 14% renewable energy in transport (European Union, 2018a). The sustainability criteria for biofuels were updated to include:

- Advanced biofuels promotion: a sub-target was introduced for so-called 'advanced' biofuels made from feedstocks listed in Part A of the Directive's Annex IX (see Table 10). Their share of final consumption of energy in transport was mandated to be at least 0.2% in 2022, 1% in 2025, and 3.5% by 2030. Moreover, Annex IX fuels may be double-counted towards energy targets (both the overall target and the advanced sub-target where appropriate)[32]; fuels listed in Part B of Annex IX are nominally limited to 1.7% of transport energy consumed in each Member State[33].
- High indirect land-use change (ILUC) risk biofuels[34]: limits were placed on biofuels categorised as high ILUC-risk, with a phase-out of their contribution to zero by 2030[35].
- Forest biomass sustainability criteria: new criteria for forest biomass aimed to address concerns about unsustainable forest management practices. This included a requirement that the biomass source country must have adequate laws and monitoring and enforcement systems in place, ensuring the legality of harvesting, forest regeneration of harvested areas, laws for nature protection purposes, requiring harvesting to be carried out "considering soil quality and biodiversity", and ensuring that harvesting maintains or improves the long-term production capacity of the forest.

32 This means that, e.g. the 3.5% advanced biofuel target for 2030 can be satisfied with 1.75% of physical fuel energy.

33 As mentioned in Section 2, a Member State may request the Commission to relax this cap. Moreover, it bears repeating that

34 Fuels from feedstocks that are identified as associated with deforestation or wetland drainage. Currently only palm-oil based fuels have been identified as high ILUC-risk.

35 Some Member States have adopted an accelerated phase-out schedule for high ILUC-risk biofuels (Soquet-Boissy et al., 2024).

Table 9. Summary table of key objectives, targets, and sustainability criteria across RED I, RED II, and RED III

Directive	Renewable energy target	Transport sector target	Transport sector sub-target	Biodiversity protection
RED I (2009/28/EC)	20% by 2020	10% renewable energy *	None	Restrictions on raw materials from high biodiversity and high carbon stock land §§
RED II (EU 2018/2001)	32% by 2030	14% renewable energy *	Advanced biofuels ††: 0.2% by 2022, 1% by 2025, 3.5% by 2030	Strengthened the RED I protections, particularly around forest biomass monitoring, plus phase-out of high ILUC-risk biofuels ‡
RED III (EU 2023/2413)	42.5% by 2030	29% renewable energy ** Or 14.5% GHG intensity reduction †	Advanced biofuels plus RFNBOs §: 1% in 2025, 5.5% in 2030	Extended ecosystem protection, including soil health and broader landscape-level impacts

Notes:

** Percentage calculated by dividing compliant renewable energy used in all transport segments (including aviation and maritime) in the numerator by the energy from all sources used in road and rail segments only in the denominator.*

*** Percentage calculated by dividing compliant renewable energy used in all transport segments in the numerator by the energy from all sources used in all transport segments in the denominator.*

† The greenhouse gas intensity reduction is with respect to a standard fossil fuel emissions intensity of 94 gCO_2/MJ.

†† Advanced biofuels are those listed in Annex IX Part A of the Directive. Their energy content is double-counted, so that e.g. the 3.5% energy target for 2030 can be met with 1.75% of physical transport energy supplied from advanced biofuels.

§ RFNBOs are renewable fuels of non-biological origin, also known as electrofuels.

§§ Including primary forests, highly biodiverse grasslands, wetlands, and peatlands.

‡ High ILUC-risk feedstocks are associated with global expansion into carbon-rich lands; at present only palm oil is categorised as such.

Shortly after the RED II, the EU adopted a revised RED III in October 2023 (European Union, 2023b) as part of a broader overhaul of climate ambition under the 'Fit for 55' initiative. RED III introduced higher targets for renewable energy – 42.5% share of total energy consumption by 2030; and for the transport sector, Member States can adopt either a 29% renewable energy share or a 14.5% reduction in lifecycle greenhouse gas emissions intensity[36]. RED III also set targets to boost the production and uptake of RFNBOs (introduced in Section 3.5): a 5.5% combined RFNBO + advanced biofuel target, and a minimum 1.2% RFNBO contribution to maritime energy[37].

RED III also included more stringent sustainability and greenhouse gas criteria for compliant

36 The greenhouse gas intensity reduction is with respect to a standard fossil fuel emissions intensity of 94 gCO_2/MJ.

37 The energy content of both advanced biofuels and RFNBOs is double-counted for the purposes of RED III targets; so, to get the physical contribution to the overall energy mix, these percentages should be divided by 2.

fuels and feedstocks. The key changes which impact biomass (set out in Article 29) include the following:

- High biodiversity value areas: RED III broadens the scope of what is considered high biodiversity value land to explicitly include old-growth forests and heathlands.
- Forest biomass sustainability criteria: the existing requirement (from RED II) that production countries have forest laws in place were extended to ensure that areas designated for protection include grassland and heathland (as well as wetlands and peatlands) and to ensure that forest from which biomass is harvested does not have the status of primary or old-growth forest, highly biodiverse forest and woodland, grassland or heathland. It states that harvesting must be "carried out considering maintenance of soil quality and biodiversity in accordance with sustainable forest management principles, with the aim of preventing any adverse impact, in a way that avoids harvesting of stumps and roots, degradation of primary forests, and of old growth forests as defined in the country where the forest is located, or their conversion into plantation forests, and harvesting on vulnerable soils, that harvesting is carried out in compliance with maximum thresholds for large clear-cuts as defined in the country where the forest is located and with locally and ecologically appropriate retention thresholds for deadwood extraction and that harvesting is carried out in compliance with requirements to use logging systems that minimise any adverse impact on soil quality, including soil compaction, and on biodiversity features and habitats."
- The cascading use principle: RED III links biomass to the loss of forest carbon sinks and encourages biomass to be utilised for long-lived uses of wood, rather than burning it for energy in the first instance. New provisions require Member States to assess biomass supply and the compatibility of forest biomass with the land sink targets (under the LULUCF Regulation).

Additionally, Member States' National Energy and Climate Plans (NECPs), first introduced under the Regulation on the governance of the energy union and climate action, are 10-year plans intended to address various dimensions of the energy union. Member States were due to submit draft updated NECPs for the period 2021-2030 by 30 June 2023, with final updated NECPs submitted by 30 June 2024[38] (European Commission, 2024e). These must include:

> *"an assessment of the domestic supply of forest biomass available for energy purposes in 2021-2030 in accordance with the sustainability criteria laid down [in RED II]; as well as an assessment of the compatibility of the projected use of forest biomass for the production of energy with the Member States' targets and budgets for 2026 to 2030 laid down in Article 4 of Regulation (EU) 2018/841; and a description of the national measures and policies ensuring compatibility with those targets and budgets."*

Member states have until 30 April 2025 to transpose RED III into their national laws, but it is important to note that RED will be implemented differently across the EU Member States, and while the targets are ambitious, they are also often, if not always, missed.

38 Though all 27 EU Member States have submitted draft NECPs, at the time of writing, just ten had submitted their final NECPs (European Commission, 2024f). These were Denmark, Finland, France, Germany, Ireland, Italy, Latvia, Luxembourg, Netherlands, and Sweden.

Table 10. List of feedstocks in Annex IX of the Renewable Energy Directive

Part A. Feedstocks for the production of biogas for transport and advanced biofuels, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be twice their energy content:
(a) Algae if cultivated on land in ponds or photobioreactors;
(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;
(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;
(d)Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex;
(e) Straw;
(f) Animal manure and sewage sludge;
(g) Palm oil mill effluent and empty palm fruit bunches
(h) Tall oil pitch;
(i) Crude glycerine;
(j) Bagasse;
(k) Grape marcs and wine lees
(l) Nut shells;
(m) Husks;
(n) Cobs cleaned of kernels of corn;
(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;
(p) Other non-food cellulosic material;
(q) Other ligno-cellulosic material except saw logs and veneer logs;
(r) Fusel oils from alcoholic distillation;
(s) Raw ethanol from kraft pulping stemming from the production of wood pulp;
(t) Intermediate crops, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land, and provided the soil organic matter content is maintained, where used for the production of biofuel for the aviation sector;
(u) Crops grown on severely degraded land, except food and feed crops, where used for the production of biofuel for the aviation sector;
(v) Cyanobacteria.

Part B. Feedstocks for the production of biofuels and biogas for transport, the contribution of which towards the targets referred to in Article 25(1), first subparagraph, point (a), shall be limited to:
(a) Used cooking oil;
(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.
(c) Damaged crops that are not fit for use in the food or feed chain, excluding substances that have been intentionally modified or contaminated in order to meet this definition;
(d) Municipal wastewater and derivatives other than sewage sludge;
(e) Crops grown on severely degraded land excluding food and feed crops and feedstocks listed in Part A of this Annex, where not used for the production of biofuel for the aviation sector;
(f) Intermediate crops, such as catch crops and cover crops, and excluding feedstocks listed in Part A of this Annex, that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained, where not used for the production of biofuel for the aviation sector.

Note: Feedstocks in Table 10 include those in Annex IX of RED II (European Union, 2018a), and those introduced by the more recent Commission Delegated Directive (European Commission, 2024a).

5.1.2. Assessing compliance

ReFuelEU Aviation and FuelEU Maritime incorporate and build upon the sustainability criteria outlined in the RED. The eligibility rules for fuels contributing to targets are enforced in the first instance through verification by approved certification bodies (the ‘voluntary schemes’ noted above). The schemes develop detailed methods and benchmarks to be used in assessment of compliance with the EU requirements, and train and appoint auditors to undertake certifications.

As an example, the certification body ISCC has developed the ‘ISCC-EU’ system documents that contain the requirements, definitions, and guidance for complying with up-to-date RED criteria. RED III proscribes the use, for instance, of biofuels “made from raw material obtained from land that was peatland in January 2008” but does not define peatland. ISCC’s documentation states “Peatland soils are soils with horizons of organic material (peat substrate) of a cumulative thickness of at least 30 cm at a depth of down to 60 cm. The organic matter contains at least 20 mass percent of organic carbon in the fine soil” (ISCC, 2023). Similarly, RED III proscribes the use of biofuel feedstocks grown on “highly biodiverse grassland spanning more than one hectare”; the ISCC provides a ten-page annex detailing what that means in practice (ISCC, 2023). ISCC auditors will be trained in assessing whether the conditions as laid out in its documents are satisfied, including what types of evidence are acceptable.

At the Member State level, competent government authorities must report data annually to the European Commission showing that they follow the RED. The Commission monitors implementation of the RED across Member States by reviewing submitted reports and cross-checking with the relevant certification bodies. Should a Member State fail to comply, the Commission can demand corrective action.

5.1.3. Chain of custody and fraud risk

The RED's sustainability requirements are enforced primarily through certification against independently operated sustainability schemes. A 'chain of custody' must be documented from the cultivation or collection of a biomass resource through to its use as biofuel feedstock so that compliance with the sustainability requirements can be assessed. While these verification systems are well established, having been in operation for several years now, there is still a risk that some batches of biofuel are associated with false information. In 2016 the European Court of Auditors raised a concern that the European Commission's process for recognising voluntary schemes for biofuel certification "does not supervise the functioning of recognised voluntary schemes, … [which] means that the Commission cannot obtain assurance that voluntary schemes actually apply the certification standards presented for recognition" (Kinšt & Jakobsen, 2016).

Investigators have also expressed concerns about the woody-biomass supply chains used by major bioenergy producers in Europe. For example, Drax power station in the UK is one of Europe's largest for burning biomass. Its supply chain has been linked to wood pellet sourcing from areas with high ecological value, including Natura 2000 sites in Portugal and old-growth forests in Canada (BiofuelWatch, 2024; Crowley, 2024). Similarly, investigations by NGOs in Estonia and Latvia have suggested that wood pellet production for bioenergy is linked to ongoing degradation of old-growth forests. The Estonian Fund for Nature documented this and connected it to instances of logging in high conservation value forests, home to numerous protected species and habitats (Kuresoo et al., 2020).

It remains unclear whether the current governance system of the RED is yet adequate to prevent wood harvesting practices for bioenergy that fall short of the RED requirements or are even illegal. Studies have shown discrepancies between reported woody biomass utilisation in the EU and reported harvested volumes. For instance, a study by the JRC revealed that in 2015 around 20% more woody biomass, amounting to 118 Mm^3, was used in the EU than was identified in reporting of biomass sources (Camia et al., 2021). The report attributes this discrepancy to the energy sector. Using trade flow data of overall wood production and utilisation in the EU, the JRC concluded that this can be explained by underestimations in official forestry removals records (which could be as high as 18%). However, it is also possible that some part of these volumes come from illegal sources. Investigations have highlighted the extent of illegal logging in parts of Eastern Europe; for example, in Bulgaria, between a third and a quarter of all felled trees were part of the black market, and in 2019 alone, the proceeds generated by those involved in illegal logging were estimated to be between $42 million and $90 million (Ivanov, 2022). Similarly, data provided by the National Forest Inventory of Romania confirms that around 20 Mm^3 of wood is illegally cut every year (Gherasim, 2024).

There is a major publicised issue about the mislabelling of virgin palm oil as used cooking oil (UCO) (Suzan, 2023). In 2019, a case emerged in the Netherlands where the Dutch transport authority announced identification of a suspected fraud in which biodiesel had illegitimately received a proof of sustainability. The suspected fraud accounted for 31.6% of all biodiesel consumed in the Netherlands in 2015 and 22.6% in 2016 (Inspectie Leefomgeving en Transport, 2019). Taking residual lipids away from existing uses is expected to have indirect effects that could include increases in palm oil production and expansion of palm oil plantations in high biodiversity ecosystems, but using palm oil directly has a much greater ILUC risk and would therefore multiply the biodiversity impact of the policy.

The analysis in this report is predicated on the assumption that the chain of custody and sustainability governance under RED/ReFuelEU Aviation/FuelEU Maritime is adequately robust, and that in general the feedstocks used will meet the RED requirements. Material identified as wood pellets from forestry residues will indeed be produced from residues rather than saw logs; material identified as rendered animal fats will indeed be animal fat rather than virgin palm oil; etc. If this assumption is not justified, then this report will understate the biodiversity risk from these policies.

5.2. Land use change

5.2.1. Direct and indirect land use change

Biofuels have been promoted to reduce the greenhouse gas emissions from transport fuels. However, many feedstocks used to produce biofuels have other potential uses and/or are produced on land which would also be suitable for producing food, feed, or fibre. To meet increasing feedstock demand, farmers may intensify activity on existing agricultural land or expand agriculture into previously unfarmed areas. This can occur in two ways (Figure 9):

i. Direct land use change (DLUC): this occurs when new areas of cropland are established specifically to produce biofuel feedstocks, such as converting forest and other natural/semi-natural ecosystems such as grassland.

ii. Indirect land use change (ILUC): this occurs when an available resource is repurposed from an existing use to support biofuel production, so that additional land is required to replace that resource. ILUC can occur in several contexts:

    a) Use of the material produced on a given land area for biofuel feedstock instead of an existing use. This is an issue for biofuels from existing food crops. For example, if rapeseed oil produced in Europe is displaced from the food market to biofuel production, then this leads to a deficit of vegetable oil in the food and feed market that could be resolved by converting new land in Europe to rapeseed production, converting new land in Southeast Asia to palm oil production, or any other mechanisms to increase vegetable oil production. ILUC models are used to develop scenarios for the mix of market responses that might be expected.

    b) Replacement of the current cropping system on an area of land with an entirely new cropping system to produce biofuel feedstock – for example replacing a food crop with a cellulosic biomass crop. For example, if switchgrass is planted on an area that was previously used to grow wheat and rapeseed in rotation, this would lead to a deficit of wheat grain, rapeseed oil, and rapeseed meal in the food market. Similarly to the first case, this deficit could lead to expansion of agricultural production elsewhere to compensate.

    c) Displacement of a residual resource away from its current use. For instance, if rendered animal fats are increasingly used to produce biofuels, the pet food industry, which previously relied on these fats, might turn to alternative materials such as palm oil or soy (Malins, 2023).

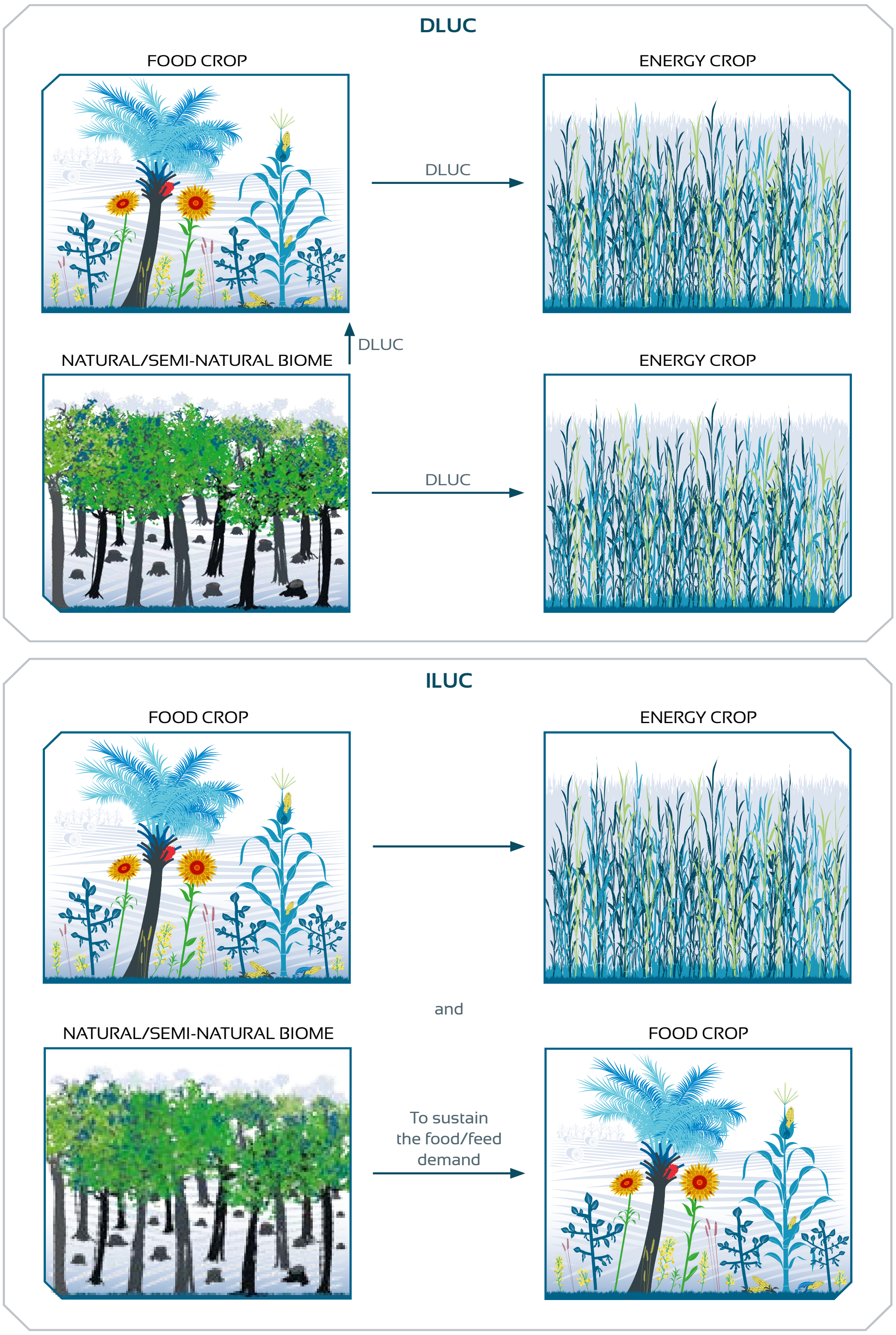


Figure 9. Direct and indirect land-use change

Source: Based on Czyrnek-Delêtre et al. (2016)

DLUC is relatively straightforward to observe and measure, because it involves identifiable, physical changes in land that can be documented and analysed, for example by using satellite imagery and remote sensing technology. However, ILUC is more complex: the effects can occur in multiple, disparate locations, and are influenced by a wide variety of economic, social, and environmental factors, making it hard to trace back to the original land use decision (Ahlgren & Di Lucia, 2016; Di Lucia et al., 2012). As such, complex modelling of the global economy is required to assess the expected ILUC impacts of diverting a given resource into biofuel production.

Of particular relevance both from a climate and a biodiversity perspective is the risk that ILUC occurs in tropical regions in ecosystems with high carbon stock and high biodiversity, leading to deforestation (Koh & Ghazoul, 2008). But ploughing of temperate grasslands and scrublands can also lead to significant carbon emissions from the soil (Fargione et al., 2008), which may far exceed the purported benefits of using biofuel to displace fossil fuel (Koh & Ghazoul, 2008; Malins et al., 2014). It is therefore possible that even if feedstock demand from ReFuelEU Aviation and FuelEU Maritime is met by RED III-compliant resources produced in the EU, there could be significant climate and biodiversity implications originating in the EU or elsewhere in the world.

The RED addresses the risk of ILUC in four ways (Sandford et al., 2024):

By capping support for 'food and feed' based biofuels, with a limit that varies by Member State but which guards against excessive displacement of existing production from agricultural land;

i. By promoting the use of advanced biofuels made from non-food feedstocks, such as those from agricultural and forestry residues and waste materials, which are assumed to have a lower risk of driving ILUC because they do not directly compete with food production;

ii. By imposing a requirement for substantial greenhouse gas emissions savings (covered in Section 5.1.1) which acts as a buffer against ILUC emissions;

iii. By establishing the 'low ILUC-risk' concept to identify crop-based feedstocks that can demonstrate the adoption of practices which avoid the displacement of other land uses.

5.2.2. ILUC modelling

Studies have attempted to model and quantify the impacts of ILUC. For example, the Global Biosphere Management Model (GLOBIOM) developed by the International Institute for Applied Systems Analysis (IIASA) has been used to assess biofuel-induced land use change and associated implications for greenhouse gas emissions. The model compares scenarios with additional biofuel consumption in the EU to baseline scenarios without that consumption and estimates the resulting land use change and its associated emissions. Valin et al. (2015) used GLOBIOM to perform a comparison of indirect carbon and land use change impacts from a variety of biofuels consumed in the EU. Their results are reproduced in Figure 10.

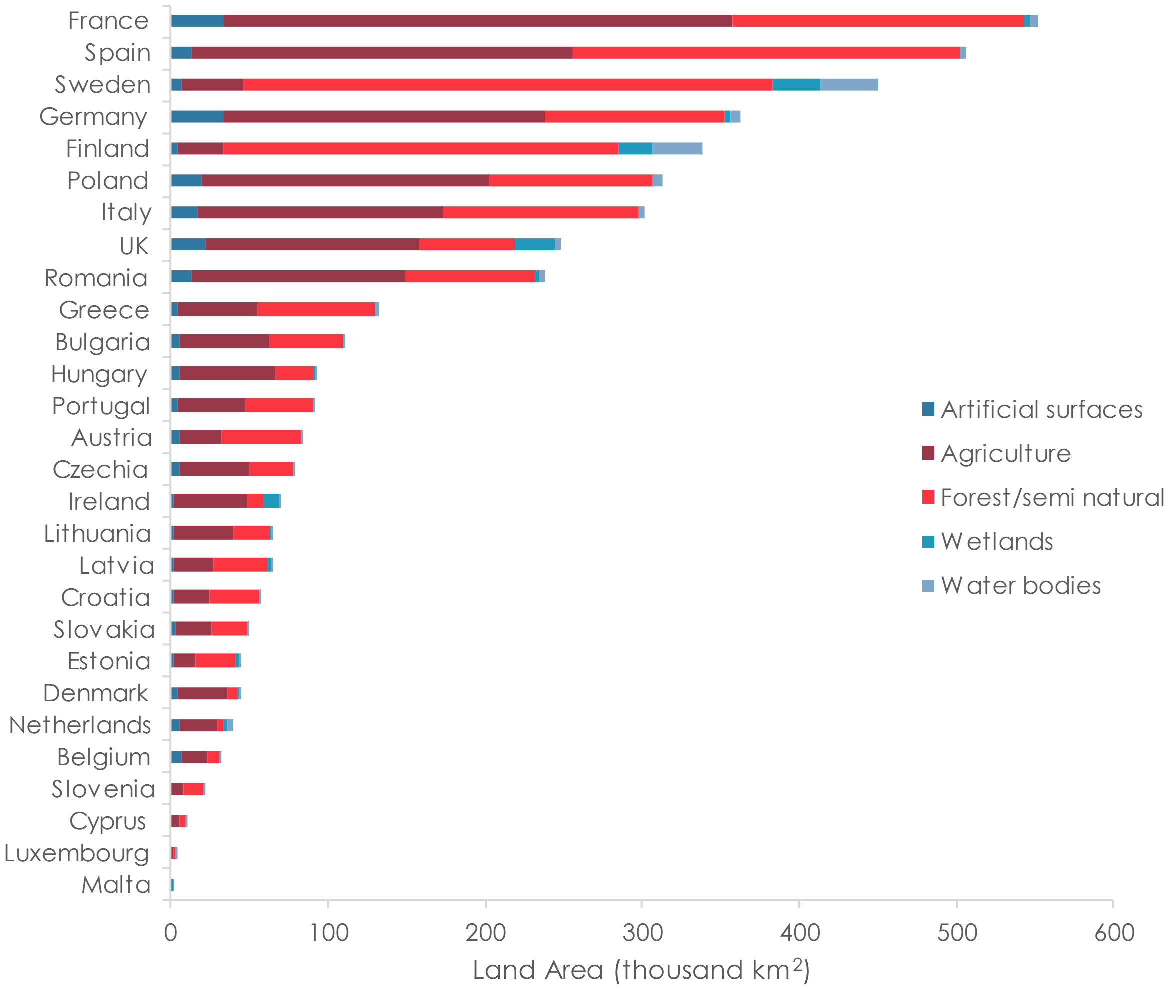


Figure 10. Land use change emissions from the GLOBIOM model

Note: The fossil fuel comparison line is set to 94 gCO_2e/MJ. The term 'natural land conversion' refers to release of carbon stored in biomass when land use change occurs – for instance, when forest land is cleared. The term 'natural land reversion' refers to the foregone carbon sequestration experienced when land used for biofuel crops would have otherwise been left to recover to a natural state[39].

Source: Adapted from Valin et al. (2015)

Valin et al. (2015) suggests that conventional biodiesel feedstocks have high LUC effects compared to the direct emissions resulting from the biofuel production process, with very high net emissions for palm oil (231 gCO_2e/MJ), soybean oil (150 gCO_2e/MJ); sunflower oil comes in at 63 gCO_2e/MJ and rapeseed oil at 65 gCO_2e/MJ. The study also suggests that advanced biofuels could have net negative LUC emissions if produced from short rotation crops (-29 gCO_2e/MJ) or perennial grasses (-12 gCO_2e/MJ). The negative net ILUC result is possible because the modelled increase in carbon stock on the land that is converted (in

39 The GLOBIOM model counterfactual accounts for carbon that would be sequestered in reverting natural land over a 20-year period.

biomass and soil) more than offsets any carbon losses from land use changes elsewhere. It should be noted that some other studies of ILUC emissions expected from cellulosic energy crops report positive results (Pavlenko & Searle, 2018).

Valin et al. (2015) also estimates land use change emissions for biofuels produced from agricultural or forestry residues (e.g. via Fischer-Tropsch hydrocarbon synthesis). The result can turn out positive even though the collection of residues does not lead to any land use change as such. The emissions instead are associated with an assumed reduction in soil organic carbon (SOC) due to removal of carbon from the system that would otherwise have decomposed in situ and become incorporated into the soil. The RED lifecycle emissions analysis requires that the emissions associated with harvesting of wood residues be accounted for; but this only covers factors like the fuel used in collection vehicles, and not the impact on soil organic carbon (which would require some sort of counterfactual). Soil carbon emissions of the type presented in Figure 10 are neglected as they are not associated with land use change.

5.2.3. Biodiversity and land use change

The discourse on land use change (and especially ILUC) has largely focussed on the emissions associated with changes in biomass and soil carbon stocks, but it also has critical implications for biodiversity. For instance, where this results in converting natural or semi natural habitats into agricultural use, it can cause habitat destruction, degradation, and fragmentation, all of which pose significant threats to biodiversity and disrupt ecological processes (IPBES, 2019). In Europe, where truly natural habitats are now limited and often have protected status, any land use change is more likely to affect semi-natural habitats, such as grasslands used for extensive pasture.

Soil health is particularly significant in the context of agricultural lands given its role in supporting productivity. However, soils also host over 25% of Earth's biodiversity and represent the world's largest terrestrial carbon pool (FAO, 2022), highlighting their significance to both biodiversity and climate. However, Gardi et al. (2013) found soil biodiversity to be under pressure in more than half of European soils tested, while another study found that soil biodiversity in 40% of soils in 14 Member States was under moderate-high to high potential risk (Orgiazzi et al., 2016).

Agricultural expansion linked to bioenergy feedstock can further degrade ecosystems through soil erosion and nutrient depletion. The increased intensity of agricultural activities also often leads to greater water consumption and pollution, adversely affecting local water resources and, consequently, the biodiversity that relies on it (Chambers et al., 2006; Scanlon et al., 2007; V. H. Smith et al., 1999). A snapshot of land use classes in the EU+UK is shown in Figure 11.

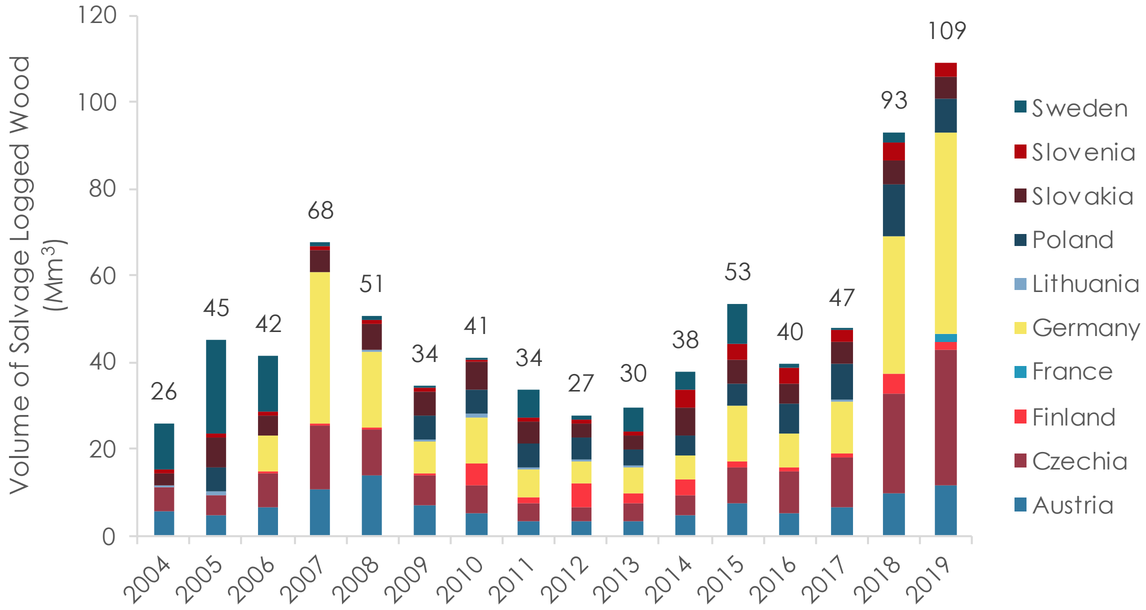


Figure 11. Land cover in 2018 by Member State for EU-27+UK

Source: Based on Copernicus Corine Land Cover (EEA, 2019)

Another consideration when addressing the biodiversity impacts of bioenergy production is the land sparing vs land sharing debate. These two approaches offer different strategies for balancing agricultural productivity with biodiversity conservation. Land sharing involves integrating wildlife-friendly practices into agricultural landscapes, promoting ecosystem services such as pollination and soil health, while enabling environmentally friendly production. Land sparing, on the other hand, focuses on concentrating high-yield agriculture in certain areas, leaving other areas as protected natural habitats to conserve species that cannot coexist with agriculture. As species move across landscapes, connectivity between shared and spared areas is essential to support both agricultural production and biodiversity. In the context of biofuel production, this debate is critical for understanding how to manage land sustainably. An integrated approach that combines context-specific land sparing and sharing strategies within connected landscapes can help balance bioenergy production with biodiversity conservation (Grass et al., 2019, 2021).

Research highlights the complexity and interconnectedness of biodiversity impacts related to biofuel feedstocks, ranging from direct effects on species and habitats to more indirect and cumulative consequences. The impacts of land use change naturally depend on the prior land use and the habitats and species affected, as well as the new land use and specifics of the farm management practices. Biodiversity impacts can be considered across different scales, from local to global, and over different timeframes, from immediate to long-term effects. For instance, the initial disturbance of establishing crops on previously uncropped land can immediately impact species diversity, habitat quality, and ecosystem function, while the continued application of pesticides and fertilisers, or changes in local hydrological cycles due to the water demands the crops may act over longer time-scales (Dauber et al., 2010).

In the following sections, we will explore the implications for land use and biodiversity in more detail, and the specific consequences associated with different bioenergy production systems and feedstocks.

5.2.4. Land abandonment

The EU has witnessed a significant trend of agricultural land abandonment in recent decades. The European Commission's Joint Research Centre (JRC) has projected that in the period 2015-2030, 4.8 Mha of agricultural land (2.7% of total agricultural area) will be abandoned (Perpiña Castillo et al., 2018), with areas of highest risk in Mediterranean France, Spain, and Cyprus, in Portugal, and in Romania, Poland, Latvia and Estonia in eastern Europe. Spain and Poland are expected to face the highest level of land abandonment by 2030, both in absolute and relative terms (5.0% and 4.8% of their UAA respectively). The drivers of declining farm profitability are complex but include degrading soils and heat and water stress exacerbated by the changing climate, alongside high input and labour costs. Moreover, many rural areas are witnessing population shrinkage as the younger generations move to cities. CAP subsidies have traditionally shored up farm incomes against cheap imports, but these tend to favour more productive regions and larger farms, which leaves marginal lands under-supported. As such, poor and mountainous areas where consolidation and mechanisation are challenging, and where economic opportunities are scarce, tend to be at high risk.

Across the EU, arable land is expected to account for more than 70% of total EU abandonment and pastoral land more than 20% (Perpiña Castillo et al., 2018). Abandoned land may be repurposed for other economic activities like renewable electricity and establishment of tree plantations (Wang et al., 2023), or it may undergo natural or artificial re-wilding. This depends on local conditions and policy incentives, and we return to the biodiversity-related impacts throughout the following sections. For the present purposes, we note that demand for bioenergy feedstocks may serve to reduce rates of abandonment, by offering new markets involving alternative crop types which may be better suited to cultivation. This will nuance our later results about the areas of additional land required for biofuels.

5.2.5. Marginal lands

There is a common narrative related to bioenergy, that biomass crops can be sustainably cultivated on marginal lands. However, this is potentially very damaging for biodiversity. Definitions of what constitutes 'marginal land' vary widely, as does the terminology used to describe such land (see Table 11). Generally, the term refers to areas that are less suitable for conventional agricultural production due to factors like adverse climatic conditions, poor soil quality, limited or excessive water availability, and adverse chemical or terrain conditions (Burland & von Cossel, 2023). However, many of these areas are still actively managed, often as extensive livestock systems that are not profitable and produce minimal yields. In practice, these lands are maintained, in part, by CAP subsidies, which are intended to support biodiversity conservation, High Nature Value (HNV) farming, and landscape preservation, as well as broader rural development objectives such as the avoidance of land abandonment and mitigation of associated risks such as scrub encroachment and increased fire hazards (Fayet et al., 2022b, 2022a; Sil et al., 2019).

Table 11. Definitions for various land types that can overlap with the definition of marginal land or are often mentioned in research concerning marginal lands

Term	Definition
Marginal land	"Lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention and also include contaminated and potentially contaminated sites that form a potential risk to humans, water, ecosystems, or other receptors".
Unproductive land	Land that is unproductive in terms of agricultural production.
Less favoured areas	Classified as areas where conditions are present that make farming more difficult due to natural constraints, which increase the costs of production or reduce opportunities for agricultural ventures.
Fallow land	Arable land that is used in a crop rotation system or is otherwise well maintained and is in good agricultural and environmental condition. Fallow land must be left to recover from the processes of agricultural production, usually for at least one entire crop year. This definition includes bare land that maintains no crops at all, land with natural growth that can be used as feed or ploughed, and green fallow areas intended to produce green manure.
Mountainous areas	Classified as areas in Nordic areas that experience temperatures similar to or lower than the highest peaks of the Alps, non-mountainous areas that form part of mountain ranges, municipalities that are 50% mountainous, but excluding isolated mountain areas that are comprised of less than 5 km^2.
Abandoned land	Abandoned land was once used for a particular purpose, such as industrial, silvicultural, or agricultural activities but has since been abandoned. Abandoned land is not the same as fallow land, since there is no intention to eventually resume activities. This land type is difficult to map.
Wasteland	Previous management, natural processes, or other events have rendered this land type unused, unstable, and without agricultural potential. This type includes active dunes, salt flats, rock outcrops, deserts, ice caps, and arid mountain areas.
Brownfields	Land that may be affected by contamination or pollution issues; may be seen as a subset of degraded land.
Degraded land	Land where productive use has been limited by anthropogenic activities. Generally, at least some degraded lands are seen as marginal.
Buffer strips	Small marginal areas near rivers, roadways, or other urban places.
Areas of natural constrains (ANCs)	Areas that are that are more difficult to effectively farm due to specific problems caused by natural conditions.

Source: Burland & von Cossel (2023b); European Commission (2024g)

Several studies have examined the availability of marginal land within the EU. Estimates vary between 38 and 54 million ha in the EU and United Kingdom (Gerwin et al., 2018; Von Cossel et al., 2020). The MAGIC project (MAGIC, 2023), which aimed to help farmers decide which industrial crops are suitable for different respective marginal locations, found that 29% of the agricultural land in the EU-28 is marginal. Researchers working on the project also estimated that 34% of marginal land in the EU-28 overlaps with High Nature Value farmland. This overlap indicates that a significant proportion of marginal lands, which may be targeted for biomass production, are already valuable for biodiversity.

Meanwhile, Allen et al. (2014) estimate that between 1 and 1.5 Mha of land could be investigated further for energy cropping but recognise that there are significant areas that are not identified easily in current agriculture or land use statistics. Cultivation of land that is in fact semi-natural habitat would result in significant biodiversity and probably carbon losses, and so the paper emphasises the importance of local or regional assessments to assess the specific environmental impacts from any new cultivation.

Thus, the narrative that biomass crops can be readily cultivated on marginal lands overlooks the ecological and wider value of these areas (Kiesel et al., 2023). While marginal lands may be underutilised and unprofitable from an agricultural perspective, they may provide significant ecological benefits, that are not immediately apparent. For example, these lands may be critical ecological corridors, support pollinators and other wildlife (Paracchini et al., 2009), serve as buffer zones, provide erosion mitigation, groundwater protection, nursery services for biodiversity, and increasingly fire prevention (Blanco-Canqui, 2016; Burland & von Cossel, 2023b; Rouet-Leduc et al., 2021). This makes the conversation around marginal lands complex and fraught with conflicting interests.

5.3. Cellulosic feedstocks

Cellulosic biomass is organic material derived from plants that is primarily cellulose, hemicellulose, and lignin. These materials are widespread and can be sourced from a variety of agricultural and forestry residues, as well as dedicated energy crops. The following sections review the main categories of cellulosic feedstocks envisaged for use in biofuel production and assessed their relative impacts on biodiversity.

5.3.1. Perennial grasses

Perennial grasses are plant species that live for more than two years, typically harvested annually and biennially, and regrow each season from their rootstock. These grasses are widely used in agriculture as forage for livestock and as biomass for energy production. Common perennial grasses used for bioenergy include:

- *Miscanthus* spp.: native to East Asia, grows in a variety of soil types, including marginal lands unsuitable for food crops. *Miscanthus x giganteus* a sterile hybrid commonly used for bioenergy, cannot reproduce by seed but propagates vegetatively, allowing it to spread over time. In its native ecosystem, miscanthus stabilises soil, contributes to nutrient cycling, and provides habitat for various organisms. *Miscanthus x giganteus* is a commonly used sterile hybrid, which means it cannot reproduce by seed. However, it still has vigorous growth and spreads through propagules. This means that any specific area under miscanthus will see the area coverage increase over time as the grass self-propagates.

- Switchgrass (*Panicum virgatum*): native to North America, thrives in prairies and open woodlands, playing a crucial role in preventing soil erosion, improving soil health through organic matter inputs, and supporting wildlife habitat including for pollinators and ground nesting birds. However, it can spread if it is not managed appropriately, raising concerns about its cultivation in non-native regions like Europe.
- Giant reed (*Arundo donax*): native to the Mediterranean Basin, typically grows along riverbanks, wetlands, and moist habitats. While it stabilises soil and provides habitat for aquatic and terrestrial species, it can become invasive outside its native range, outcompeting native vegetation and altering local hydrology and habitats (Bell, 1997).

The biodiversity impacts of perennial grasses vary depending on the specific crop, location and management practice. These grasses can offer certain biodiversity benefits compared to conventional crops, especially when replacing intensive arable land. For example, they require less water and fewer inputs such as fertilisers and pesticides due to their deep root systems, which can improve water infiltration, retention, and reduce runoff and soil erosion (Dauber et al., 2010; Monti & Zatta, 2009). The reduced need for frequent soil disturbance can also promote soil health and structure. For example, increased soil organic matter (SOM) from root biomass and leaf litter improves soil fertility and supports soil-dwelling organisms, enhancing overall soil biodiversity (Hoffland et al., 2020). Studies have also suggested that perennial grasses can have positive effects on soil carbon sequestration (L. Fernando et al., 2018). Ledo et al. (2020) found that replacing annual with perennial crops, increased soil organic carbon by 20% between 0-20 cm and 10% over 0-100 cm.

Studies suggest that fields of *Miscanthus x giganteus* support higher densities of certain bird species compared to conventional arable fields, likely due to the shelter provided by the crops and the abundance of non-crop plants and insects associated with them (Bellamy et al., 2009; Clapham & Slater, 2008; Semere & Slater, 2007b, 2007a). However, Bellamy et al. (2009) also noted that these benefits can diminish over time if the crops are managed solely to maximise yields, leading to a loss of features that attract and support wildlife.

Perennial grasses can also positively impact invertebrates. For instance, miscanthus fields have been found to host a greater abundance and diversity of invertebrate groups, such as ground beetles, butterflies and arboreal invertebrates, compared to other biomass crops (Semere & Slater, 2007b). This is attributed to the diverse weeds that establish within their stands, which serve as food and habitat for invertebrates, especially over-winter. However, other studies have reported significantly lower ground beetle and arachnid species richness, biomass and abundance than an adjacent mixed-use arable field, and significantly lower ground beetle biomass and abundance than adjacent grassland (Williams & Feest, 2019).

While perennial grasses can provide certain environmental benefits, the overall impact on biodiversity is context dependent. These crops are beneficial to biodiversity when they replace intensive arable lands (Haughton et al., 2009, 2016) rather than when they replace semi-natural habitats, which are typically more valuable for biodiversity. Miscanthus has been extensively studied in Europe for bioenergy production. Studies suggest that while the grass can provide significant biomass yields, careful site selection and management practices are crucial to minimise impact (Von Cossel et al., 2020). Currently the areas cultivated for perennial grasses are relatively limited: for example, approximately 20,000 ha of miscanthus is grown across the EU (Lewandowski et al., 2018). However, large-scale cultivation of perennial grasses could lead to habitat loss and fragmentation, with significant impacts for local flora and fauna. Ultimately, as for all bioenergy crops, it depends on the type of land which is converted. For instance, the conversion of semi-natural habitats such as grasslands and scrubland would be highly detrimental for biodiversity, especially if it affects HD Annex I habitats. In contrast, conversion of some areas of cropland monocultures can increase habitat heterogeneity, benefiting some farmland species.

5.3.2. *Annual energy crops*

Annual energy crops are plants which complete their life cycle within a single growing season., making them suitable for integration into existing agricultural systems without long-term land commitments. These crops are favoured for their rapid growth rates and flexibility in cultivation. A common example is biomass sorghum (*Sorghum bicolor*), a drought-tolerant crop originally from Africa that is well-suited to warm climates and can grow in various soil types. With its deep root system, sorghum can contribute to soil stabilisation and improve soil productivity (Lamb et al., 2022).

However, while the risk of invasiveness for most annual energy crops is generally low with proper management, there are concerns that sorghum species could spread into unintended areas (Barney & DiTomaso, 2010). Large-scale cultivation, particularly in monocultures, can drive habitat loss and fragmentation, negatively affecting local flora and fauna, by replacing diverse ecosystems with less heterogeneous environments (Dauber et al., 2010; R. G. Smith et al., 2008). Monocultures reduce habitat heterogeneity making the land less hospitable for a range of species and increasing vulnerability to pests and diseases (Ballogh, 2021).

From an agricultural perspective, annual energy crops provide greater flexibility than perennial crops, because they can be switched after a single year of cultivation. However, this generally is associated with more intensive agricultural practices, with annual crops generally require higher inputs of chemicals and energy than perennial energy crops (Ford et al., 2024). This input demand can have a range of impacts on biodiversity, from harming non-target organisms such as beneficial insects and soil microbiota, and through nutrient runoff, which can pollute water bodies, causing eutrophication and harming aquatic ecosystems (Smith et al., 1999). Insecticide use has been linked to declines in pollinator populations, especially bees. These chemicals can affect bees foraging behaviour, memory for navigation, colony and nesting success (Goulson, 2013).

Additionally, annual energy crops will require substantial fertilisation. Data from the JRC put biomass crops' demand for nitrogen and potassium compounds at 60-80 kg/ha and phosphate at around 10 kg/ha (see C.4.5 for the discussion and reference). High fertiliser application rates can result in nutrient runoff, leading to eutrophication of nearby water bodies, which harms aquatic ecosystems by causing algal blooms and hypoxic conditions (Smith et al., 1999). Moreover, while sorghum has low water requirements compared to others like maize and wheat, it is likely to need irrigation in arid regions (Mundia et al., 2019), which could create competition for water resources and exacerbate water scarcity.

A review by Klenke et al (2017) found that increase maize cultivation for bioenergy in Germany has had strong negative impacts on a range of species, including earthworms, hoverflies, solitary bees, bumblebees, and birds, with most studies highlighting reduced biodiversity, abundances, and biomass in maize fields relative to other habitats. While some species, like spiders and carabid beetles, showed mixed responses, the overall biodiversity in maize fields was consistently lower than in more natural or semi-natural habitats, such as grasslands, fallows, or fields with less intensive management. Negative impacts were particularly evident for farmland birds, whose populations have been in continuous decline over the past 25 years, exacerbated by the loss of rotational set-aside land and the expansion of maize cultivation around biogas plants, which reduced crop diversity in rural landscapes. Although some positive effects were observed, such as the reduced need for tillage post-harvest, which increased undisturbed areas for feeding and resting during migration, the overall findings suggest that achieving a balance between bioenergy production and biodiversity conservation would require significant measures, such as increasing the area of fallow land to at least 10% to halt farmland bird declines (Klenke et al., 2017).

Though maize (as a food and feed crop) does not qualify to support the ReFuelEU Aviation and FuelEU Maritime targets for advanced biofuels, the review by Klenke et al. (2017) serves as a strong example of the biodiversity impacts of energy crop expansion. Additionally, to avoid competition with food production, annual energy crops are increasingly promoted for cultivation on marginal lands. However, as we have already considered in Section 5.2.5, converting these lands can also have a detrimental effect on biodiversity. Such conversions may degrade ecosystems that provide vital habitats for various species, highlighting the need for careful consideration and management strategies when choosing sites for bioenergy crops.

5.3.3. Agricultural residues

Agricultural residues refer to the biomass left in fields after the harvest of primary crops, including leaves, stems or stalks, corn stover, wheat straw and rice straw. These residues are not the primary goal of agricultural production but offer a significant potential source of biomass for energy production, reducing competition with food production. The total agricultural biomass produced annually in the EU is estimated at around 959 million tonnes (Mt) per year between 2006-2015, of which 46% (approximately 442 million tonnes) are agricultural residues (Camia et al., 2018). Residues such as corn stover (leaves, stalks, and cobs), wheat straw, and rice straw are commonly considered for biomass energy production, including pellet production, biogas, or dedicated biomass combustion plants.

Agricultural residues can provide a sustainable source of bioenergy, potentially reducing the pressure to convert additional land for bioenergy production. Several studies estimate that around 122 million tonnes of agricultural residues are currently sustainably available for advanced biofuels (Harrison et al., 2014) (see also the list of literature estimates in Table 19 below); this would be enough to produce around 1,000 PJ (24 Mtoe) of fuel. However, data on the extent of the use of agricultural residues remain scattered (Bowyer et al., 2020), and availability estimates are generally based on empirical models, with relatively large uncertainties (Camia et al., 2018).

While using agricultural residues for bioenergy could reduce the need for converting other land for biomass production, it also poses risks to soil health and biodiversity. When left in the field, these residues play a crucial role in maintaining soil health by providing ground cover that reduces soil erosion, retains moisture and contributes to soil organic matter. They also support various ecological processes such as nutrient cycling, and soil biota (Karlen, 2011; Lal, 2005) (Mulumba & Lal, 2008).

The decomposition of these residues is essential for nutrient cycling, returning nutrients to the soil, enhancing fertility, and maintaining soil structure (Bolinder et al., 2020; Panteleit et al., 2018). Removing too many residues can deplete soil nutrients, reduce soil organic carbon (Blanco-Canqui & Lal, 2009a), and cause physical changes in the soil, potentially leading to reduced future productivity (Blanco-Canqui & Lal, 2009b, 2015; Klopp & Blanco-Canqui, 2022). Studies suggest that leaving at least one-third of residues in the field is necessary to sustain soil quality (Wilhelm et al., 2004).

Agricultural residues provide critical habitat and resource for various wildlife, including birds, small mammals, and invertebrates. They support detrital[40] food webs, which drive ecosystem services (López-Mondéjar et al., 2018) by influencing soil structure, microbial communities, and plant productivity (Lavelle et al., 2006). Residues also offer food and cover for small mammals, such as field mice (*Apodemus sylvaticus*) and voles (*Microtus* spp.) (Heroldová et al., 2021), which has knock-on impacts at higher trophic levels (Bowers et al., 2021; Sereda et al., 2015), for example for predators like owls and other birds of prey.

Birds also utilise post-harvest materials. For instance, stubble, containing weed seeds and split grain, left behind after cereal harvesting is attractive to small birds, such as Greenfinch, Twite, Corn Bunting and Skylarks (Hancock et al. 2016). Similarly, residues can influence invertebrate populations, such as beetles and spiders, which are essential for many birds' diets. Studies on the impact of conservation tillage, which leaves crop residues on the surface of fields, have shown mixed results on invertebrate abundances in the USA and Europe (Cunningham et al., 2004; Holland, 2004).

While it is acceptable to remove some agricultural residues, excessive or frequent removal (especially over the long-term) could have significant ecological impacts, especially on soil health, biodiversity, and long-term productivity. Careful management practices, such as leaving sufficient residues in the field and integrating crop rotation, can help maintain soil quality and ecosystem functions (Powlson et al., 2008). Additionally, minimising residue removal will be essential to sustain the biodiversity of soil invertebrates and microorganisms, which play crucial roles in nutrient cycling and soil structure (Mulumba & Lal, 2008). To balance bioenergy needs with environmental sustainability, it is critical to consider both the potential benefits and negative impacts of residue removal. Ensuring that agricultural residues are managed appropriately can help maintain soil health, soil biodiversity, and contribute to the EU's renewable energy goals.

5.3.4. Short rotation forestry

Short rotation forestry (SRF), also known as short rotation coppicing (SRC), involves cultivating fast-growing tree species such as willow (*Salix spp*.) and poplar (*Populus spp*.), for biomass production. These trees are harvested at regular intervals: willow every 2-4 years, and poplar every 5-10 years. SRF is characterised by its adaptability to various soil types and conditions (Mola-Yudego & Aronsson, 2008; Volk et al., 2004), making it a popular choice for biomass production across Europe. SRF covers approximately 50,000 hectares in the EU (Rodrigues et al., 2020).

SRF offers several ecological benefits when established on intensive agricultural land:

40 Soil detritivores, also known as decomposers, comprise several large groups of invertebrates such as earthworms, beetles, snails, flies, mites and woodlice that play critical roles in many soil processes.

- Soil stabilisation and nutrients: both willows and poplar have extensive root systems that help stabilise soil, prevent erosion, and improve soil structure, particularly along riverbanks and floodplains (Baum et al., 2009). They contribute to soil health by adding organic matter through leaf litter decomposition and nutrient cycling (Hangs et al., 2014). Reduced soil disturbances in SRF systems also promotes soil carbon sequestration (Kahle & Janssen, 2020).
- Water quality: SRF, especially willow, is effective in reducing nutrient runoff (such as nitrogen and phosphorus) into adjacent water bodies, thereby improving water quality (Johnston, 2024). Willow root systems also help filter water, by trapping sediment and absorbing pollutants, such as heavy metals, making SRF suitable for 'phytoremediation' on contaminated sites (Dickmann, 2001; Vervaeke et al., 2003).
- Carbon sequestration: fast-growing SRF species, such as willow and poplar, can sequester significant amounts of carbon dioxide, contributing to climate change mitigation (Isebrands & Richardson, 2014; Rytter et al., 2015)[41].

Since plantings are staggered, biomass can generally be harvested from a given plantation on an annual basis. The estimated production of biomass from SRF in Europe is significant. For instance, in Sweden, willow SRF yields range from 5-12 tonnes of dry mass per hectare per year (Mola-Yudego & Aronsson, 2008).

SRF plantations can support local biodiversity by providing habitats and resources for various species, including birds, mammals, and invertebrates. Studies indicate that SRF fields can host higher abundance and diversity of species compared to equivalent arable or grassland areas, including species characteristic of scrub or woodland habitats (Sage et al., 2006; Vanbeveren & Ceulemans, 2019). The progression from open-field to a more forest-like structure as SRF matures attracts different bird and arthropod communities and supports small mammals to fulfil their habitat requirements. Other studies have noted that with increasing age of SRC, forest birds become more common (Dauber et al., 2010).

However, biodiversity benefits are context dependent. While SRF can enhance biodiversity when replacing intensive arable land, it can be detrimental if it replaces semi-natural habitats, which are typically richer in biodiversity (Dauber et al., 2010). Moreover, the establishment of SRF as monoculture may reduce overall habitat diversity and heterogeneity with adverse impacts on local biodiversity (Ballogh, 2021) and increase the risk of pest outbreaks (Dalin et al., 2009).

A significant concern with SRF is the risk of invasiveness. Species used in SRF are selected for their fast growth and adaptability. These trees can propagate by seed and vegetative means (Isebrands & Richardson, 2014), such as through broken branches taking root downstream (Richardson & Rejmánek, 2011). These traits, while beneficial for biomass production, and even for habitat restoration (Boothroyd-Roberts et al., 2013; Desrochers et al., 2020; McLeod et al., 2001; Smulders et al., 2008), can make these species invasive outside their native range (Cremer, 2003).In Europe, non-native species such as *Populus deltoides* (Eastern Cottonwood) and various *Populus* × *canadensis* hybrids, have been widely planted (Vanden Broeck et al., 2005). Hybrids which escape cultivation and establish themselves in natural habitats, sometimes outcompete native vegetation (Richardson & Rejmánek, 2011), and hybridise

41 Though of course all the carbon dioxide is released again if the wood is used for fuel.

with native species, reducing genetic diversity (Vanden Broeck et al., 2005). Similar concerns apply to willows, such as *Salix viminalis* (common osier) and *Salix x fragilis* (crack willow), which have shown invasive tendencies in some regions of Canada and the USA (CABI, 2019).

Black locust is a particularly relevant example of SRF gone wrong, particularly in Italy, where it was extensively planted for biomass. It yields significant biomass, up to 12 tonnes of dry biomass per hectare, each year under optimal conditions (Vítková et al., 2017). Vigorous growth and resilience have contributed to its successful establishment in various environments, from agricultural lands to urban green spaces (Richardson & Rejmánek, 2011), where it forms dense stands which outcompete native vegetation such as sweet chestnut and oak (Campagnaro et al., 2023Campagnaro et al., 2023). Moreover, it fixes nitrogen, which significantly alters soil nutrient dynamics, benefiting its own growth while disadvantaging native species adapted to lower nitrogen levels (Kleinbauer et al., 2010).

Studies have shown that willows can be used as vegetation filters to treat wastewater (Perttu & Kowalik, 1997) from agricultural land (Elowson, 1999), and remove nutrients from municipal sludge (Perttu, 1999). However, while SRF plantations can improve water quality, they may also impact local water availability. Livingstone et al. (2022) found that SRF used as riparian buffers could reduce groundwater recharge, necessitating careful site selection and water management practices to balance water use. Additionally, SRF practices can lead to soil compaction and nutrient depletion if harvesting cycles are intensive, affecting soil health and productivity over time (Kleinbauer et al., 2010).

SRF offers multiple ecological benefits, such as soil stabilisation, water quality improvement, and carbon sequestration, which can support biodiversity and ecosystem services. However, the potential risks related to invasiveness, reduced habitat diversity, and water use must be managed carefully. The selection of appropriate sites, ongoing monitoring, and adaptive management practices will be essential to maximise the benefits while minimising ecological impacts.

5.3.5. Stemwood

Stemwood, also known as roundwood, is the main trunk of trees. It represents a significant source of biomass in the EU. The most recent estimate of the total use of wood from EU forests to our knowledge comes from 2015 and was estimated to be around 921 Mm^3, with the proportion of wood used for energy estimated at 49% (Cazzaniga et al., 2019). Harvesting regimes can broadly be separated by the extent to which the forest canopy is opened or removed, the way that harvesting is distributed over the forest area and the impact of this on the overall forest structure (Table 12). These regimes will differ in their impacts for biodiversity and ecosystem function. However, limited information is available on which harvesting systems are applied across Europe.

Statistics on wood removals and tree felling may not be directly comparable because of differences in reporting methodologies and definitions (EEA, 2024c). However, a range of issues arise around the utilisation of stemwood for energy. Harvesting whole sections or stands of trees lead to broadscale habitat loss and fragmentation, affecting multiple species across different trophic levels (Haddad et al., 2015). Removing the canopy increases temperatures in cleared areas, raising erosion risks, and leading to a decline in soil moisture and water retention, which affects plant and animal species dependent on stable soil conditions

(Pimentel et al., 1995). For species dependent on stemwood and deadwood this could be detrimental (Siitonen, 2001).

Table 12. Description of typical harvesting regimes adopted in European forest management

Harvesting regime	Impact on canopy	Impact on Forest Structure
Clear cutting: removes everything	Complete canopy removal, results in large open space and exposed soils	No layers remain, significant alteration of forest structure
Shelterwood regime: intermittent tree harvesting	Partial canopy removal, some areas opened, some soils exposed	Multiple forest layers remain, more complex structure
Single tree / group selection: limited selection and removal over area	Scattered removal, canopy mostly intact, or partial removal	Largely maintains complex forest structure

Source: Adapted from Forest Information System for Europe (EEA, 2024c)

The use of whole trees for biomass is contentious. While some forestry stakeholders have argued that it's not economically viable to use whole trees for bioenergy, many NGOs provide evidence of clearcut trees being used for exactly this purpose. Instances of clearcutting trees for biomass have been documented in several European countries, raising concerns about the long-term sustainability and ecological impact of such practices (EASAC, 2017).

Additionally, natural disturbances such as wind, insect outbreaks and fire can drive changes in forest structures (Camia et al., 2021). Natural disturbances have dramatically increased in Europe in the last forty years, especially during the first decade of the twenty-first century (insect outbreaks +602%, wildfires +231% and windstorms +140% relative to 1971-80) (Seidl et al., 2014) and it is expected that natural disturbances will become more frequent and intensive due to climate change (Seidl et al., 2017). Forest management measures may be taken to minimise the risk of such disturbance, for example removing leaf litter, needles and other woody debris, to reduce the risk of wildfire. However, post-disturbance management depends on the type of disturbance.

Salvage logging (i.e. felling and removing trees in disturbed forests) is most broadly used in the case of windstorms, wildfires and insect outbreaks, and is becoming an increasingly common practice in many EU countries (see Figure 12). For example, the practice has been widely used as part of measures to control bark beetle outbreaks in forests of Norwegian spruce after windstorms or severe drought periods. However, salvage logging also reduces forest carbon storage by removing the carbon stored in disturbed trees (Dobor et al., 2020).

The JRC's study in 2021 concluded that a limited removal of 'fine woody debris' (low diameter branches, leaves, needles, etc.) would result in a neutral / positive impact for the climate and biodiversity (Camia et al., 2021). The summary of their results is reproduced in Figure 13. However, the study noted that afforestation on former agricultural land or areas under low-intensity land management could also have neutral or positive outcomes. It is important to clarify that this is not always the case; for instance, some low-intensity agricultural lands, such as dry cereal fields in Spain and Eastern Europe, are crucial habitats for threatened species like certain bird populations, and afforestation of these habitats could be highly detrimental

(Bota et al., 2005). The significant risks associated with the afforestation of biodiverse habitats are also emphasised in studies like Bowyer et al (2020), which indicate that such activities can lead to considerable biodiversity loss and ecosystem disruption.

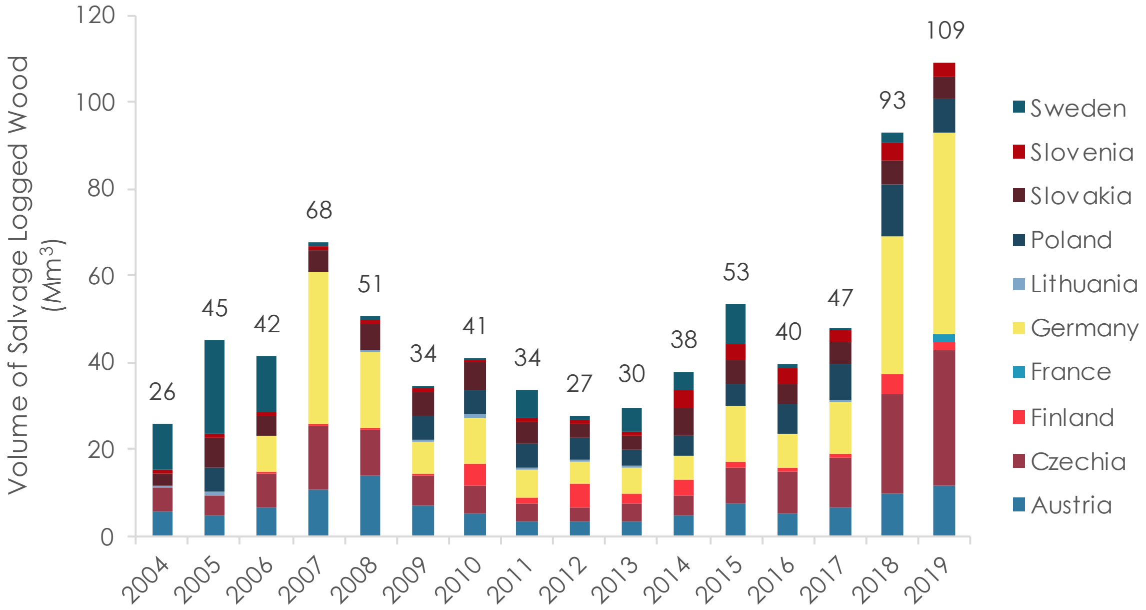


Figure 12. Volume of salvage logged wood in ten EU27 countries 2004-2019 in million cubic metres, with total shown at the top of the columns

Source: Based on EEA (2024d)

Meanwhile, the harvesting and burning of 'coarse woody debris' – that is, logs, stumps and other large chunks of wood left over after logging – is a "high risk for biodiversity and climate" (Camia et al., 2021). The study did not assess the impact of harvesting stem wood, despite the acknowledgement of its significant contribution to energy. Nor did the scenarios assess the impact of salvage logging, which currently contributes significantly to the forest wood burned for energy in the EU. Previous work cited in the report such as a study by Booth (2018), found that the carbon impacts of harvesting stem wood generally exceed those from fossil fuels for decades to centuries. Moreover, a study from Chatham House (Brack et al., 2021) found that US-sourced wood pellets burnt in the UK were responsible for 13-16 million tonnes of CO_2 emissions in 2019, equivalent to the emissions from between 6 million and 7 million passenger vehicles. Though this report is predominantly focused on EU domestic biodiversity impacts, there can be significant GHG impacts from imported feedstocks.

Meanwhile, Annex IX of the Renewable Energy Directive (see Table 10 above) includes the biomass fraction of wastes and residues from forestry and forest-based industries: bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil; as well other ligno-cellulosic material except saw logs and veneer logs (under points (o) and (q) respectively). Burning stemwood, wood pellets, and wood chip for electricity can count towards renewable energy targets, but RED III has eliminated direct financial support for burning stumps and roots, saw logs and veneer logs, and 'industrial grade roundwood' (i.e. wood that is suitable for other uses).

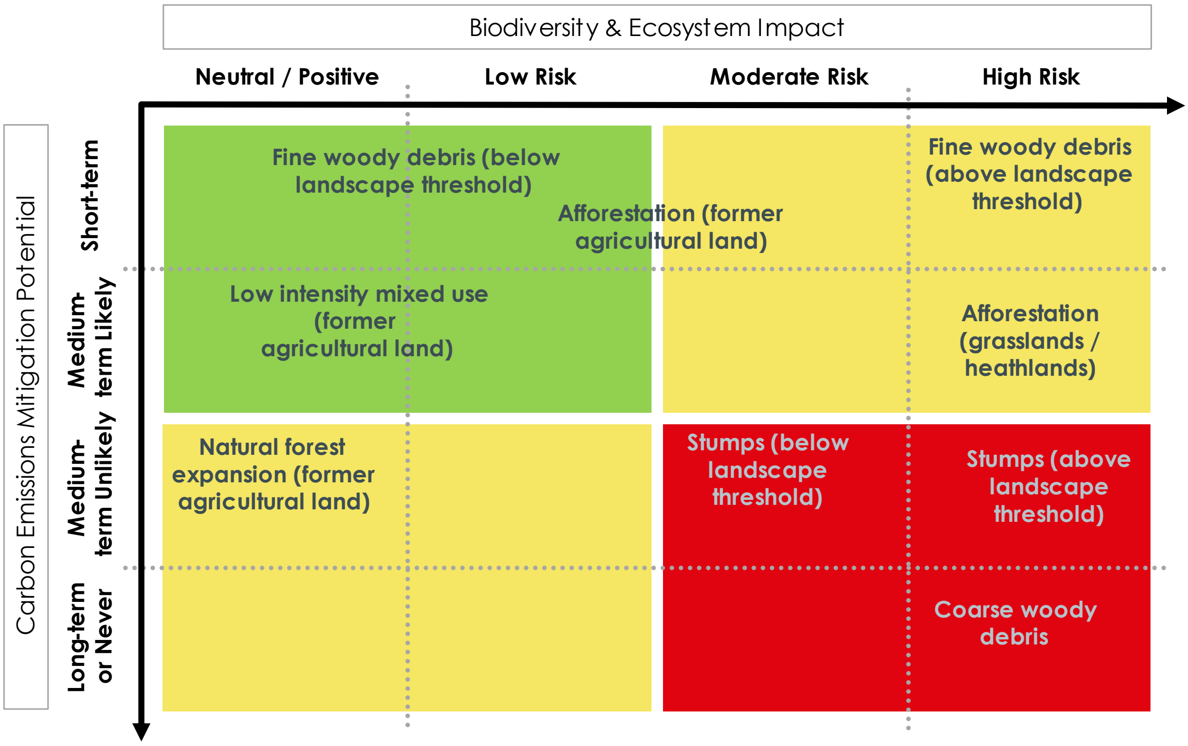


Figure 13. Climate and biodiversity impact assessment of different pathways of utilising woody biomass for energy in the EU

Source: Adapted from Camia et al. (2021); see the original source for a more nuanced breakdown.

5.3.6. Forest residues

Forest residues are the unprocessed materials remaining after forest extraction activities, including branches, twigs, treetops, leaves and other materials left over following logging operations (such as removal of commercial roundwood or stemwood). These materials, fall under 'fine woody debris' as outlined in Figure 13, and are distinct from secondary residues from industrial wood processing, such as sawdust or woodchips from sawmills. Forest residues are primarily used to produce wood chips for energy, though some are used for pellet production. Additionally, low value' wood, such as rejected sawlogs, material from thinning practices, and small diameter stem wood can also be utilised (UNECE, 2013).

Interest in utilising forest residues for bioenergy production has increased in recent years, but there is limited data on how logging residues are currently extracted in Europe (EEA, 2024c). Camia et al. (2018) estimated that, on average, 281 million tonnes (Mt) of wood are felled yearly in Europe, of which 224 Mt are removed from forests while 57 Mt (or 20%) remain as logging residues. Interest in utilising forest residues for bioenergy production has increased in recent years, but there is limited data on how logging residues are currently extracted in Europe (EEA, 2024c). However, the study also acknowledges that removals could be underestimated by up to 20%. While leaving some biomass as residue on the ground is important for maintaining soil organic matter, nutrients, and physical properties, removing forestry residues for bioenergy can also have significant implications for biodiversity and environmental health.

Di Gruttola & Borello (2021) used the FAOSTAT database to estimate forestry production of wood fuel, saw logs and veneer logs, pulpwood (round and split), and other industrial roundwood coming from both coniferous and non-coniferous roundwood. They developed an estimate of forest residue availability across EU Member States in 2025, shown in Figure 14.

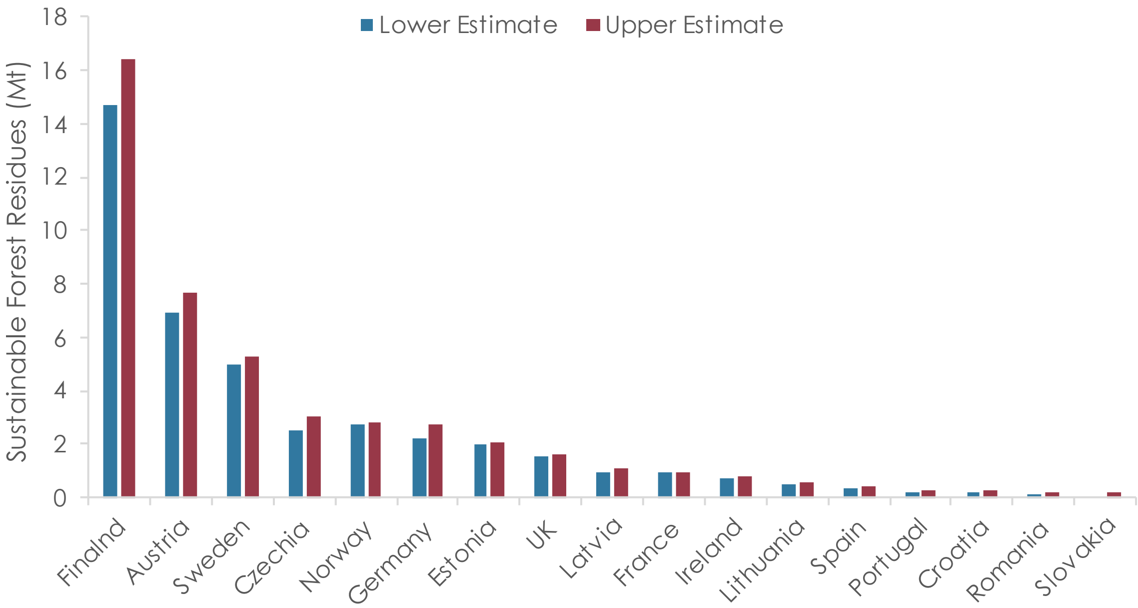


Figure 14. Forestry residues availability in Europe in 2025, in million tonnes per year

Note: Only showing European countries estimated to have greater than 0.1 Mt/year resource.
Source: Based on Di Gruttola & Borello (2021)

Forest residue harvesting encompasses a broad range of materials, from fine woody debris such as slash (tops and branches) and thinnings, to coarse woody debris, including whole trees, snags (standing dead trees) and high stumps (i.e. stemwood). Stands damaged by insects, disease or fire may also be 'salvaged' for biomass (Figure 12). Additionally, low stumps and roots could be considered under this umbrella, although these no longer qualify for financial incentives under RED III. These materials play interconnected roles within forest ecosystems, and their harvesting is often part of the same management regime for a specified forest area. To assess the biodiversity impacts accurately, it is necessary to differentiate these categories and evaluate the relative impacts of harvesting different types of residues.

Harvesting whole trees or stemwood, which removes essential components of the forest ecosystem, has significant ecological impacts, particularly for biodiversity. Clear-cutting sections of forests or stands of trees fundamentally alters the forest's characteristics, removes habitat and resources, and creates a fragmented habitat with open areas. The loss of climate buffering canopy cover from clear-cutting operations can significantly disrupt the forest microclimate, leading to increased light levels, higher daytime temperatures, and elevated rates of evaporation, which can reduce soil moisture and increase soil erosion (cf. L. Gustafsson et al., 2010; Lindner et al., 2010). Consequently, plant and animal species which depend on stable climatic conditions are likely to suffer (Pimentel et al., 1995). While small-scale selective felling can somewhat benefit biodiversity by creating open habitats and increasing habitat heterogeneity, typical large-scale clear cutting is highly detrimental.

Deadwood, such as standing dead trees or snags, provides critical habitat for around 25% of forest species (Haeler et al., 2024). Saproxylic invertebrates, including many species of beetles, ants, flies, termites and their predators or parasites, depend on dead or decaying wood, for at least part of their life cycle. This includes the 693 species of saproxylic beetle recorded on the IUCN European Red List in 2018 (IUCN, 2018), many of which are rare and threatened. Additionally, many species of forest fungi are saproxylic. Together, these organisms play a vital role in nutrient cycling, decomposition and ecosystem stability within the forest (Rajala et al., 2015; Ramachandra et al., 2018). The removal of woody debris which would otherwise decompose and return nutrients to the soil can disrupt these species and their ecological functions.

Additionally, many bird species, such as woodpeckers, depend on stemwood for nesting and foraging. For instance, the three-toed woodpecker (*Picoides tridactylus*) preys on bark beetles, contributing to pest management and overall forest health (Oksuz & Correia, 2023). Woodpeckers also create cavities in dead or decaying trees, which are then used by other species for nesting. Owls, like the tawny owl (*Strix aluco*) and great grey owl (*Strix nebulosa*), rely on large tree cavities for nesting (e.g. Baroni et al., 2020; Yatsiuk & Wesołowski, 2020). Meanwhile, bats, which control insect populations and contribute to pollination, also use tree cavities for roosting. The loss of older trees can have severe consequences for bat populations (Kunz et al., 2011).

Leaving residues on the forest floor post-harvest helps retain soil moisture and reduce soil erosion. Removing residues can exacerbate soil erosion and decrease water retention, negatively impacting plant and animal species (Pimentel et al., 1995). Since twigs and foliage are rich in nitrogen and other elements, harvesting all above-ground biomass could remove a significant proportion of nutrients. Therefore, maintaining at least some of this material is vital for preserving forest soil fertility (Jandl et al., 2007). Residue removal also reduces the availability of habitat and shelter for wildlife seeking refuge after harvesting has taken place. Similar comments apply to salvage logging where dead wood is removed from a landscape following an outbreak of disease or natural disturbance (Basile et al., 2022).

While some level of residue removal can be achieved without significant negative impact, careful practices are required. Studies suggest that leaving a portion of residues on the forest floor can mitigate soil compaction and nutrient depletion while supporting biodiversity (Siol et al., 2023). Titus et al. (2021) reviewed guidelines for residue harvesting in the different regions (US, Canda, Europe and East Asia), collated the approaches recommended for maintaining or improving biodiversity, such as (i) retaining forest biomass with critical habitat value (live or dead, e.g. den or cavity trees, nut- and fruit- producing vegetation, snags, and large downed coarse woody debris), (ii) retaining harvest residues (piled or scattered) used by wildlife; (iii) retaining travel corridors for wildlife, and (iv) avoiding harvesting during key breeding or migratory periods. Most guidelines assessed advised leaving some standing live or dead trees and downed wood when harvesting biomass. Additionally, around half of those guidelines reviewed had minimum retention thresholds for woody debris ranging from 20% for Sweden, 30% for Finland and 50-66% in the UK. Our review of the literature has not found evidence on the extent to which these guidelines are followed in the practice. Inconsistencies

As outlined in the RED II, Member States must have their own national forest regulations for ensuring the legality of forest biomass. However, inconsistencies across Member States in implementing forest guidelines and practices remain a challenge. The Ministerial Conference on the Protection of Forests in Europe - FOREST EUROPE (2020), outlines pan-European indicators for sustainable forest management, but a lack of harmonisation in national forest regulations for ensuring legality and sustainability of forest biomass is problematic. As shown by Titus et al. (2021), only a few countries, such as Sweden and Finland, have specific guidelines on sustainable forest residue retention levels. Thus, establishing consistent standards across Member States could be essential for ensuring that forest residues are harvested sustainably, balancing bioenergy production with the preservation of forest ecosystems and biodiversity.

5.3.7. Process residues

Process residues are by-products from industrial wood processing activities, such as sawdust, wood chips, and bark. These residues are typically generated in sawmills and other wood processing facilities. Utilising these materials for bioenergy typically has minimal direct biodiversity impacts as it does not involve any additional land use change or habitat disruption. Utilising these materials can also reduce waste and promote the efficient use of forest resources, aligning with principles of the circular economy (García-Nieto et al., 2013), and because these residues are produced at industrial facilities, they are relatively easy to collect and reuse.

There are some potential indirect impacts because the collection and transport of process residues can contribute to greenhouse gas emissions, as well as air pollution affecting plant and animal health in the surrounding areas. These indirect issues arise for all the biomass utilisation pathways presented in this section. Additionally, all technology pathways for converting process residues and other biomass feedstocks into biofuel leads will produce residues like ash (the nature and amount of residue depends on the pathway and the feedstock). If not appropriately disposed of, this can cause soil or water acidification, negatively impacting soil health and local plant and animal species and communities (Augusto et al., 2008).

5.3.8. Municipal, industrial and construction waste

Municipal, industrial, and construction waste includes a wide range of materials which are generated from various sectors such as households, manufacturing industries, and construction sites. These materials can be repurposed for bioenergy production, while contributing to waste management. Examples include biodegradable municipal waste (e.g. food and garden waste), industrial by-products (e.g. waste from food processing and paper mills), and construction and demolition waste (e.g. wood debris).

Like process residues, the use of municipal, industrial and construction waste for bioenergy typically has minimal direct biodiversity impacts. These materials are already considered waste and their repurposing for energy does not necessitate land use changes or habitat disruption (Metz et al., 2007).

As with the indirect impacts listed for process residues, the collection, sorting, transportation, processing and combustion of waste materials can produce emissions which contribute to air and water pollution (Brunner & Rechberger, 2015). Additionally, improper handling and disposal can lead to soil contamination, with impacts for soil health and biodiversity. So, it is crucial to manage these waste materials properly and ensure safe utilisation and disposal practices to prevent soil pollution (Beesley et al., 2011).

5.4. Lipid feedstocks

Lipids (oils and fats) are attractive because the technologies for conversion into biofuels are already mature (see Section 3.3). There are two main categories of lipid feedstock which are compliant with Annex IX and hence are eligible to count towards ReFuelEU Aviation and FuelEU Maritime targets: those derived from intermediate oilseed crops which satisfy the relevant sustainability criteria, and residual oils and fats. The next two sections provide more detail.

5.4.1. Intermediate oil crops

Intermediate crops are grown between main crop harvests. Traditionally they have been used as cover crops or catch crops to prevent soil erosion, reduce nutrient runoff, and retain soil moisture, while potentially offering habitats for beneficial animal species; in a well-managed rotation, intermediate crops can improve yields of the main crop (Poeplau & Don, 2015). Before planting the next main crop, the intermediates may be ploughed into the soil or treated with herbicide to give the main crop room to propagate; but in the context of bioenergy, the intermediate crop is harvested and used. Lignocellulosic intermediate crops are generically classed as RED Annex IX feedstocks; for other crop types like short-rotation oil seeds, they must satisfy the Annex IX eligibility conditions (cf. Table 10). For example, *Camelina sativa* is a short-cycle oilseed with a cultivation period of around 90-100 days, it can be produced as a summer intermediate crop, between two primary crops without displacing them.

However, incentivising cover crops under the RED could give rise to issues and concerns for biodiversity. If cover crops are heavily fertilised to maximise yields for bioenergy, this can give rise to nutrient runoff and water pollution, effectively counteracting the environmental benefits that cover crops are supposed to bring (Dabney et al., 2001). When waterbodies are loaded with nutrients from agricultural runoff, this can degrade water quality and drive eutrophication (Chambers et al., 2008). For aquatic ecosystems, the consequence of eutrophication can be devastating, causing oxygen depletion and loss of aquatic life. Additionally, if cover crops (or any other bioenergy crop) significantly replace fallow land, which is normally of high biodiversity value for many declining farmland species, this will have significant implications for biodiversity.

5.4.2. Low grade oils/fats

Low-grade oils and fats refer to waste materials that can be repurposed for bioenergy production. These include UCO collected from industrial food processors, restaurants, and households, as well as animal fats categorised under the Animal By-Products Regulation. These materials are included in Annex IX Part B.

- UCO is collected from various food industry sources and households. It's been estimated that the EU could collect about 1.5 to 2.5 million tonnes of UCO annually (Malins, 2023).

- Animal fats: are residual materials derived from slaughterhouses, meat processing plants and the rendering industry. According to the data for 2021 that was shared at the 2022 EFPRA congress, in 2021 EFPRA members rendered about 3.9 million tonnes of animal fats (Dobbelaere, 2022). Of these, 2.4 Mt were Category 3, and 570 kt were Category 1 & 2 (Malins, 2023).

Other estimates of the availability of these feedstocks exist (e.g. O'Malley & Baldino, 2024), frequently painting a similar picture of feedstock availability. The primary concern with using low-grade oils and fats for bioenergy is displacement. These feedstocks are already used in other industries, such as road biodiesel, pet food, animal feed and cosmetics. Diverting them to biofuel production for aviation and maritime could indirectly drive demand for other raw materials like palm oil or soy oil, which have significant environmental impacts. This gives rise to ILUC.

The use of UCO and category 1&2 animal fat is well-established in road biodiesel production, with approximately 3,000 ktoe and 850 ktoe of biofuels based on these feedstocks consumed in 2022 in the EU (Eurostat, 2023). Shifting these feedstocks to other uses could create a supply gap. Additionally, the petfood and cosmetics industry rely on animal fats, and diverting them to biofuels can lead to increased prices and demand for alternative fats (Malins, 2023).

Increased demand for alternative oils can lead to deforestation and habitat destruction, especially in tropical regions where palm oil and soy are produced. The production of palm oil and soya oil are associated with significant biodiversity loss and greenhouse gas emissions (Malins, 2020), especially where plantations are established on peatlands or replace tropical forests (Koh & Ghazoul, 2008). Consequently, the main concerns with the use of UCO and animal fats are related directly to the risk of ILUC and its impact on biodiversity. Where forests are cleared to establish or expand oil palm and soya plantations, this results in complete habitat destruction, leading to habitat loss for many species. This disrupts the entire ecosystem and leads to a decline in overall biodiversity – we explore this in more detail in Annex B.1.

5.5. Reducing the impacts of conventional cropping

Conventional cropping refers to traditional agricultural practices which often prioritise high yields and economic efficiency, usually characterised by extensive use of chemical fertilisers, pesticides and monoculture practices. This method typically involves planting a single crop variety over large areas, year after year, leading to soil degradation, reduced biodiversity, and negative impacts on water quality due to runoff containing nutrients and pesticides (Tilman et al., 2002). The use of chemical inputs has been linked to reduced invertebrate abundance, and reduced populations of specific bird species[42] such as house martins, swallows, and swifts (Møller et al., 2021).

These impacts undermine ecosystem services, such as pollination, nutrient cycling and water purification, which maintain agricultural production and environmental health. With the increasing pressure to balance demands for food, animal feed, materials, and energy, it is crucial to adopt practices which reduce the most damaging aspects of agriculture,

42 In general, thriving populations of insects and other invertebrates will be critical to support numbers of insectivorous birds and bats, whose diets may moreover be quite specialised to a certain subset of native invertebrates (Tallamy & Shriver, 2021).

improving the sustainability of land use and its capacity to support biodiversity (Geiger et al., 2010).

Reducing the impacts of conventional cropping partly requires the adoption of a more holistic view of agriculture that considers the entire agricultural ecosystem rather than only short-term returns. Implementing these practices can lead to more sustainable and resilient farming systems which better support biodiversity, enhance soil health, and contribute to long-term food and resource security. A broad body of research has examined practices that can reduce the impact of conventional cropping, including:

- Crop rotation: which involves alternating the types of crops grown on a particular piece of land across different growing seasons. Regenerative rotation models have been shown to enhance soil health, reduces the risk of pests and disease cycles, improves crop yields, and support a wider range of species (Beillouin et al., 2021; Panoutsou et al., 2022).
- Intercropping: is the practice of growing two or more crops simultaneously on the same field. This may increase habitat diversity and can reduce pest pressure by disrupting pest cycles (Panoutsou et al., 2022).
- Cover cropping: planting cover crops to protect soil from erosion, improve soil structure, and enhance soil organic matter.
- Integrated pest management (IPM): combines biological, cultural, physical and chemical tools to manage pest populations in an economically and ecologically sound manner. Techniques include introducing natural predators, using pheromone traps, and applying pesticides only when necessary. This reduces need for chemical pesticides, thereby protecting non-target species and reducing environmental contamination (Gurr et al., 2003; Pywell et al., 2015).
- Agroforestry techniques: which integrate trees into farming systems with crops, can improve habitat complexity and provide habitat and resources for various species. This can also bring additional benefits such as improved soil health, as well as well as improved water retention (Torralba et al., 2016).
- Conservation tillage: implementing reduces or no-till practices to maintain soil structure and reduce erosion (Sapkota, 2012).
- Organic farming: transitioning to organic farming methods, reduces the use of synthetic fertilisers and pesticides (Tuomisto et al., 2012). However, as this only tackles some of the pressures from intensive farming biodiversity, benefits are modest, being on average a 30% increase in species richness and 50% increase in species abundance (Bengtsson et al., 2005; Lampkin & Pearce, 2021; Tuck et al., 2014) and can be overridden by landscape factors (Gabriel et al., 2010; Winqvist et al., 2012). Furthermore, as organic yields are often substantially lower (Ponisio et al., 2015; Seufert et al., 2012), net biodiversity benefits in terms of production rather than area may be minimal (Gabriel et al., 2010) or even negative because of ILUC impacts. Consequently, other environmental measures, such as crop diversification, and maintaining small fields and seminatural habitat patches can have greater biodiversity benefits than organic certification (Tscharntke et al., 2021).
- Buffer strips (Mayer et al., 2007) and hedgerows (Marshall & Moonen, 2002),

establishing buffer strips along waterways to reduce nutrient runoff and protect aquatic ecosystems meanwhile hedgerows and field margins planted with flowering plants can support pollinators or pest predators (Pywell et al., 2015).

5.5.1. Mixed systems

Mixed bioenergy cropping systems offer an alternative to the traditional monoculture model, providing greater opportunity to support biodiversity and ecosystem health. These systems can integrate a variety of crops and land-use practices, providing numerous ecological benefits. Mixed systems can include agroforestry, polycultures, and other diversified cropping strategies that maintain soil health, enhance biodiversity, and provide multiple ecosystem services.

Agroforestry systems mix trees and shrubs with crops or livestock on the same land. This integration creates a more complex habitat structure, offering refuge and resources for invertebrates, birds, insects and other wildlife. This can enhance biodiversity by providing a more diverse habitat capable of supporting a greater diversity of species, as well as improving soil structure and soil fertility. Agroforestry systems have been shown to increase species richness and abundance compared to monoculture (Torralba et al., 2016).

Silvoarable systems, are another type of agroforestry. This involves the integration of trees with arable crops and has been shown to enhance biodiversity (Torralba et al., 2016), as well as improve water management and enhance soil carbon sequestration. Trees in silvoarable systems offer shade and wind protection for crops, reducing soil erosion and providing habitat and resources for a range of species. Research has shown that silvoarable systems support a greater variety of species compared to arable controls with similar farming practices, including natural predators and biocontrol and most soil organisms and their related services (Kletty et al., 2023).

Polyculture practices involve the cultivation of multiple crop species together, which can provide multiple benefits including support for pollinators, integrated pest management approaches and soil health. Establishing crops within polyculture systems can also reduce the need for chemical inputs like pesticides and fertilisers (Cong et al., 2015), reducing pollution risk for biodiversity and ecosystems. For instance, planting legumes alongside bioenergy crops has been shown to enhance nitrogen fixation in the soil, reducing the need for synthetic fertilisers to support crop productivity. Enhancing the diversity of crops can also enhance the diversity and function of soil organisms (Brooker et al., 2021). Compared to monocultures of annual bioenergy crops, intercropping perennial grasses with legumes can support a higher diversity of flora and fauna (Tilman et al., 2002).

We do not explicitly consider the land use and environmental impact mitigation potential of these systems for the scenario modelling in Chapter 7. Instead, we treat them discursively as an example of best practice methods wherever they are applicable.

6. Biodiversity impacts of other fuels

6.1. Power for RFNBOs

As noted in Section 3.5, we assume that additional renewable power required for RFNBO production will be delivered by the deployment of additional renewable energy generation capacity in the form of wind farms and solar farms.

6.1.1. Hydrogen for transport and renewable electricity

Electricity consumption in the aviation and maritime sectors takes two main forms: direct airport or shore supply for running appliances and charging batteries, and, likely more significantly, production of RFNBOs based on hydrogen from electrolysis ('green hydrogen'). Figure 15 shows that the transport sector is expected to become a significant consumer of hydrogen (Gulli et al., 2024), and it is expected that a significant portion of this will come from renewables-powered electrolysis (Hydrogen Europe, 2019).

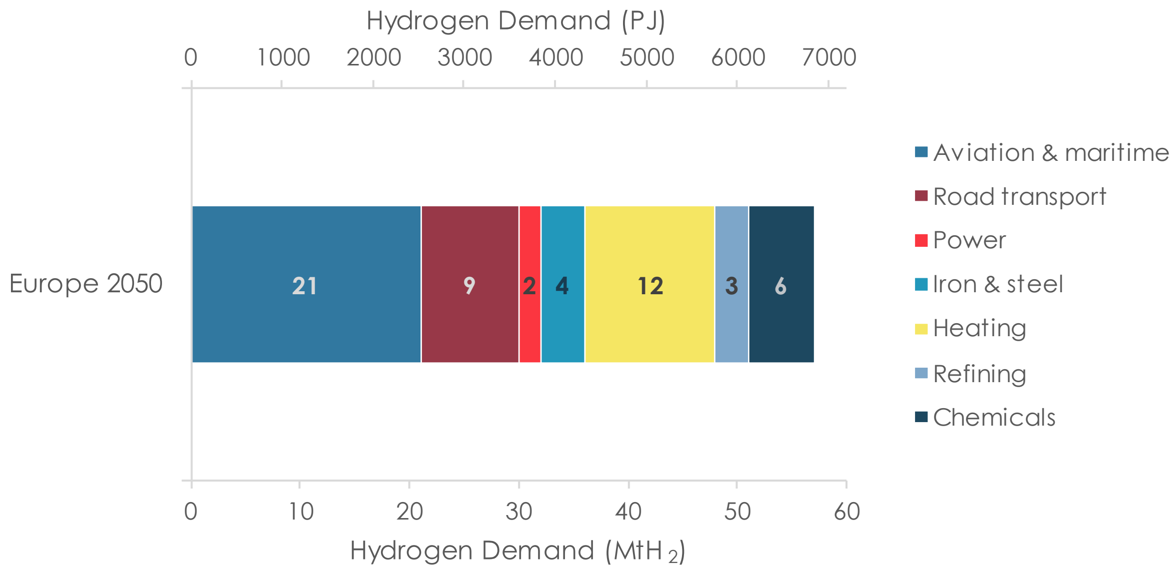


Figure 15. Annual hydrogen demand in Europe in 2050

Note: Europe means the sum of EU-27, UK, and Norway. Recall that 1 MtH_2 corresponds to 120 PJ of energy (LHV). Source: Gulli et al. (2024)

The growth of renewable electricity generation in the EU is shown in Figure 16. Reliance on fossil fuels for electricity generation declined to 33% in 2023, while combined wind and solar generation grew fivefold between 2009 and 2023 to reach 27% of the total in 2023.

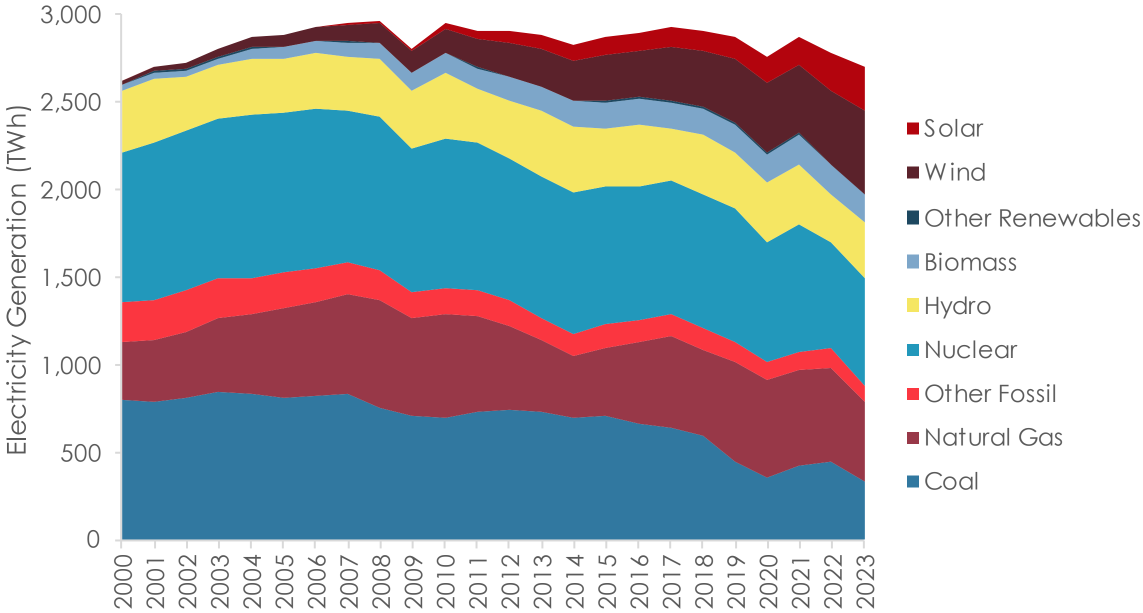


Figure 16. EU electricity generation mix

Source: Brown & Jones (2024)

The power sector leads the EU's renewable energy goals (Ciucci, 2024). RED III establishes a requirement for Member States to carry out, by 2025, coordinated mapping for the potential deployment of renewable energy in their territory (both land and sea) (European Union, 2023b, Article 15b). This mapping is to consider local generation potential and local demand, as well as grid connectivity. Preference is to be given to projects which minimise impacts on existing land uses, or to favour projects which make efficient use of land by stacking multiple uses.

This leads us to the question of what form this renewable electricity capacity is likely to take. For the purposes of this report, we shall focus on solar PV and on/off-shore wind generation as the most relevant sources in the near to medium term. Droughts and high temperatures have reduced hydropower generation over the past decade, decreasing from 372 TWh in 2010 to 317 TWh in 2023 (Brown & Jones, 2024); and a downward trend is expected to continue into the future (PAC, 2020) – especially given the environmental impacts associated with hydropower coming under greater scrutiny (European Commission, 2018b). This, along with the problematic sustainability impacts of biomass-for-power and the relatively minor contribution made by other renewable sources like geothermal (cf. Figure 16), contextualises a focus on solar and wind as the sources that will have to meet rising electricity demand from the aviation and maritime sectors.

Figure 17 below shows the mix of generation sources used in EU Member States, indicating which countries already have developed solar and wind sectors.

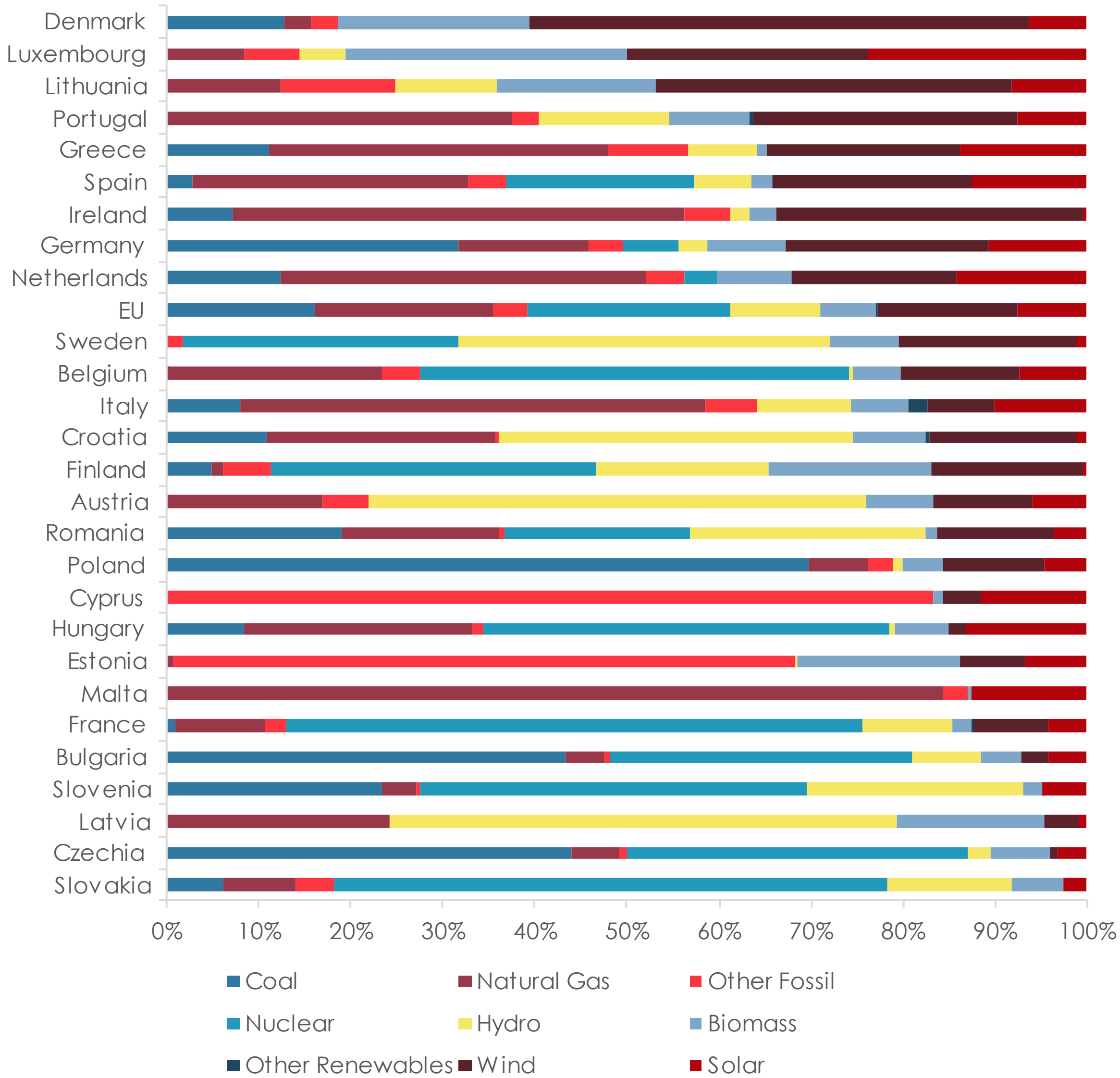


Figure 17. Electricity generation by source for EU-27 countries and the EU overall in 2023, ordered by the share of wind and solar

Source: Brown & Jones (2024)

The remainder of this section reviews existing knowledge of biodiversity impacts for wind farms and solar farms, including habitat alteration, degradation and/or loss; habitat fragmentation and barriers to species movement; species behavioural changes and implications for ecosystem services. The nature and extent of these impacts depend on the type of infrastructure being constructed and deployed. It also depends on the design and the location of the plant.

6.1.2. Electricity transmission

Increasing reliance on electricity as a primary energy source entails expansion of electricity transmission infrastructure, including pylons, cables, and substations. Such infrastructure is not by and large considered a major biodiversity threat; however, specific impacts identified in the academic and policy literature should be acknowledged. These impacts can be both direct and indirect, affecting a range of species and ecosystems, and are dependent on design and location with respect to migration routes and feeding, breeding, and resting sites (European Commission, 2018a).

There is a direct land requirement for constructing transmission lines, substations and other infrastructure. This tends to require land clearance, leading to habitat loss for various species. To add, electricity transmission corridors can fragment habits, inhibiting wildlife from moving freely (Martín et al., 2022). Construction and maintenance activities can cause disturbance, generating noise and light pollution. The increased human activity during construction and maintenance can cause stress and the displacement of wildlife, as can persistent/intermittent bright lights.

Besides these direct impacts, construction activities can alter local water drainage patterns, by increasing runoff and affecting water quality and silting. These changes can impact aquatic ecosystems and the species that depend on them (UN, 2006). There is also a question of fire risk if growing vegetation is allowed to come into contact with power lines in dry conditions, either because land clearance is poorly maintained or because of a break-down of transmission structures in high winds.

Distribution lines and pylons are attractive perches and nesting sites for certain bird species but can pose an electrocution risk for those whose wing-spans are large enough to simultaneously contact live and neutral/ground lines. Species that are long-lived, have low reproductive rates and/or that are rare or are already in a vulnerable conservation state, such as eagles, vultures and storks, are of particular concern (European Commission, 2018a, Annex 5). Collisions with lines and pylons are also a problem, especially for birds with poor frontal vision and/or flight manoeuvrability when visibility is low (at night or in fog). A species-dependent risk characterisation can be found in Table 1 of European Commission (2018a); a thorough ecological survey pre-construction can identify risk hot-spots (e.g. nesting areas and migration routes) to avoid. Impacts on bat populations appear to have been less well studied than those on birds.

The impact of transmission infrastructure has been characterised as detrimental to birds, but low priority compared to the environmental benefits of electrification (Turney & Fthenakis, 2011). Nevertheless, it is worth considering examples of good practice which can be found in countries such as Germany, Luxembourg, Netherlands, and Sweden. Here, most low- and medium-voltage lines are buried underground (Tarimo, 2011), and there has been a push to use larger spacings between conductors[43], and fit 'bird diverters' and other deterrents (Raptor Protection of Slovakia, 2021). These can provide promising safeguards for target populations. One ongoing project covering France, Belgium, and Portugal seeks to achieve an 80-100% reduction in bird mortality (SafeLines4Birds, 2023); while past smaller-scale studies have reported different deterrence strategies reaching 40-94% reductions (Ferrer et al., 2020; Gális et al., 2020).

43 Cf. the discussion of 'killer poles' in Raptor Protection of Slovakia (2021).

To avoid costly retro-fits, there are opportunities for more careful planning protocols at the route design stage to avoid ecologically sensitive areas and migration corridors. A number of species habitat and migration databases that can aid planning decisions are discussed by Martín et al. (2022), which also showcases efforts to conduct geographical sensitivity mapping to identify areas at particular risk of disruption (e.g. Derouaux et al. (2020) shows collision risk hotspots in Belgium).

6.1.3. Solar PV

Utility-scale solar projects can have major impacts on species and habitats, primarily if construction requires removal of vegetation and surface grading (Gasparatos et al., 2017). If the land is then covered with an artificial surface, or if herbicides are routinely used to control vegetation growth, then these impacts may be permanent; there may furthermore be implications for runoff and nutrient balances in soils and waterways (Bennun et al., 2021, Table 4-1).

Instances can be found in the literature where solar plants situated on both brownfield and agricultural land report a greater diversity of plants, invertebrates, and birds than prevailing land uses such as intensive crop cultivation (Montag et al., 2016). Freeing up such land for nature restoration is generally preferable from a local biodiversity perspective, but in situations where this is not feasible establishing a solar installation may bring some benefits when the initial biodiversity value of the land is low and nature-conscious management of the site is adopted (such as allowing vegetation to grow on the site and selectively hand-trimming weeds when necessary rather than routinely spraying herbicide, Montag et al., 2016). Depending on the needs and behaviours of the local wildlife mix, habitat-level disruptions from solar farms can be moderated by maintaining buffer zones and corridors between rows of arrays (Bennun et al., 2021).

Productivity displacement effects can be avoided in models which co-locate electricity production with other land uses. A prime example of this is 'agri-photovoltaics', where a PV farm is built in such a way that agricultural activity continues on the same land. There is evidence to suggest that some crops (potatoes, tomatoes, peppers, lettuce, broccoli, corn) may benefit from the shading and moisture retention (Thompson et al., 2020; Weselek et al., 2021). Ongoing research seeks to identify crop rotations and agricultural machinery that could be a suitable match for agri-PV cropping models. A JRC report found that the EU's Solar Strategy target for 2030 (around 730 GW) could be completely fulfilled with 0.5-2.3% coverage of the EU's utilised agricultural area (Chatzipanagi et al., 2023). It is worth bearing in mind that, from an energy production standpoint, dedicating this land to solar electricity generation is likely to be many times more efficient than using it to grow crops, which lends some perspective to the relative impacts of electrification versus bioenergy.

Solar installations have been found to affect some species more directly than others. PV modules reflect highly polarised light, meaning that aquatic insects may mistake them for a water surface and lay eggs ('oviposit') which then have no chance of hatching. At-risk species include mayflies, stoneflies, dolichopodid dipterans (long-legged flies), and tabanid flies (Horváth et al., 2010). To mitigate against this, textured module surfaces or white frames can be used as they are less attractive to these 'polarotactic' aquatic insects (Fritz et al., 2020; Horváth et al., 2010).

While the majority of PV capacity is land-based, the potential of floating facilities installed on canals, reservoirs, and lakes is being explored. The largest EU project under development has a planned capacity of 744 MW (Q ENERGY, 2023), but in all this is not expected to be a major component of EU generation. Floating installations reduce land pressure while benefiting from improving efficiency due to cooling (Ghosh, 2023). They can also reduce algal blooms, thereby improving safety and the health of fisheries. However, shading will inevitably impact other aquatic organisms (Benjamins et al., 2024).

6.1.4. Onshore wind

The scientific and operational understanding of the biodiversity trade-offs associated with onshore wind energy continues to develop. The same concerns from the previous section about competition for land still apply (Bennun et al., 2021), though wind turbines in a given project site are considerably sparser than say solar PV (Ash et al., 2020, Table 4-7; Lovering et al., 2022); this means that the total land footprint is greater, but the space in-between wind turbines may provide relatively protected habitat where no other development is possible.

The Habitats Directive makes no blanket exclusion of wind farms on or near Natura 2000 areas, though it does set out protocols for environmental baselining, screening, and assessment of potential sites (European Commission, 2020f), including risks of habitat loss, degradation, fragmentation, barriers to movement and migration, disturbance to identified local species, and indirect effects like changing hydrology that can have broader knock-on consequences. As with solar PV and electricity transmission, affected areas for wind farm construction, access, and support infrastructure may exclude many nature-rich and ecologically sensitive areas from being considered potential project sites. One study which focussed on Greece recommended a wind farm free zone covering 58.6% of the country and reported that these restrictions would have minimal impact on the potential to achieve renewable energy targets (Kati et al., 2021).

In terms of direct species impacts, bird collisions with moving wind turbine blades have long been a contentious subject. Mitigation measures include establishing passage space between clusters of turbines, and orienting them parallel to any migration routes, and of course, avoiding particularly sensitive area (Bennun et al., 2021). Putting the numbers in perspective, however, Sovacool (2013) concluded that wind farms were responsible for ten times fewer bird fatalities per GWh than fossil-fuelled power stations. Furthermore, even if onshore wind were to scale up to provide 100% of electricity demand, its impact on bird mortality would still be orders of magnitude lower than that of pesticides, windows, or cats (cf. Gibon et al., 2022).

Nevertheless, concerns of adverse effects for vulnerable bird and bat populations[44] have prompted the development of a range of mitigation strategies – most critically, guidelines to avoid siting wind projects in particular sensitive habitats or migration routes. Adapting the spacing of wind turbines is shown to reduce risk of collision (van der Winden et al., 2015). Including aural and visual signals can prompt evasive action: for example, May et al. (2020) reported that painting one of the blades reduced fatalities by 70%. Some energy companies slow or stop rotation during critical migratory periods, while a more high-tech solution is to selectively stop wind turbines following a trigger by specialised bird detection systems based

44 Large numbers of insects are also killed through collisions, and the build-up of debris can impede efficient wind turbine operation. It is unclear whether there is any significant impact on insect populations (Voigt, 2021).

on automated image and/or radar processing (van der Winden et al., 2015). To take one example, a 15-year study of such a stopping protocol in Spain reported a 61.7% fatality reduction for soaring birds and a 92.8% reduction for griffon vultures which are particularly at risk (Ferrer et al., 2022). It was estimated that the wind farms generated about 0.5% less energy due to the stops.

6.1.5. Offshore wind

Offshore wind is the most common type of offshore renewable energy, and lesser space constraints mean that a single project can reach far greater scales than onshore project. An average facility is constructed 52 km from shore at a water depth of 44 m (Ramírez et al., 2020). The site assessment stage of developing an offshore wind farm typically requires up to five years of seismic and/or sonar surveys to create a geophysical map of the layers of earth beneath the seabed. These can negatively affect marine life which uses sound to navigate, feed, and mate (Zero Carbon Analytics, 2022): one study in the North Sea showed a decrease in porpoise echolocation signals (suggestive of displacement) during seismic surveys (Sarnocińska et al., 2020).

Noise pollution during the construction stage of offshore wind farm development is generally a greater concern than during site assessment and is similar to other construction such as offshore oil and gas extraction (Galparsoro et al., 2022). Sound (and hence behaviour) disturbances from these kinds of activities can travel for tens of kilometres, and within a few hundred metres can produce temporary or permanent damage to marine mammals and fish. The duration and intensity depend on the type of foundation – see Table 13. Most installations in Europe use monopile foundations, followed by jackets (Ramírez et al., 2020) – these are associated with the highest disturbance levels. Floating foundations represent a very small share at present with 270 MW capacity installed globally, but there is suggestion that their use will grow rapidly in future, as planned projects amount to 244 GW (Dhavle et al., 2024).

Table 13. Offshore wind farm foundation types and their acoustic effects

Monopile, jacket, tripod foundations	Suction bucket	Gravity	Floating
Pile driving – including circular drilling and vibratory driving – causes significant noise and vibration	Lesser pressure wave disturbances during installation compared with pile driving	Installed using dredging, which also produces comparatively low noise levels	Smaller piles result in smaller acoustic effects from installation Anchors (including deadweight anchors, dynamically embedded anchors, or suction caissons) also have low noise impact

Source: Horwath et al. (2020)

During the operational phase, underwater noise from the turbines' head ('nacelle') is transmitted through the tower to the foundation, from which it is radiated into the water and through the sea bed. While marine mammals were found to have varying levels of sensitivity to this disturbance, it is considered unlikely to cause serious problems (Tougaard et al., 2009). Similar comments apply to the electromagnetic fields generated from submarine cables carrying electricity to shore[45] – magneto-sensitive species such as bony fish, elasmobranchs, marine mammals, and sea turtles could find their navigation disrupted, but this isn't expected to a major issue.

Figure 18 reproduces an indicative summary of offshore wind farms' biodiversity impacts on different animal types (Zero Carbon Analytics, 2022). Pre-construction activities are rated to have the greatest negative effect on aquatic creatures; once established, the wind farms are rated as having a positive effect on aquatic creatures, and a moderately negative effect on birds.

Development stages	Activity	Fish	Birds	Seals	Dolphins	Whales
Pre-construction & construction	Seismic activities	-2	0	-2	-2	-2
	Sonar surveys	0	0	0	-1	-1
	Foundations (piling)	-1	0	-1	-2	-2
Operation	Structured underwater habitat	2	0	1	0	0
	Sanctuary effects	2	1	1	1	1
	Wind turbine blades	0	-1	0	0	0
Maintenance	Vessel traffic	-1	-1	-1	-1	-1

Figure 18. Impact of bottom-fixed offshore wind farms on different animal types, on a scale of -2 (worst) to +2 (best)

Source: Zero Carbon Analytics (2022)

6.1.6. Comparing land use and biodiversity impact

Table 14 provides a summary of some of the major biodiversity impacts identified in previous sections, putting the three generation sources side by side.

45 High-voltage cables may be designed to carry alternating current or direct current, depending on the distance to shore and the relative costs of power rectification and inversion, as well as reactive power compensation (Soares-Ramos et al., 2020). Assuming steady power supply, only alternating currents will produce magnetic fields.

Table 14. Summary and comparison of biodiversity risks from three major renewable electricity sources

Risk	Impact	Solar PV	Onshore wind	Offshore wind
Land	Land use	Relatively large footprint, land clearance and ongoing vegetation control	Relatively small footprint from turbine bases, but larger permanent habitat loss from access roads	Relatively small footprint, with seabed disturbance from fixed-foundation turbines
	Habitat fragmentation	Barrier effects from large areas of PV panels and associated facilities	Barrier effects to animal movement from closely spaced turbines and access roads	Lesser impact of physical barriers
Species	Direct threats	Polarised light from surfaces causes maladaptive behaviour changes in some birds and insects	Collision risks for birds and bats. Risks where increased human access to remote areas.	Collision risks for birds and bats Injury and behavioural effects associated with underwater noise
	Displacement	Depending on prior land use, some important semi-natural habitats could be lost	Animals avoid disruption during the construction phase	Animals avoid disruption during the survey and construction phase
	Invasive species	No specific threat	No specific threat	No specific threat
Resources	Water use and quality	Pollution of waterways from dust suppressants and herbicides Changes to runoff patterns	Changes to runoff patterns, especially from access roads	Not applicable
	Other pollution	Dust, waste, noise, and light pollution from construction and decommissioning	Dust, waste, noise, and light pollution from construction and decommissioning	Dust, waste, noise, and light pollution from construction and decommissioning

Having highlighted some of the potential negative biodiversity impacts arising from renewable electricity generation, it is important to take a step back and consider how they compare with those of biogenic fuels (biofuel, biogas, and biomass fuel for thermal generation). A simple proxy is the land footprint of the different energy sources.

Indicative values for electricity production per unit of land (in kWh/m^2/year) are presented in Table 45 of Annex C.4.4[46]. This shows that wind has a small land footprint per unit of energy produced compared to solar (including access roads and other on-site facilities). Both are sure to improve over time with technological advancements, and even solar is an order of

46 These are the average values we use in the modelling; naturally, actual energy production will depend on location and weather conditions.

magnitude more efficient than biomass burned in thermal generation plants. This strongly suggests that the land impact of renewable electricity production will be much lower than that of biogenic fuels, and this is indeed borne out in the modelling results reported in Section 7 and Annex A.

6.1.7. Impact assessments

This sub-section introduces some of the regulations covering the development of renewable electricity sources in the EU. Prospective developers of any significant new infrastructure are required to perform an environmental assessment, of which there are two major categories: the Strategic Environmental Assessment (SEA, established by the SEA Directive, European Union, 2001) and the Environmental Impact Assessment (EIA, established by the EIA Directive, European Union, 2014a). Both aim for a high degree of environmental protection for infrastructure developments such as nuclear power stations, motorways, waste disposal, etc. SEAs have a relatively wide scope, providing a broad environmental framework for a Member State's policies, plans, and programs; EIAs are undertaken at the project level within that strategic context, and establish channels for focussed public consultation. Table 15 compares some of the main characteristics of the two assessments.

Table 15. Characteristics of the EU's two major environmental assessments with relevance to renewable electricity generation and infrastructure projects

Aspect	Strategic Environmental Assessment	Environmental Impact Assessment
Level of Application	Policies, plans, and programs	Specific projects
Legal Basis	SEA Directive (European Union, 2001)	Amended EIA Directive (European Union, 2014a)
Purpose	Integrate environmental considerations into strategic decision-making	Assess significant environmental effects of specific projects
Timing	Early in the planning process	At the project proposal stage
Scope	Broad, cumulative, and synergistic impacts	Detailed, specific impacts
Alternatives	Examines reasonable alternatives, including the "do-nothing" scenario	Considers alternatives primarily in the context of project design
Public Participation	Broad consultation with stakeholders and public	Focussed consultation on project-specific impacts
Mitigation Measures	General recommendations for sustainability	Specific mitigation measures for identified impacts

The EU aims to scale up renewable electricity generation to meet its ambitious targets (see Section 6.1.1) and has authorised some relaxation of permitting requirements for 'Renewables Acceleration Areas' (RAAs) (European Union, 2023b, Article 15c). Member States may establish RAAs in areas which are covered by an SEA and are not categorised as environmentally sensitive (and all Natura 2000 sites are off-limits), with a preference for brownfield sites (that is, artificial and built surfaces like rooftops, industrial sites, waste sites, and transport infrastructure). Applications to develop renewable electricity projects within an RAA are to be fast-tracked for processing and, crucially, are exempted from undertaking EIAs – instead there is a simplified screening process.

Reactions to the European Commission's guidance to Member States on the siting of RAAs (European Commission, 2024b) from NGOs and civil organisations have been cautiously positive, as the stipulations on assessing, mitigating, and at worst compensating any environmental harms appear to be carefully thought through (The Nature Conservancy, 2024). However, concerns remain that Member States may apply ecological sensitivity mapping inconsistently and with poor-quality data (Wingenbach et al., 2024). The loss of the EIA's public consultation requirements which are regarded as critical for fostering acceptance among local residents, conservation experts, and other stakeholders (European Environmental Bureau, 2024; Renewables Grid Initiative, 2024; The Nature Conservancy, 2024; Wingenbach et al., 2024). (2023) also details how, in spite of safeguards, EIA exemption may yet conflict with key conservation legislation like the Habitats Directive, the Birds Directive, and the Water Framework Directive.

The SEA and other assessments required for establishing an RAA will not achieve the level of granularity about specific project impacts that an EIA would. Moreover, it is worth remembering that, even if the incremental disruption from individual projects in a carefully-sited RAA meets acceptable criteria, some of the overall ecological effects will be cumulative. The Commission guidance recognises that cumulative effects may need consideration but leaves this to the discretion of the relevant authority in Member States (European Commission, 2024c).

The SEA and other assessments required for establishing an RAA will not achieve the level of granularity about specific project impacts that an EIA would. Moreover, it is worth remembering that, even if the incremental disruption from individual projects in a carefully-sited RAA meets acceptable criteria, some of the overall ecological effects will be cumulative. The Commission guidance recognises that cumulative effects may need consideration but leaves this to the discretion of the relevant authority in Member States (European Commission, 2024c).

6.1.8. Carbon dioxide capture and utilisation

As well as renewable electricity for producing hydrogen, PtL fuels use carbon dioxide to provide the carbon atoms for synthesising hydrocarbon molecules. There are a few options for sourcing this CO_2. Industrial point sources may produce CO_2 of fossil origin (for example cement plants, gas power plants, steel plants) or of biogenic origin (for example bioenergy power plants, ethanol plants, and Fischer-Tropsch biofuel plants). Capturing CO_2 from point sources is cheaper and more energy efficient than capturing from the atmosphere because it is already at a higher concentration. We would therefore expect that in the near term, most CO_2 for CCU will be captured from point sources. In the longer term, capturing and utilising fossil CO_2 is seen as problematic because the fossil CO_2 still ends up in the atmosphere contributing to climate change – just with the carbon having been used twice instead of only once. This explains the requirement under the RED III that, from 2036 onwards, PtL fuels must only use CO_2 of biogenic origin or from DAC. To first order, this carbon dioxide can be treated as coming with zero land use impact, since the footprint of DAC plants is low, and since the biogenic carbon dioxide is a waste that would have been emitted anyway (and as such is a 'free resource' at the point of collection).

However, CO_2 of biogenic origin may be produced by facilities that are themselves associated with significant biodiversity impacts – for example bioenergy power plants sourcing wood in a way that negatively affects biodiversity. Carbon capture units added to such facilities require energy to run, and in some cases this energy will be supplied by increasing biomass consumption at the plant[47], but this represents a negligible additional biomass demand due to sourcing CO_2 for RFNBOs when compared to the biomass demand for biofuel production. In this report, we therefore treat the risk of biodiversity impact due to CO_2 capture for PtL fuels as insignificant compared to the risk of biodiversity impacts from biofuel production and exclude it from our calculations.

6.2. LNG

Importing liquified natural gas (LNG), predominantly methane, converted into liquid form for ease of storage or transport, has become a strategic priority for the EU to diversify its energy suppliers and routes for obtaining natural gas. This has gained urgency since Russia's invasion of Ukraine, prompting the EU to reduce its reliance on Russian gas imports.

The EU's gas demand is around 330 billion cubic meters (bcm) per year, accounting for roughly a quarter of the EU's overall energy consumption. A significant portion of this demand is met with imports, totalling 120 bcm in 2023. The EU stands as the world's largest importer of liquified natural gas, with France, Spain, Netherlands and Belgium and Italy leading among EU Member States.

In 2021, LNG constituted 20% of the EU's total gas imports. This share grew to 42% by 2023, partly due to expanded LNG storage and import infrastructure. Import capacity grew by 40 bcm in 2023, with an additional 30 bcm expected to become available in 2024. Meanwhile, the United States remains the largest LNG supplier to the EU representing 46% of LNG imports in 2023, followed by Norway (49% compared to 30% in 2021), North-Africa (19%) and Azerbaijan (7%) (European Council, 2024).

47 For example, for CHP plants with heat recovery following the CCS process, (K. Gustafsson et al., 2021) finds that feedstock consumption would need to increase by 2% to 4% to maintain energy output, and that the ratio of heat to electricity produced by the CHP plant would increase.

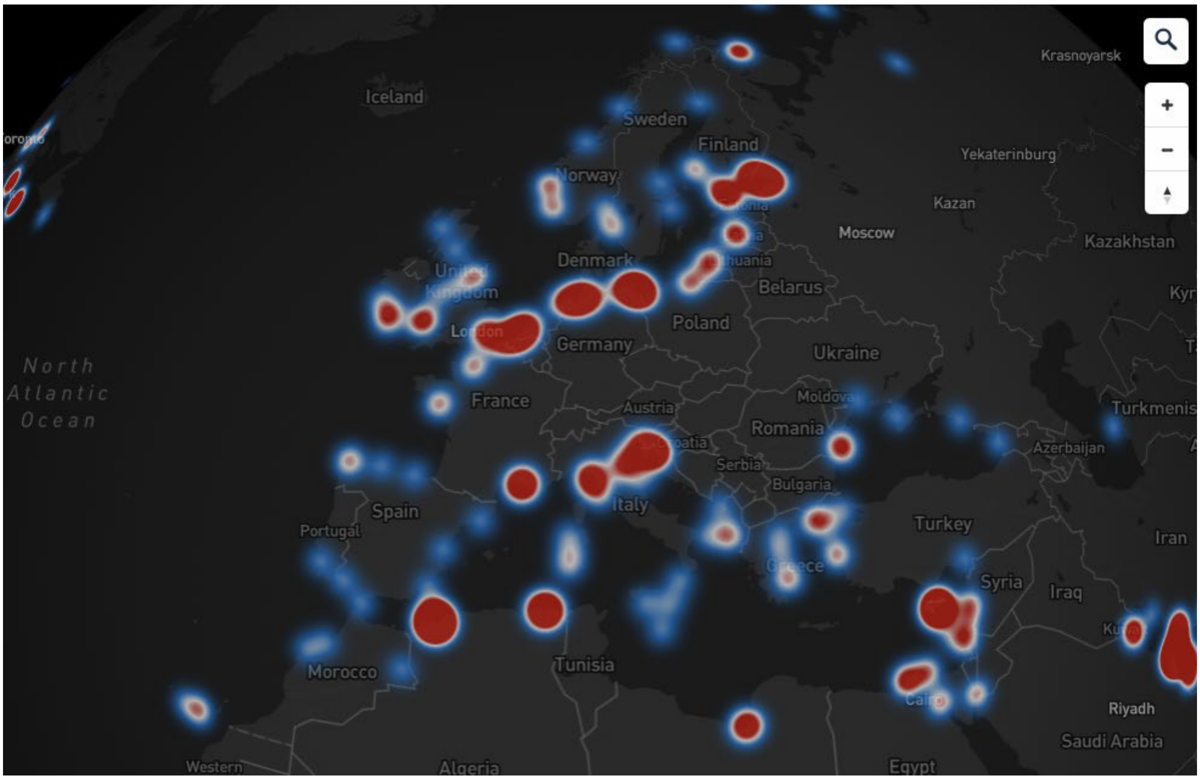


Figure 19. Heat map of proposed LNG expansion over EU

Source: Earth Insight (2024)

The EU Commission's 2019 annual report on CO_2 emissions from maritime transport note that LNG accounted for only 3% of the total maritime fuel consumption in 2018 (European Commission, 2020c). Additionally, according to the fourth GHG study of the International Maritime Organization (IMO), in 2018, 98.4% of the fleet in in 2018 had conventional fuel oil engines (Faber et al., 2021). However, LNG is likely to play a crucial role under the Fuel EU Maritime initiative. The policy recognises that the lack of greener maritime fuels makes LNG a necessary transition fuel for decarbonising maritime. LNG is considered low carbon because it contains less carbon per unit of energy than conventional marine fuels, and burning it emits less CO_2. However, LNG consists mostly of methane, which traps more heat in the atmosphere, the climate benefits are uncertain (Comer et al., 2022). Work by the ICCT on lifecycle analysis of LNG has shown that unburned fuel in the form of 'methane slip' emitted from dual fuel internal combustion engines on ships, combined with the methane leakage that happens throughout the LNG supply chain, can result in higher well-to-wake (WTW) CO_2 emissions from ships using LNG compared with conventional marine fuels.

LNG is expected to play a transitional role in the decarbonisation of maritime transport, particularly as it is seen as a cleaner alternative to traditional heavy fuel oil. By 2050, LNG could contribute significantly to reducing greenhouse gas emissions from maritime transport, although the exact volumes and share in the fuel mix are still subject to ongoing analysis and projection. This uncertainty arises from the evolving landscape of alternative fuels and the pace of technological advancement and regulatory changes. For the most part, this report has excluded analysis of the biodiversity impacts of energy generation outside of the EU. However, given the significance of natural gas in the EU's overall energy consumption and its anticipate role in maritime decarbonisation under Fuel EU Maritime, it is pertinent to consider the implications of LNG production and utilisation.

The extraction, processing and transport of LNG can have substantial biodiversity impacts, both in areas of natural gas extraction and in regions where LNG infrastructure is developed. Although the risks are most severe in regions where the natural gas is sourced, this often takes place outside of Europe. Natural gas extraction, particularly through methods like hydraulic fracturing (i.e. fracking) can have significant impacts. For example, extracting natural gas requires substantial land, which leads to habitat loss and fragmentation, disrupting ecosystems and driving a decline in local biodiversity. For instance, the drilling of wells and construction of well pads, and creating infrastructure such as pipelines and access roads. This drives habitat loss, fragmentation and disturbance to wildlife and the ecosystem.

While the well pads typically take up between 1-3 ha each transporting the gas requires extensive pipeline networks, which linearly dissect through a landscape, fragmenting habitats and affecting land use over large areas (Jones et al., 2015). Aside from the impacts on biodiversity and ecosystems in proximity to extraction sites, the infrastructure required for LNG, including liquefaction plants, storage facilities and shipping terminals, can also have considerable environmental impacts. For example, converting natural gas to LNG for storage and transport involves large-scale facilities for liquefaction and the source and regasification at the destination. These facilities are substantial in size and can have significant localised impacts, for example LNG terminals are often located in coastal areas, which can disrupt marine species, habitats and ecosystems (Jones & Pejchar, 2013). Additionally, the construction and operation of these facilities can affect marine biodiversity through habitat destruction, noise pollution, and water pollution from leaks and spills (Earth Insight, 2024).

Recognising that the planned global expansion of LNG infrastructure is likely to put coastal and marine ecosystems under pressure, US-based NGO Earth Insight, analysed the potential impact of announced development plans across Latin America, Southeast Asia, and East Africa, finding that the bulk of proposed LNG facilities in these regions are set to impact environmentally sensitive areas[55]. In these biodiversity hotspots, the negative impacts of expanding infrastructure will be significant.

Natural gas extraction requires large volumes of water (Entrekin et al., 2011), and the fluids used to fissure rock formations contain numerous chemicals which can contaminate local water bodies and be detrimental to local water quality (Jones et al., 2015) This can be toxic, not only to aquatic ecosystems and species reliant on these water sources and threaten groundwater and drinking water supplies (Gordalla et al., 2013).

Methane leaks during extraction also contribute to air pollution and climate change through increased greenhouse gas emissions. Methane is approximately 28 times more climate-polluting than carbon dioxide over a hundred-year timescale, and 84 times more potent over a 20-year period (European Commission, 2024d), further exacerbating the risks to biodiversity through climate change altered habitats and ecosystems.

Quantifying the exact land impact per unit of energy derived from LNG is complex and would vary by region and extraction method. Studies suggest that the footprint of natural gas infrastructure can be extensive, with significant cumulative impacts on land and ecosystems over time. It is important to emphasise that on a per unit of energy basis, the areas of land required for LNG is far smaller than those required for renewable energy or biomass. However, while LNG offers a lower-carbon alternative in the short term, its broader environmental, biodiversity and climate implications warrant careful consideration.

6.3. Ammonia

Ammonia may be suitable for use in future maritime combustion- or fuel-cell-powered engines. It can be produced from reformed fossil natural gas or from renewable hydrogen, e.g. green electrolytic hydrogen; the feedstock source naturally has implications for the climate performance of the final fuel, though as pointed out in Section 3.5.2 above, emissions of nitrous oxide throughout the supply chain also make a contribution. Concerns have also been raised about potential risks to the nitrogen cycle, air and water quality, and ecological damage from potential spills – risks which are again independent of the hydrogen source.

Using ammonia as a fuel could worsen air quality through the emission of nitrogen oxides (NO_x) and fugitive ammonia, both of which contribute to the formation of ground-level ozone and particulate matter. Wong et al. (2024) suggests that without stringent emission controls, widespread use of ammonia could lead to hundreds of thousands of premature deaths per year due to deteriorating air quality. This could also have significant consequences for plant health and local biodiversity by contributing to acid rain.

Further, the use of ammonia raises concerns about the potential ecological impacts of spills. Dawson et al. (2022) examines these risks, highlighting that ammonia spills (especially during fuel bunkering or ship collisions) could negatively impact certain habitats and species more than others. Ammonia is 'very toxic to aquatic life' (National Center for Biotechnology Information, 2024), especially in ecosystems with less saline water and higher temperatures. Although ammonia is less likely to disperse as widely and persist as long in the environment compared to conventional oil spills, there are still likely to major implications for aquatic food chains, particularly in areas where these habitats intersect with major shipping routes.

Ammonia leakage could also drive eutrophication and acidification of aquatic ecosystems. Research by Kanchiralla et al. (2023) highlights the relative risk of environmental impacts of different decarbonisation options in the maritime sector, their assessment suggests that use of ammonia could have a relatively high impact on acidification and eutrophication in terrestrial and marine systems. This is concerning as eutrophication (which is begins with increased nutrient loading) is a leading cause of impairment in many freshwater and coastal marine ecosystems. Nutrient loading in water bodies can drive excess plant growth and harmful algal blooms, which reduces oxygen levels in the water, to the detriment of fish and other aquatic life, and has been associated with 'dead zones' in areas with high levels of runoff and low water circulation. Furthermore, acidification can alter the pH balance of aquatic ecosystems, affecting sensitive species such as shellfish and reefs.

Chen et al. (2024) notes that significant demand for ammonia as a shipping fuel could significantly alter the global nitrogen cycle. While current literature is based on limited known cases of ammonia excess, there is insufficient understanding to fully quantity the potential environmental impacts of increased ammonia release at a global scale. Chen et al. (2024) calls on the marine science community to urgently consider the consequences of substantial ammonia excess, to understand the implications of a global scale up in bunkering and usage of ammonia as a fuel.

6.4. Underwater noise

Section 6.1.5 considers the impact of underwater noise on biodiversity from offshore wind developments. However, ships themselves are a major source of underwater noise pollution at a range of frequencies, primarily caused by cavitation at the propellor (Wittekind & Schuster, 2016)[48] a phenomenon where gas bubbles formed in low-pressure regions around propellors rapidly collapse when ambient pressure is restored, producing shock waves which travel through the surrounding medium. This noise can significantly impact marine life, causing both behavioural and physical effects, depending on the noise level and frequency. For example, ship noise has been shown to affect 95% of marine life in studies reviewed by Duarte et al. (2021). Marine mammals are particularly sensitive to underwater noise due to their reliance on hearing for foraging, communication, and navigation (Findlay et al., 2023), and noise from vessels can mask these acoustic cues.

Electric propulsion systems generate significantly less noise than traditional diesel engines, as evidenced by noise reductions at ports using onshore power (Larsen, 2018). However, there are few studies directly evaluating the underwater noise of fully electric ships and preliminary research suggests that on-board diesel engines are a minor part of the overall underwater noise for ships at sea, suggesting that the benefits of transitioning to electric propulsion could be limited (Andersson et al., 2024).

Small reductions in cargo vessel speed, also known as slow steaming, have been shown to significantly reduce noise impacts on marine mammals (Findlay et al., 2023), highlighting the potential for noise mitigation strategies that involve both speed regulation and technological innovations and wind-assisted propulsion. Speed reductions also offer additional benefits of improved fuel efficiency and reduced greenhouse gas emissions, meaning that conservation goals can align with climate goals (Faber et al., 2017). The potential of slow steaming to reduce maritime energy and land demand is explored under our modelling scenarios in Section 7.4.5.

48 Engine vibrations also contribute to airborne noise and to underwater nose at higher frequencies (Genell et al., 2023; Wittekind & Schuster, 2016).

7. Compliance model and decarbonisation scenarios

7.1. Fulfilling EU targets

The EU's regulations for aviation and maritime decarbonisation entail a rapid scale-up of alternative fuel production capacity but leave some flexibility as to the precise mix of fuels that are to be used. In this context, a 'compliance model' is a tool for exploring the various pathways for reaching (or failing to reach) those goals.

A compliance model and scenarios for satisfying the EU's ReFuelEU Aviation and FuelEU Maritime targets has been developed for this report. Key model inputs include the projected demand for energy in the relevant sectors, characteristics of conventional and alternative fuels (such as their lifecycle greenhouse gas emissions), and constraints on the supply of biofuel feedstocks. A more detailed description of the model and its inputs is provided in Annex C; in this chapter we introduce our illustrative model scenarios, and the main results thereof.

7.2. Scenario descriptions

We present four scenarios to illustrate the implications of relying on different fuel production technologies and feedstock types: see Table 16 for a characterisation of each. All scenarios are designed to meet – at least approximately – the regulatory targets for aviation and maritime segments, spanning the period 2025 to 2050. Usage of alternative fuels other than those featuring in the scenario names (e.g. electricity or fossil natural gas) is assumed to be fixed for all scenarios, and residual energy demand in any given year is met with conventional petroleum-based fuels (meaning jet kerosene and MGO/HFO).

Table 16. The compliance scenarios used in the energy modelling

Scenario	Description
High RFNBO	Emphasis on the deployment of liquid and gaseous RFNBOs leads to increased demand for renewable electricity
High Lipid	Emphasis on first-generation lipid-based fuels leads to increased demand for waste and residual oils and development of intermediate oilseed crops
High Biomass Crop	Emphasis on the use of ligno-cellulosic material from energy crops relies on development of biomass-based fuel production technology, and leads to expansion and/or intensification of crop land
High Residue	Emphasis on the harvesting of ligno-cellulosic residues and wastes from agriculture, forestry, and industry for biomass-based fuel production

The consumption of each fuel type in the model may be broken down further into fuel sub-types and fuel feedstocks: these are listed in Table 17 (refer back to Section 2 for an introduction to the different types). Annex C.1 further describes some of the characteristics of these categories.

Table 17. Modelled fuel types and sub-types, differentiating between aviation and maritime fuels, and the feedstocks they are based on

Fuel Type	Segment	Fuel Sub-types	Feedstock Types
RFNBOs	Aviation	Kerosene, Hydrogen	Renewable electricity[49]
	Maritime	MGO/HFO, Hydrogen, Ammonia, Methanol, LNG	
Lipids	Aviation	Kerosene	UCO, category 1 & 2 fats, Annex IX crops
	Maritime	MGO/HFO	
Biomass Crops	Aviation	Kerosene, Hydrogen	Cellulosic cover crops, annual biomass crops, perennial grasses, SRF
	Maritime	MGO/HFO, Hydrogen, Ammonia, Methanol, LNG	
Residues	Aviation	Kerosene, Hydrogen	Agricultural residues, forestry residues, process residues, true wastes
	Maritime	MGO/HFO, Hydrogen, Ammonia, Methanol, LNG	
Other Biofuels	Aviation	Kerosene, Hydrogen	Various
	Maritime	MGO/HFO, Hydrogen, Ammonia, Methanol, LNG	
RCFs	Aviation	Kerosene	Industrial gases, unrecyclable plastic & rubber
	Maritime	MGO/HFO, LNG	
Electricity	Aviation	Electricity	Grid electricity, renewable electricity
	Maritime	Electricity	
Wind	Aviation	--	Wind
	Maritime	Wind	
Natural Gas	Aviation	--	Fossil natural gas
	Maritime	LNG, Ammonia, Methanol	
Petroleum	Aviation	Jet kerosene	Petroleum
	Maritime	MGO, HFO, LPG	

Note: '—' indicates that the fuel is not used in that transport segment.

The scenarios from Table 16 are defined and distinguished by the mix of fuels that contribute

49 Hydrocarbon and alcohol RFNBOs also need a source of carbon to build the fuel molecules. This will come from carbon capture, though we remain agnostic as to the precise source of the carbon. Refer to the discussion in Section 3.5.3.

to the overall energy pool[50]. As the ReFuelEU Aviation target is an energy quota (Section 2), an aviation scenario can be constructed by dividing the evolving quota level into contributions from different fuels. An example for a single scenario is shown in Figure 20. All scenarios are constructed to deliver compliance with ReFuelEU Aviation's RFNBO sub-target.

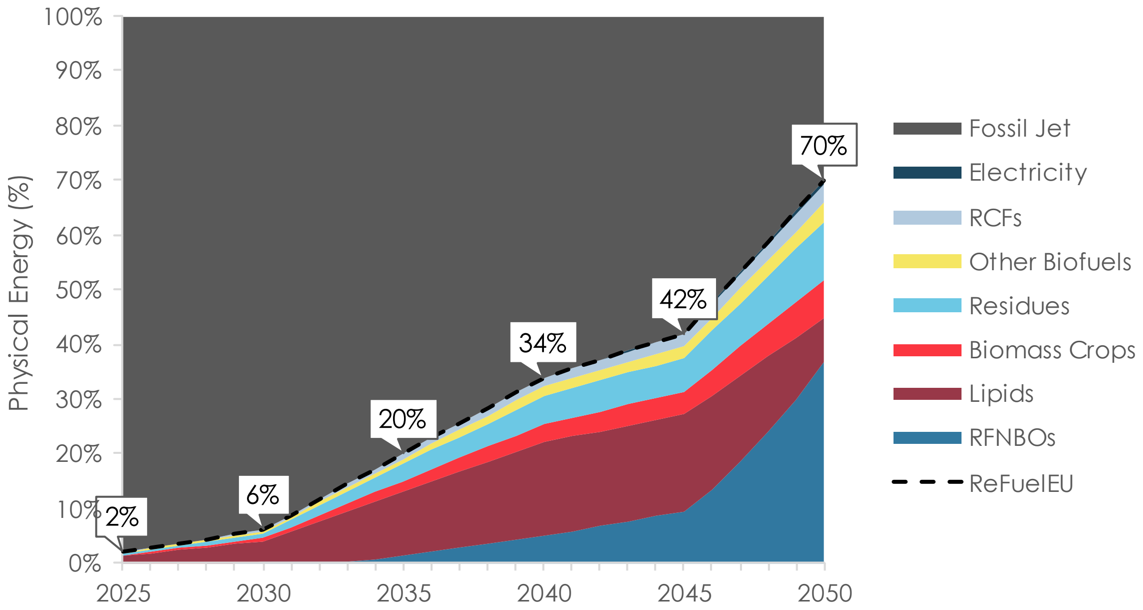


Figure 20. Evolving aviation energy mix for the High RFNBO scenario, consistent with the ReFuelEU Aviation target (black dashed line)

50 The consumption of fuels and fuel sub-types also connects to the deployment of alternative engine types – for instance, more fuel cell engines entail more green hydrogen consumption. This is discussed further in Annexes C.1 & C.2.

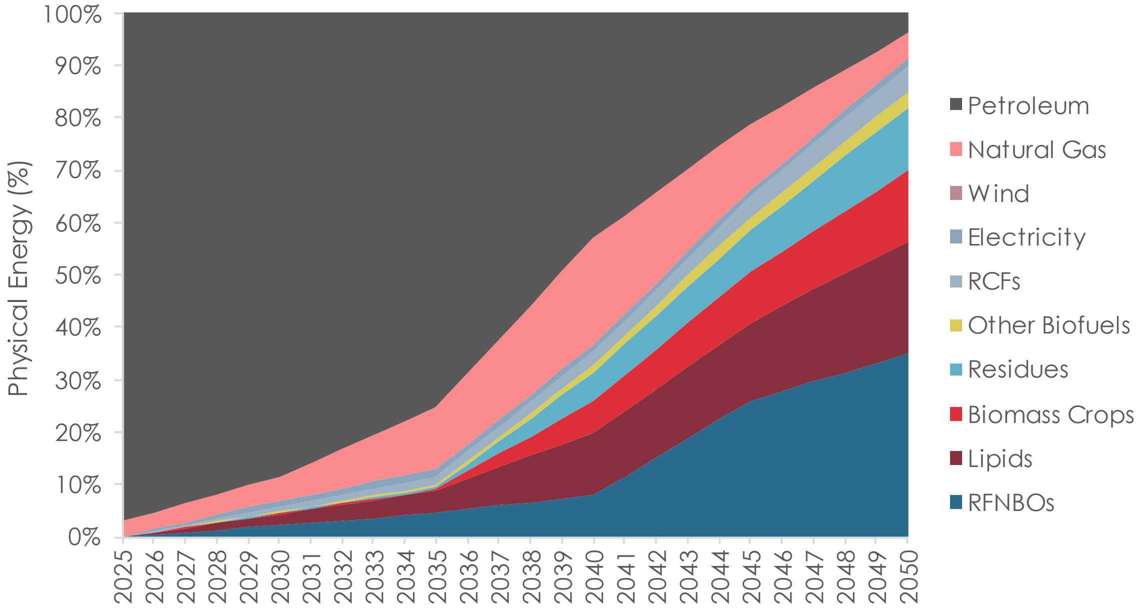


Figure 21. Evolving maritime energy mix for the High RFNBO scenario, consistent with FuelEU Maritime targets

For the FuelEU Maritime emissions intensity target, we define the scenario in the same way – i.e. as the contributions of different fuels to the overall mix. However, assuring compliance is a little more convoluted and approximate: we describe the process in Annex C.3. An example scenario is shown in Figure 21, where we see conventional fossil fuels on their way to being eliminated after 2050.

When it comes to calculating greenhouse gas emissions, it is worth emphasising that the emissions per unit of fuel that are used in the modelling are indicative of lifecycle emissions scores that would obtain under the two regulations. They neglect important indirect effects such as ILUC, as well as significant non-CO_2 effects like aeroplane contrails and black carbon from ship exhausts. Any assessment of EU aviation and maritime compliance with the established regulatory systems – including this report – will therefore under-estimate their full climate impact.

7.3. Modelling framework

This section highlights two features of the model that are important for interpreting the results in Section 7.4. More detail on how the model works can be found in Annex C.

7.3.1. Feedstock supply

In general, the modelling does not impose any explicit constraint on feedstock availability – the purpose of this report is to illustrate the implications of delivering a certain level of fuel supply, even if this leads to displacement of existing systems and sustainability issues. The only exception to this principle is residual lipids. We impose explicit constraints on the use of the residual lipids UCO and category 1&2 animal fat, as the scope for scaling up supply of these feedstocks is known to be limited (especially considering the growing demand for alternative fuels in other markets). The European Union reports that about 128 PJ (3,050 ktoe) of UCO and 35 PJ (843 ktoe) of category 1&2 fat were used in transport in 2023 (Eurostat, 2024g). This figure includes imports – for instance, it has been estimated that only about 570 kt (515 ktoe) of category 1&2 fat is produced domestically in the EU-27 (Malins, 2023).

For the model scenarios which do not emphasise lipid-based fuels, we assume that the total supply of residual lipids is fixed at the 2023 level[51], and that the entirety of this resource is made preferentially available to aviation and maritime fuel producers. As we shall see in the next section, the available resource is quickly exhausted and leaves none for the road transport segment or for any other economic sector. In the High Lipid scenario, we relax this constraint and allow the residual lipid supply to increase gradually over time, under the assumption that a strong value signal will allow the EU to outcompete other markets and import it from around the world[52]. For all scenarios, lipid demand that exceeds the supply of residual oils is met with oilseed crops which are grown compatibly with Annex IX definitions.

7.3.2. Types of land demand

Model results for biofuel feedstock demand, differentiated by type of crop, can be combined with assumed agricultural yields to estimate the implied land footprint associated with each crop. Our assumptions on agricultural yields are discussed in more depth in Annex C.4.4. Some feedstocks and farming models will require the conversion of new crop land, while others may require more intensive cultivation on existing land.

As a point of reference, the GLOBIOM model considers the stocks and flows of land categories, including cropland, grassland, abandoned land, forest, and other natural land. Valin et al. (2015) modelled the shifts in land use arising from a hypothetical 1% biofuel share in the EU energy mix; the results generally show growth in crop land at the expense of other land categories. Biofuel made from rapeseed oil, for instance, has a relatively high land requirement, 42% of which is met with abandoned land, 35% with other natural land, and 23% with grassland. This contrasts with palm oil, which has a lower land requirement but of which 54% is met with forest land, 26% with grassland, 19% with other natural land, and only 1% with abandoned land.

In this report we take a different approach. We are interested in changes to land use dynamics that go beyond LUC, as feedstock production based on changing management practices (with fixed land type) can have important implications for biodiversity; thus, in a sense we must go beyond the GLOBIOM categories. On the other hand, our modelling framework is based on relatively simple scenarios rather than on creating demand shocks in a complex global economic model. This means that the balance between feedstock production pathways in our results arises more directly from our scenario definitions rather than modelled market forces. Our modelling is furthermore focussed on demand for different types of biofuel feedstock rather than different types of land, and so when additional crop land is brought

51 Similar assumptions were made in O'Malley & Baldino (2024) which provides further discussion and justification.

52 A strong value signal would need to be accompanied with robust chain-of-custody monitoring to mitigate fraud risk. This was discussed in Section 5.1.3.

into production the model is agnostic about the original land type. New crop land could have formerly been pasture, abandoned land, forest, or any other category. The land use dynamics considered in our modelling are summarised in Table 18.

The first category in Table 18 is arguably the most heterogeneous, as it covers both direct and indirect conversions, and the whole range of original land uses. A direct conversion is where a plot of non-farmed land is cleared, tilled, and planted (for instance scrubland is turned into a miscanthus farm); an indirect conversion is where the bioenergy crop replaces some other crop that was formerly grown there (for instance, a wheat field is planted with sorghum instead). In the latter case, we assume that demand for the original crop (wheat) has not changed, and so to first order new land elsewhere must be cleared to grow it. The result either way is the same – new land must be brought into production.

Where this new land comes from is another question. In the EU, forest and wetland protection laws are relatively strong, and it is unlikely that trees would be cut, or bogs drained to make way for crops; but pasture, semi-natural grasslands, and scrub could be converted (this includes abandoned agricultural land that is slowly returning to a natural state). Since the model does not distinguish these land types, we will use GLOBIOM results to inform our conclusions.

The other three dynamics in Table 18 are less nuanced, and further explanation isn't necessary. We use the term 'land footprint' to refer to the area of land that is affected by any of the four changes listed. For example, the land footprint of 'conversion to crop land' is the new area that is required for crop production; the land footprint of 'residue harvesting on crop land' is the area of existing agricultural land where e.g. straw is collected for cellulosic biofuel production. These two land footprints, even if they have the same area, would have drastically different biodiversity impacts.

Table 18. Types of land use and land management changes considered in the model

Land use / management change	Description	Model feedstock categories
Conversion to crop land[53]	Land is converted from some existing use (pasture, grassland, forest, etc.) to crop land. This is a land use change. It could be a direct result of biofuel feedstock cultivation in previously unfarmed areas, or an indirect result of switching to biofuel feedstock production from some other crop, such that the original crop must be grown elsewhere to meet demand.	Biomass Crops | Annual Grass Biomass Crops | Perennial Grass Biomass Crops | SRF
Intensification of crop land	Activity on existing crop land is intensified through the addition of intermediate crops into rotations. This does not constitute a land use change but has biodiversity implications.	Lipids | Annex IX Crop[54] Biomass Crops | Cover Crop
Residue harvesting on crop land	Activity on existing crop land is intensified through the introduction of residue harvesting. This does not constitute a land use change but has biodiversity implications.	Residues | Agricultural
Residue harvesting on forestry land	As in the row above, but on forest land (in principle both natural and planted forest could be involved).	Residues | Forestry

Before presenting the modelling results, we note that Table 18 only covers feedstocks that originate in fields and forests. Other non-agricultural / non-forestry feedstocks may also stimulate indirect land demand if diverting them from some original use has knock-on effects. Malins (2023) reports how low-grade fats from livestock carcass rendering have existing uses in industries such as oleochemicals and animal food. Using the fats to make aviation or maritime fuels will force these industries to resort to alternative feedstocks, such virgin vegetable oils like palm. Other examples, from sawdust to tall oil pitch, abound: see the assessment by the European Commission on possible addition of feedstocks to Annex IX (Haye et al., 2021). In short, consumption of fuels made from industrial and processing residues may cause indirect land use change and associated biodiversity impacts, but we do not report such results here.

53 Note that this includes land for SRF, even though this might intuitively be considered woodland rather than cropland. In EU land use statistics, SRF is included in UAA, and so for our purposes it makes sense to use a combined category.

54 Recall that our Annex IX lipid crop category covers sequential crops, intercrops, and crops grown on severely degraded land that qualify for RED II Annex IX status. We expect the last category to make a negligible contribution, which is why this whole feedstock category is treated as a crop land intensification.

7.4. Scenario results

This section presents results from the modelling.

7.4.1. Energy and emissions

Figure 22 shows a snapshot of energy demand for the two transport segments in 2050, broken down by fuel (the projections used for the overall sectoral energy demand are discussed in Annex C.2). Note that the maritime segment has a higher overall energy demand, and a larger demand for alternative fuels. This is because projected 2050 total maritime energy demand is higher than aviation energy demand, and because whereas aviation may still use 30% fossil jet fuel in 2050, meeting the 80% emissions reduction target in the maritime sector implies near-elimination of fossil fuels.

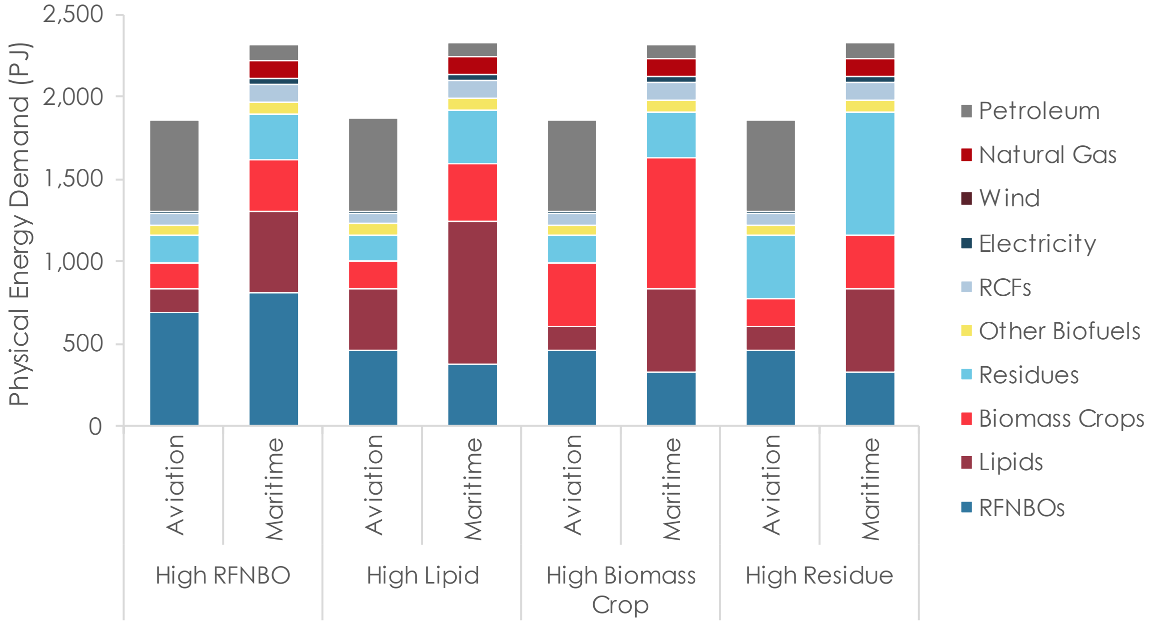


Figure 22. Physical energy consumed by each fuel type in aviation and maritime segments in 2050 for each scenario

Note: Physical energy demand may differ very slightly between the scenarios due to their deployment of alternative engine technologies with different energy efficiencies.

Figure 23 and Figure 24 respectively show the modelled greenhouse gas emissions from 2025 to 2050 for the High RFNBO scenario as an example. The dashed black line at the top of each graph shows the 'counterfactual' emissions that would occur if all transport energy demand were met by conventional fossil fuels. The grey wedges represent modelled emissions (divided into conventional and alternative fuels), and the coloured wedges represent emissions *savings* attributable to each alternative fuel.

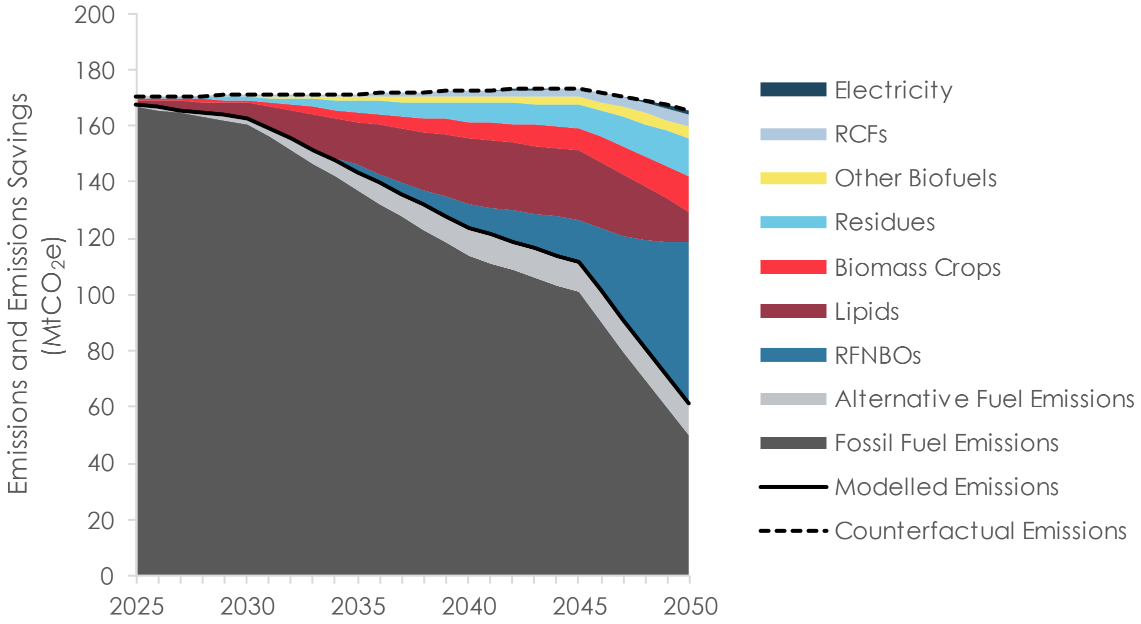


Figure 23. Emissions and emissions savings in the aviation sector for the High RFNBO scenario

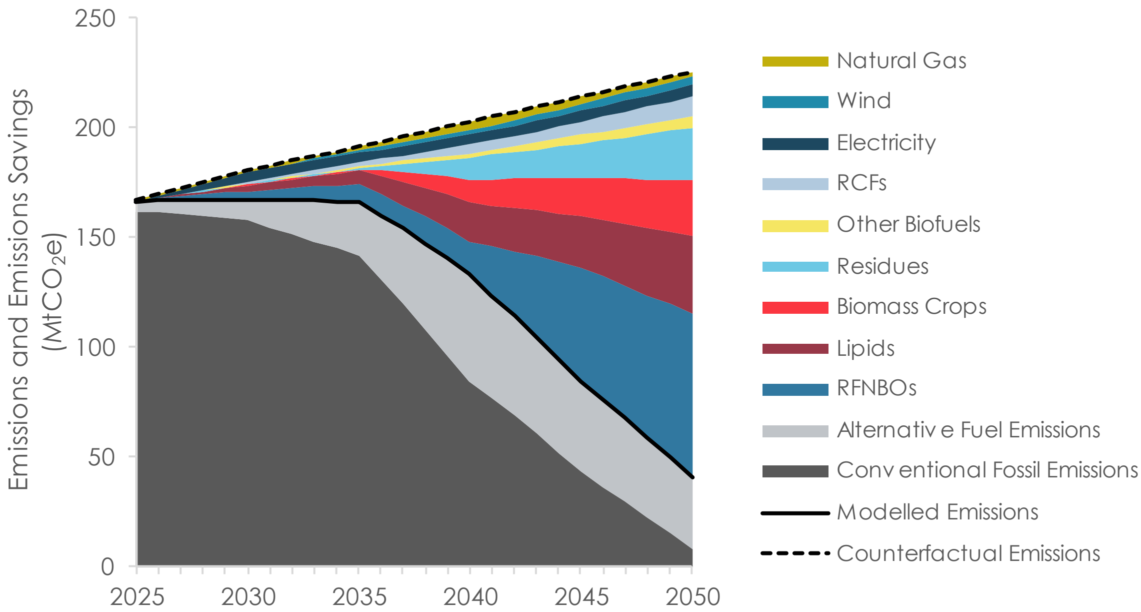


Figure 24. Emissions and emissions savings in the maritime sector for the High RFNBO scenario

Our scenarios all achieve a 72-74% saving in reportable greenhouse gas emissions by 2050 compared to a fossil-only counterfactual (Figure 25). This means that, though they follow different paths towards decarbonisation, they all arrive at roughly the same place.

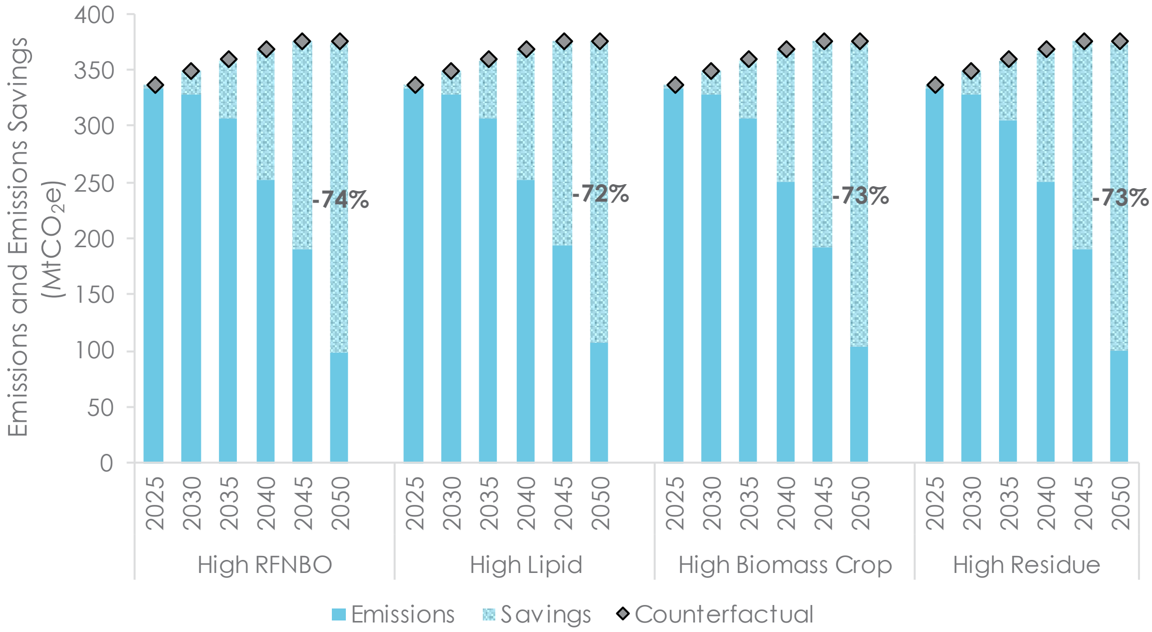


Figure 25. Modelled emissions over time, summed over aviation and maritime sectors, and compared with the fossil-only counterfactual for each scenario

Greenhouse gas emissions and emissions savings are reported here according to the ReFuelEU Aviation and FuelEU Maritime methodologies so as to be consistent with the goal of regulatory compliance. The actual climate impact of our fuel usage trajectory would be a more subtle issue, due to indirect displacement effects and the existence of non-CO_2 warming which are not reflected in the regulatory methodology. The next two paragraphs cover these in a little more detail.

Displacement refers to the phenomenon whereby resources taken from one sector to feed another must be replaced in the original sector. Starting a project to use renewable electricity to make aviation fuel could yield zero or even negative climate benefit if the resulting unmet demand in other sectors has to be compensated with fossil-based power. Similarly, diverting used cooking oil from the road biodiesel industry into HEFA production would at best simply move greenhouse gas reductions from one transport segment to another – though efficiency penalties mean that net greenhouse gas emissions would likely rise. Another form of displacement happens when the cultivation of biofuel feedstocks impairs the productivity of other crops. For instance, if an intermediate crop were to delay planting of the main crop, yields of the latter may suffer, and the pressure to compensate lost productivity would stimulate ILUC. On the other hand, a well-managed intermediate crop can improve long-term yields and thus have a doubly positive effect (BIKE, 2023).

Non-CO_2 warming has already been mentioned in Section 2, as well as in Annex C.4.1. It refers to the creation of heat-trapping contrails and tropospheric nitrogen oxides in the wake of aircraft, and the production of sulphate aerosols and black carbon by maritime vessels. While these effects can be significant (D. S. Lee et al., 2021), they have no regulatory weight and are not reflected in our greenhouse gas calculations. The same goes for leakage of methane and hydrogen during the many stages of fuel production and supply. These are important considerations: scenarios that depend more heavily on methane (fossil or biogenic) and hydrogen (fossil, biogenic, or electrolytic) pose greater climate risks than suggested by our regulation-focussed conclusions (cf. Sections 3.2.2 and 3.5.1 respectively).

7.4.2. Feedstock demand

In this section, we analyse modelled demand for biofuel feedstocks under the four named scenarios. As a first example, Figure 26 shows that demand for lipid biofuel feedstocks is significant even in the High RFNBO scenario (the graph is in units of PJ for easier comparison with energy targets). As the use of residual oils is constrained (discussed in Section 7.3), demand must be satisfied by production of Annex-IX-compatible crops. Total lipid usage is seen to peak in the 2040s and then comes down as it is displaced by RFNBOs and other technologies.

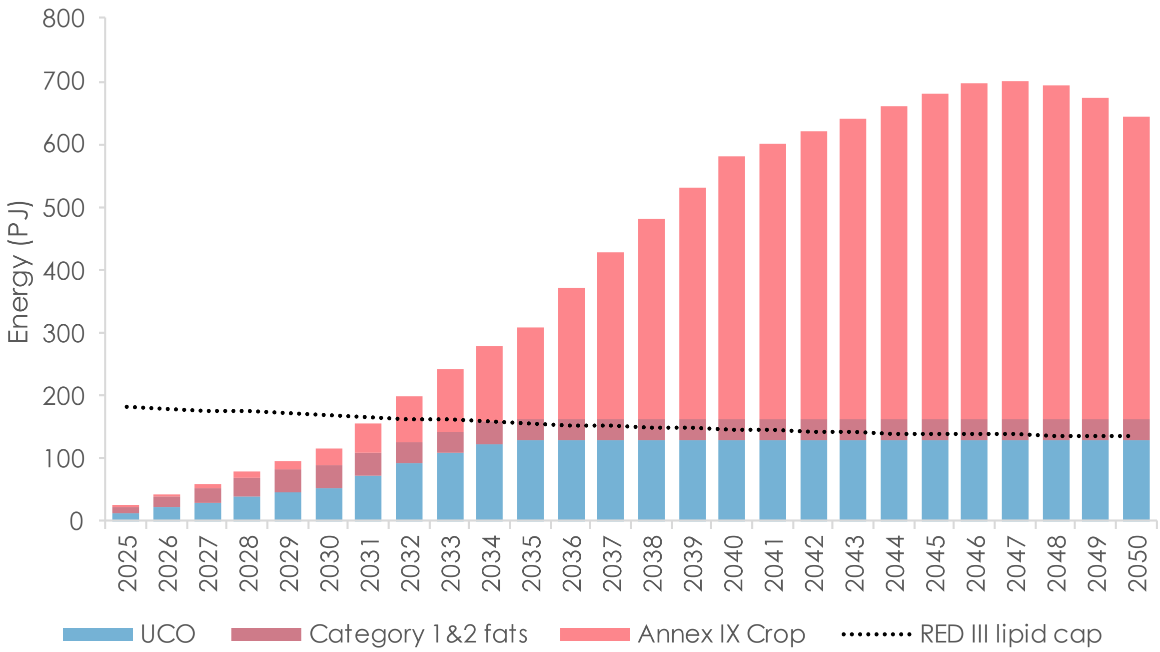


Figure 26. Lipid feedstock demand (aviation and maritime) over time for the High RFNBO scenario

Note: The RED III lipid cap is 1.7% of total transport energy, as estimated by the EU Reference Scenario 2020 (European Commission, 2020e).

Modelled feedstock demand for lipids, biomass crops, and cellulosic residues in the year 2050 is shown in Figure 27, Figure 28, and Figure 29 respectively. These are all presented in terms of megatonnes of feedstock consumed each year, but the vertical scales differ: because of the different qualities of the feedstocks, the jump in demand for lipids in the High Lipids scenario is smaller than the jump in demand for biomass crops in the High Biomass Crop scenario or cellulosic residues in the High Residue scenario.

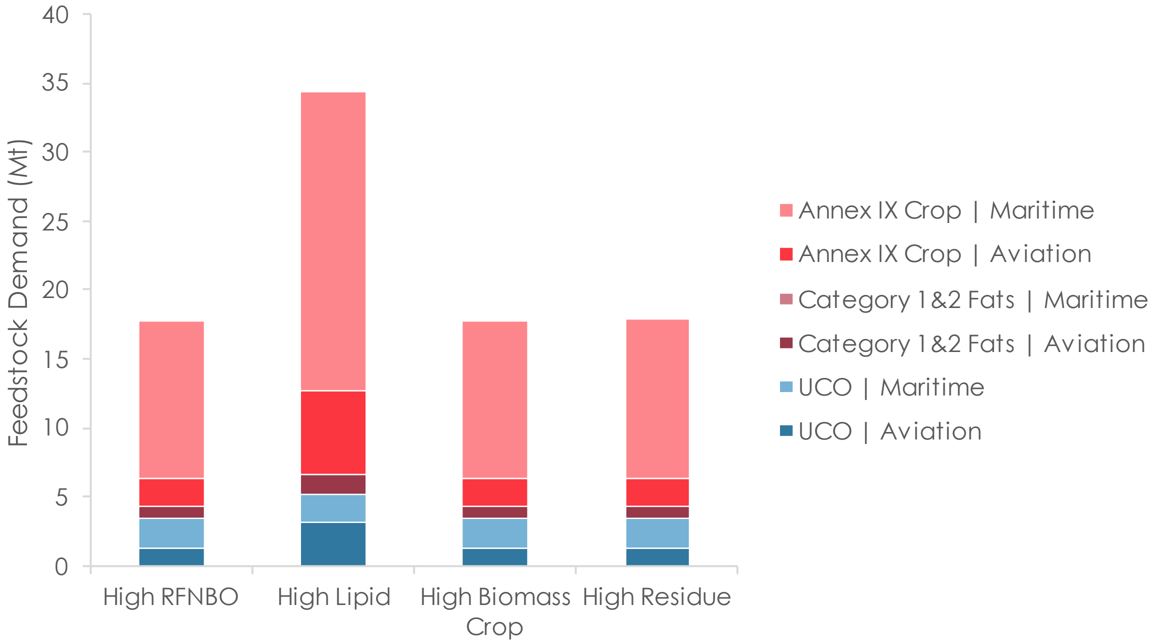


Figure 27. Lipid feedstock demand in 2050 for each scenario

Note: Megatonnes of 'Annex IX Crop' is the mass of oil rather than seeds, for better comparability with the other two feedstocks, and because oilseeds have highly differing oil content.

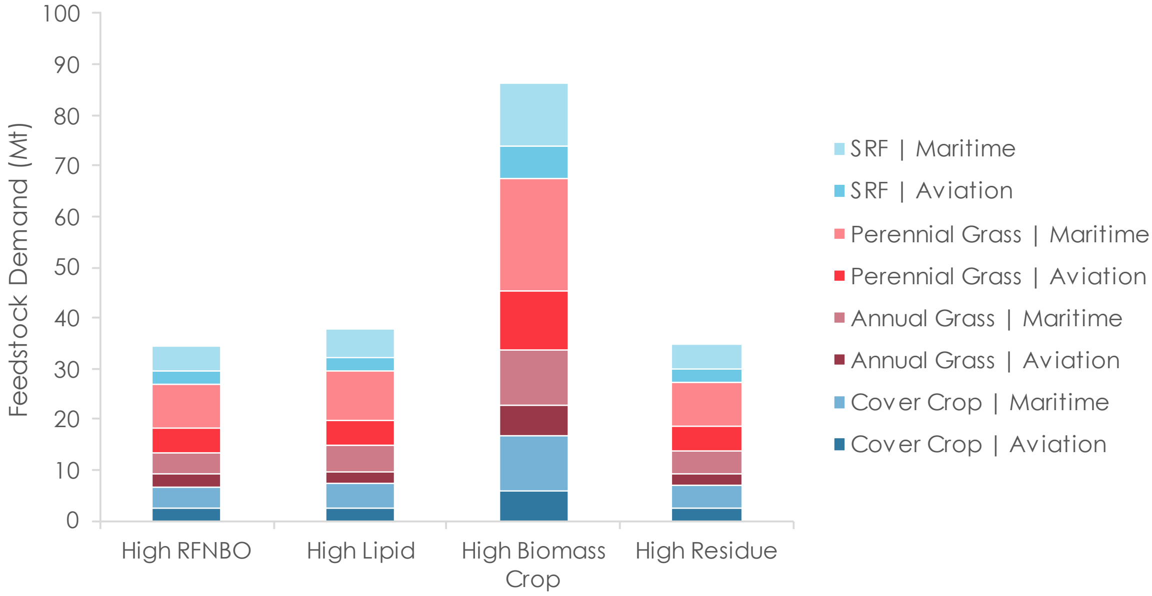


Figure 28. Biomass crop demand in 2050 for each scenario

Note: This does not include the use of biomass to produce bio-hydrogen for fuel refining steps. See Figure 51 in Annex C.6.

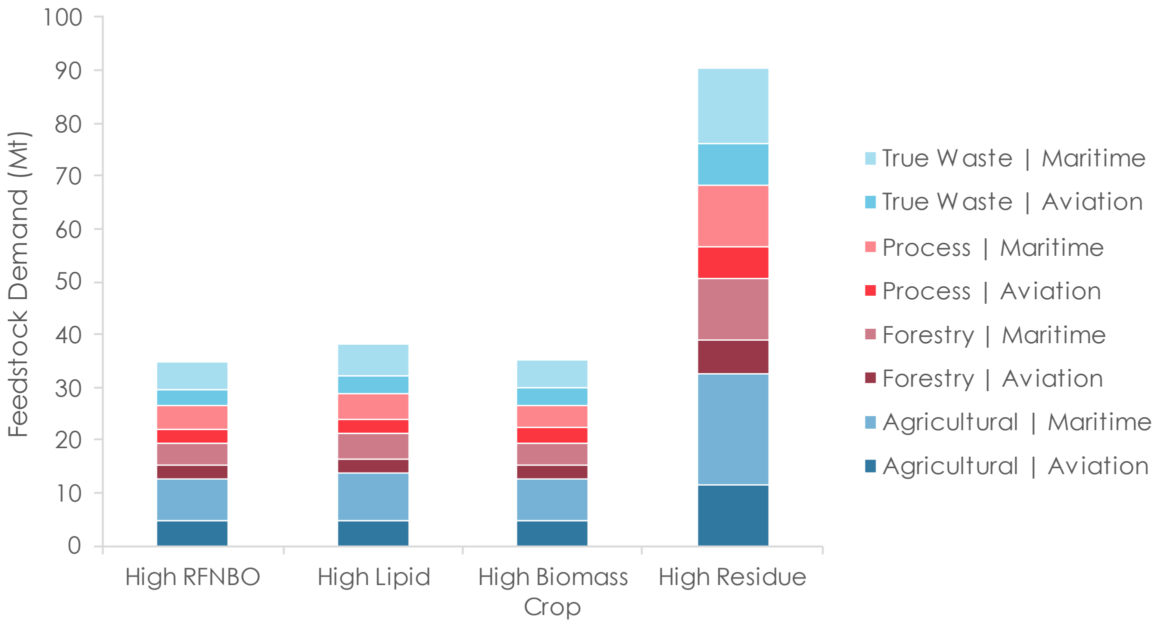


Figure 29. Cellulosic residue demand in 2050 for each scenario

Note: See the note below Figure 28.

This modelled EU demand for such feedstocks may be compared with assessments of the

EU volume of sustainably available feedstock from the literature, presented in Table 19 and Figure 30. For the sake of comparability, we have mapped the feedstock categories used in the original source onto our categories introduced in Table 17, taking 'energy crops' to encompass cellulosic cover crops, perennial grasses, and SRF.

Table 19. Selected estimates of biomass-based biofuel feedstock availability from the literature

Source	Feedstock	Availability
Searle & Malins (2016)	Agricultural residues	74 Mt in 2020 77 Mt in 2030
	Forestry residues	7 Mt in 2020 5 Mt in 2030
	Wastes	42 Mt in 2020 21 Mt in 2030
E3MLab et al. (2017)	Forestry residues	12 Mt in 2016 12 Mt in 2030
	Wastes	7 Mt in 2016 8 Mt in 2030
Panoutsou & Maniatis (2021)[55]	Energy crops	36 Mt in 2030 42 Mt in 2050
	SRF	293 Mt in 2030 308 Mt in 2050
	Agricultural residues	224 Mt in 2030 248 Mt in 2050
	Forestry residues	265 Mt in 2030 282 Mt in 2050
Kowalczewska et al. (2023)	Energy crops and agricultural residues	85 Mt in 2023
	SRF and forestry residues	426 Mt in 2023
	Process residues and waste	91 Mt in 2023

55 This source provides three estimates: low, medium, and high. Here we quote values for low.

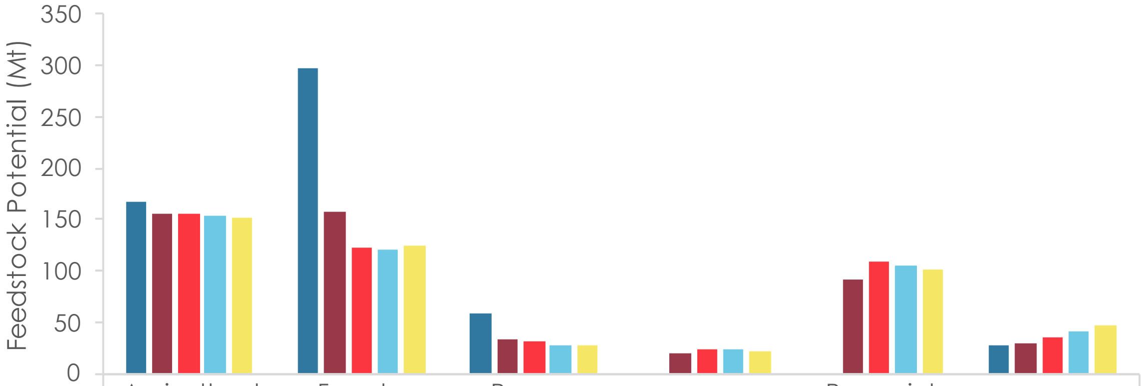
Source	Feedstock	Availability
Material Economics (2021) *	Energy crops	47 Mt in 2020 82 Mt in 2050
	Agricultural residues	41 Mt in 2020 74 Mt in 2050
	Forestry residues	324 Mt in 2020 332 Mt in 2050
	Process residues	106 Mt in 2020 100 Mt in 2050
	Wastes	82 Mt in 2020 126 Mt in 2050
European Commission Joint Research Centre (2023)[56] *	Shown in Figure 30	
van Grinsven et al. (2020)[57] *	Agriculture	376 Mt in 2030 324 Mt in 2050
	Forestry	500 Mt in 2030 694 Mt in 2050
Wiesenthal et al. (2006) *	Energy crops	216 Mt in 2020 295 Mt in 2030
	Agricultural residues	275 Mt in 2020 283 Mt in 2030
	Forestry residues	113 Mt in 2020 110 Mt in 2030
O'Malley & Baldino (2024)	Agricultural residues	83.3 Mt in 2030
	Forestry residues	8.4-11.2 Mt in 2030

*Note: Datasets marked with a * have been converted from energy to mass units using an approximate conversion factor. The conversion factor between Mt and PJ depends on the particular feedstock under consideration. One may use an approximate conversion of 10-20 PJ/Mt to get an order-of-magnitude estimate.*

Figure 30 shows results from an analysis by the European Commission's Joint Research Centre – this is among the most comprehensive single datasets.

56 The dataset and methodology are described in Ruiz et al. (2019). We present their 'Medium' scenario.

57 These figures are for the EU-28. For 2030, we have selected the lower end of the sustainable biomass availability range.



	Agricultural residues	Forestry residues	Process residues	SRF	Perennial grasses	Wastes
2010	166	296	58	0	0	27
2020	156	158	34	20	92	29
2030	155	122	30	23	108	35
2040	153	120	28	23	105	40
2050	152	124	28	23	101	46

Figure 30. Ligno-cellulosic feedstock production potential in the EU-27, from the ENSPRESO Medium scenario

Note: Converted from energy to mass units using an approximate conversion factor.
Source: European Commission Joint Research Centre (2023); Ruiz et al. (2019)

Comparing the scenario's feedstock consumption with these estimates of sustainable availability, we may make a few observations. Modelled demand for cellulosic residues is generally within the limits found in the literature, though in the High Residue scenario it exceeds the lower end of the range (e.g. Searle & Malins, 2016). Similarly for cellulosic biomass crops: demand is generally within the limits, except for the High Biomass Crop scenario which exceeds the more pessimistic availability estimates. In all cases, aviation and maritime fuel production would eat considerably into the available resource leaving little for other sectors of the bio-economy (such as road transport, textiles, and chemicals). These would have to resort to imports of feedstocks and/or finished products into the EU – a conclusion also reached in O'Malley & Baldino (2024), which estimates that the sustainable EU-based feedstock resources for aviation biofuels may be sufficient to satisfy near-term (i.e. 2035) ReFuelEU Aviation targets but fall short of the 2050 target.

7.4.3. Land demand for biofuel feedstocks

The model results presented here cover the different types of land footprint introduced in Section 7.3.2 – that is, stimulation of a need for additional crop land, additional forest land, crop intensification, and residue harvesting on crop and forestry land[58]. Modelled land footprints per unit of relevant fuel (kha/PJ) are shown in Table 20 – this includes, for comparison, the land

58 As was discussed in Section 7.3.2, we will not consider indirect land use change from the use of feedstocks which are not themselves directly produced from land (e.g. industrial residues and wastes).

footprint required for electricity generation, both for direct supply and RFNBO production (see Section 6.1). This establishes a clear hierarchy, with harvesting of residues requiring a relatively large area of existing agricultural or forested land; then compliant lipid crops requiring a large area of intensified agricultural production; then biomass crops on additional and intensified land; and finally, electricity-based fuels needing relatively negligible amounts of additional land. The remainder of this section considers only biofuels' contribution to modelled land footprint, and results on electricity-related land use are shown in Annex C.6.

Table 20. Land footprint for different fuel types in 2030 and 2050, including biofuels and electricity-based fuels, and indicating the footprint category for reference

Fuel Type	Feedstock	Land Footprint	Unit	2030	2050
RFNBOs	Renewable Electricity	Additional land	kha/PJ	0.03	0.02
Electricity	Grid Electricity	Additional land	kha/PJ	0.02	0.02
	Renewable Electricity	Additional land	kha/PJ	0.02	0.02
Lipids	Annex IX Crop	Crop land intensification	kha/PJ	27.2	15.2
Biomass Crops	Cover Crop	Crop land intensification	kha/PJ	5.5	3.3
	Annual Grass	Additional agricultural land	kha/PJ	4.9	3.0
	Perennial Grass	Additional agricultural land	kha/PJ	6.6	3.9
	SRF	Additional agricultural land	kha/PJ	7.8	4.7
Residues	Agricultural	Crop land harvesting	kha/PJ	43.8	42.8
	Forestry	Forestry land harvesting	kha/PJ	40.3	39.4

Note: Renewable electricity for RFNBOs comes from solar, wind, and geothermal generation only. The conversion efficiency of electricity into green hydrogen is included in the figure.

Note: These values are for the High RFNBO scenario, but the differences between scenarios are very small or zero so they can be taken as representative.

In Figure 31, we stack all land footprint contributions for the High RFNBO scenario. The total can be understood as the 'total affected land area' – a relatively heterogeneous category which we break down in the plots that follow. The Figure 31 land footprint grows over time, though the relative contribution of different feedstocks (and hence different land use impacts) changes.

The next three figures break down the overall land footprints in 2030 and 2050, for each of the scenarios. Figure 32 concerns additional land conversion to new crop and forestry land; Figure 33 concerns intermediate cropping of biomass and oilseed crops; and Figure 34 concerns residue harvesting on existing agricultural and forest land.

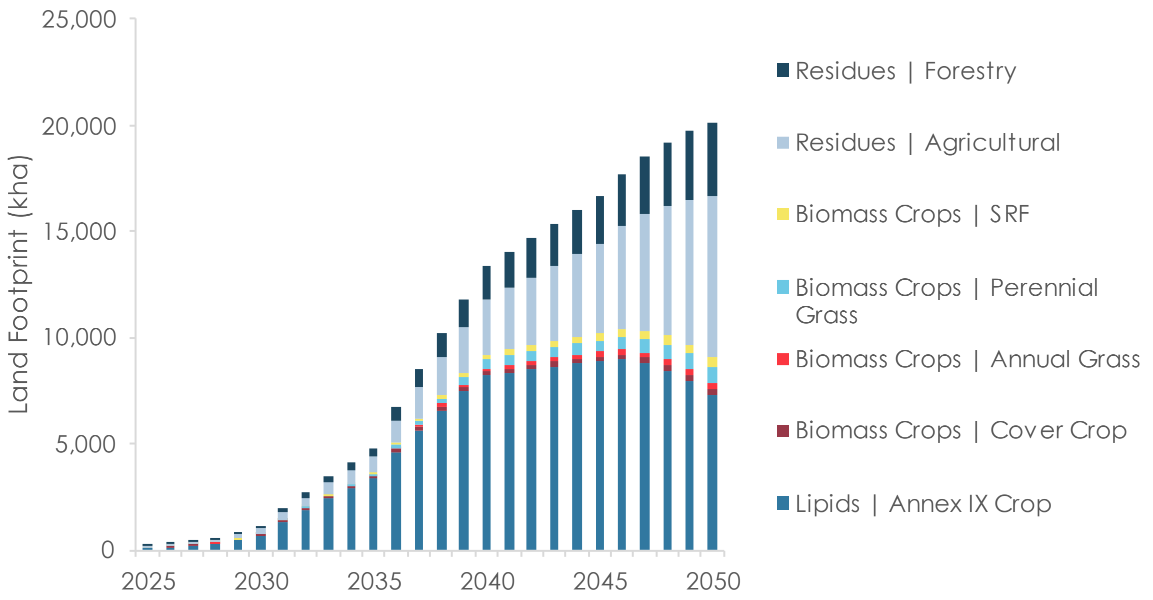


Figure 31. Annual land affected by land-based biofuel feedstocks in the High RFNBO scenario, distinguished by feedstock type

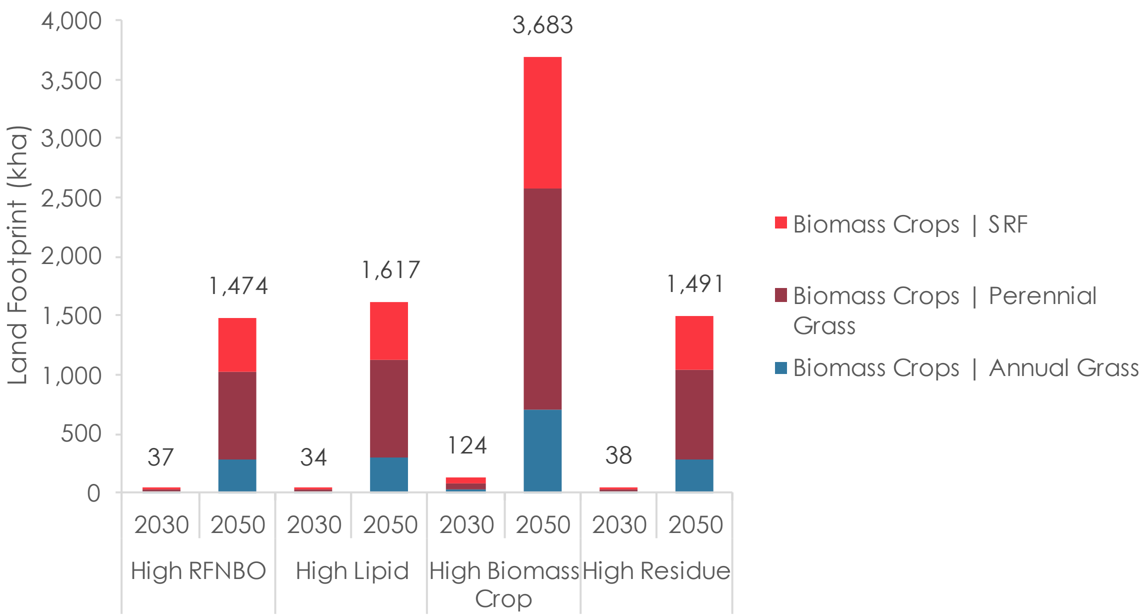


Figure 32. Land area converted to biofuel production in 2030 and 2050 under the four scenarios (this represents additional crop and forestry land)

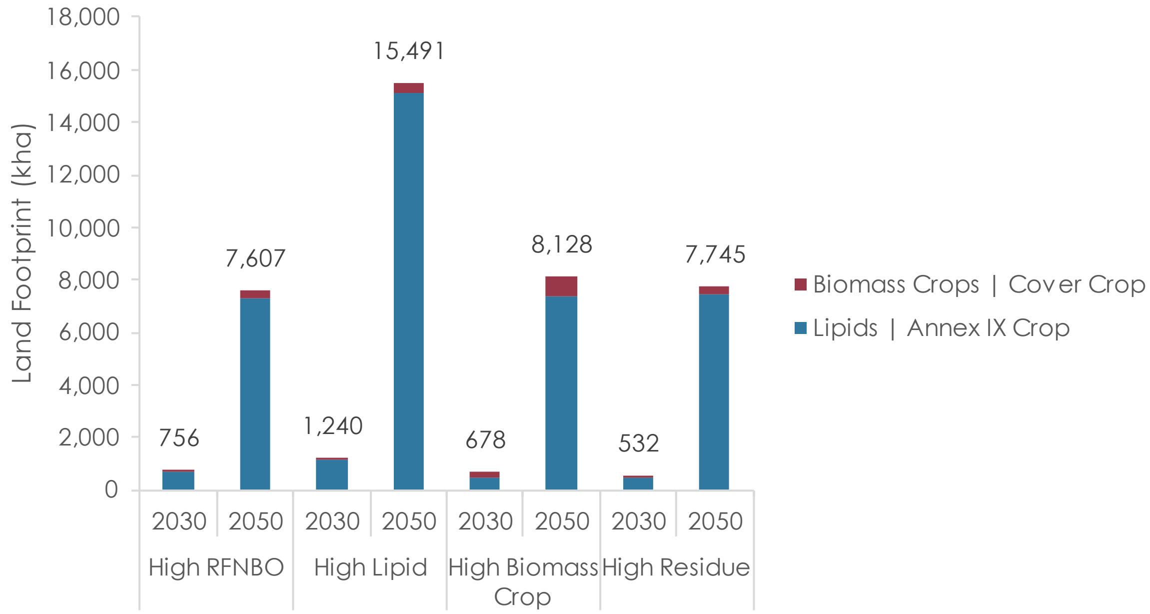


Figure 33. Land area covered by intermediate crops for biofuel production in 2030 and 2050 under the four scenarios (this represents crop land intensification)

Note: We have assumed that the majority of Annex IX lipid crops comes from intermediate cropping systems.

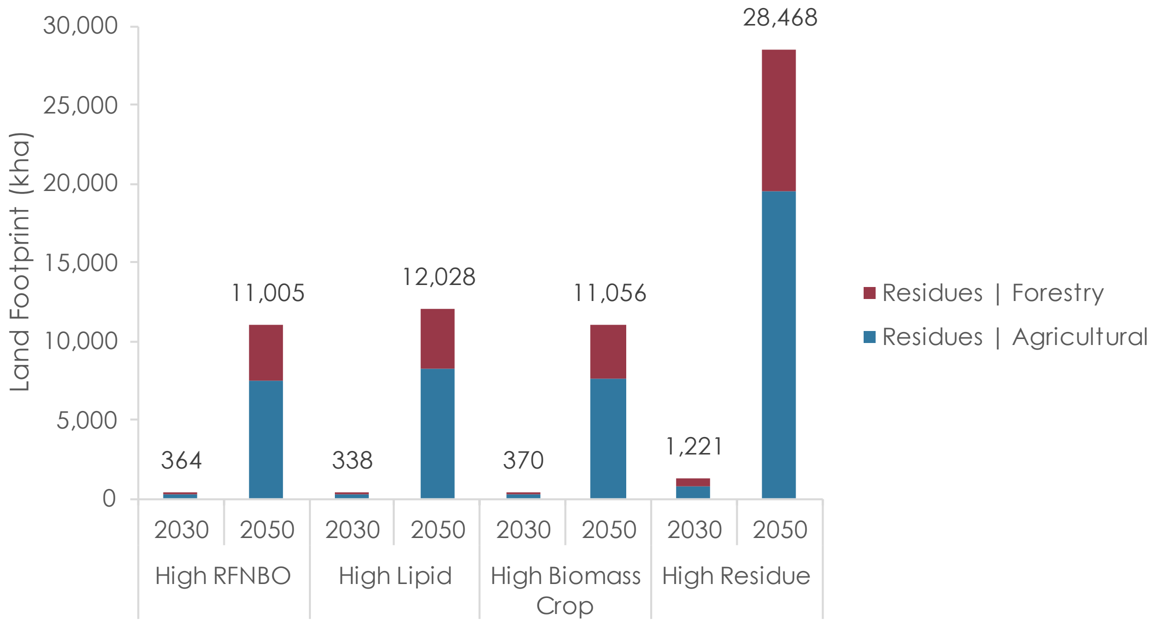


Figure 34. Land area where residue harvesting intensifies for biofuel production in 2030 and 2050 under the four scenarios (this represents residue harvesting on crop and forestry land)

To contextualise these results, the cultivated areas of major crops in the EU is graphed in

Figure 35. Depending on the scenario, the area of new land conversions in 2050 may be comparable to the annual planting of oats or sunflower seeds, while the area where intermediates must be introduced into rotations is comparable to the planting of rapeseed or wheat. Looking at Figure 36, which shows the evolution of forested area in the EU-27, we see that the above area affected by forest residue harvesting under our scenarios is a small fraction of total forest land. However, rather than low-intensity residue harvesting over the entire available area, we would expect future activity to be concentrated in higher-density, higher-yielding forest areas, especially those which are close to existing infrastructure like roads and settlements.

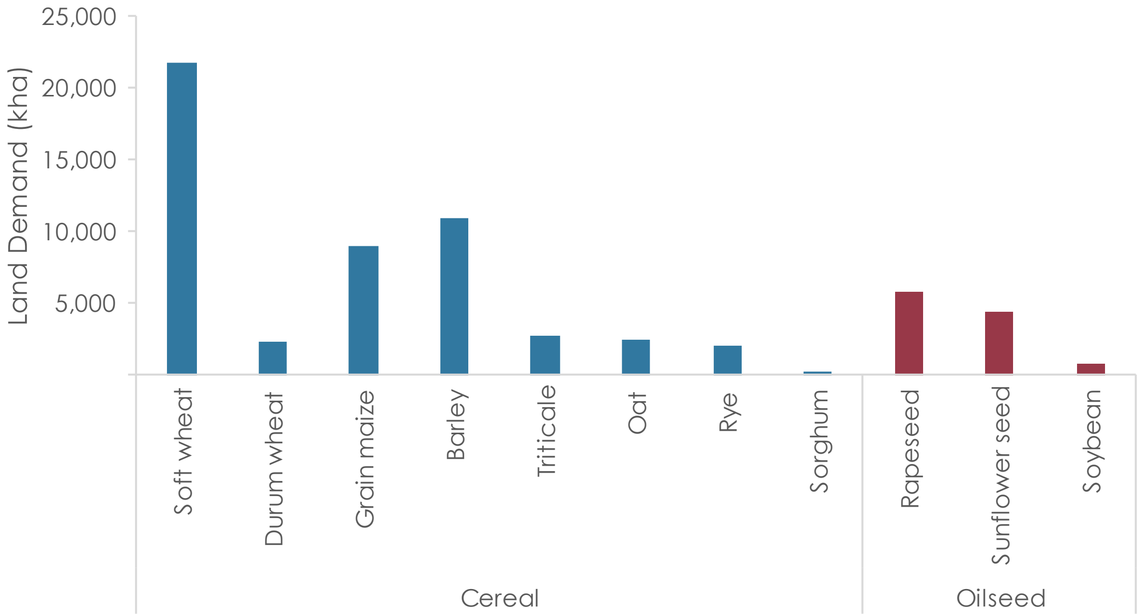


Figure 35. Average land demand for cereal and oilseed crops in the EU-27 for the period 2011-24

Source: European Commission (2024b, 2024h)

Note: Data for the years 2022-2024 has not been finalised.

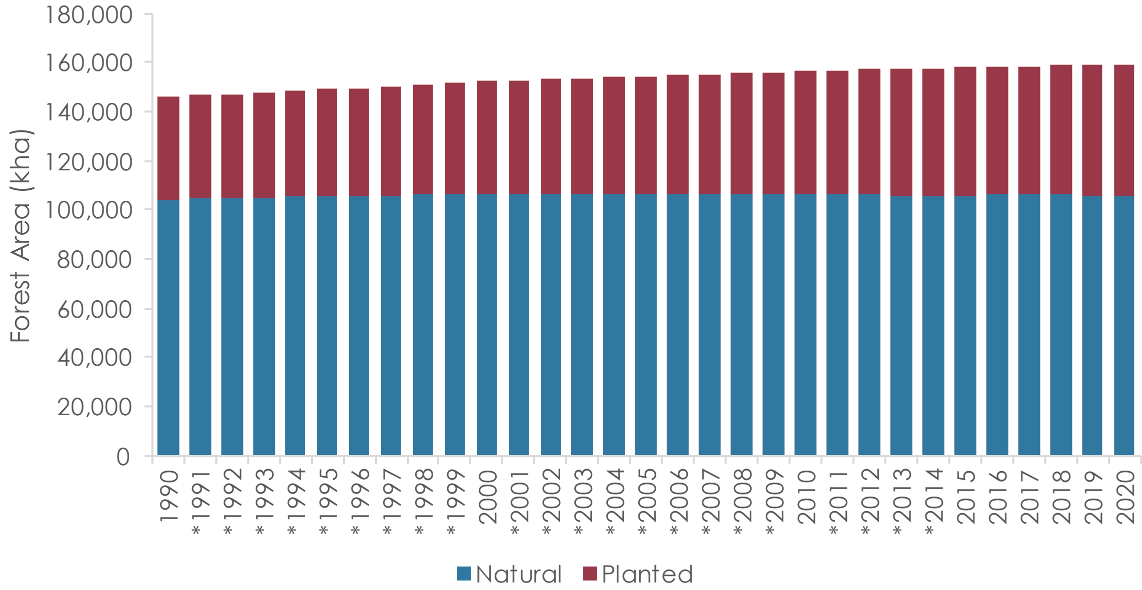


Figure 36. Forested area in the EU-27, 1990-2020

Note: Years marked with an asterisk are linearly interpolated from the original data points.

Note: The general category 'planted forest' is forest created through human intervention. A subset of planted forest is plantations: these consist of one or two species with an even age class and regular spacing and are not planted for ecological restoration purposes.

Source: UN FAO (2020a)

Modelled land use for renewable electricity production (cf. Section 6.1) is discussed in Annex C.6[59]. A principal conclusion that arises from this analysis is that, though biomass-based power contributes little to the overall electricity demand because it is not eligible to count towards RFNBO production, in three of the four scenarios it contributes the majority of electricity's land demand. This re-iterates the inefficiency of bio-based fuels' land footprint.

7.4.4. Resource consumption

In addition to consuming biomass feedstocks, biofuel production requires water, fertilisers, and pesticides for crop production, electricity for charging batteries and running electrolysers, CO_2 for PtL synthesis, and hydrogen for refining hydrocarbons. Then there are agricultural inputs: water, fertilisers, and pesticides for feedstock production. This section covers water and electricity demand, while demand for other resources is discussed in in Annex C.6.

Figure 37 shows the modelled water demand, in billion tonnes, for one of the scenarios, split into green (i.e. rainfed) and blue (abstracted/irrigated) components. It should be stressed that agricultural input requirements are heavily dependent on where and what time of year the crop is grown, and on farm management practices; the resource requirement presented here should be understood as indicative of a hierarchy and order of magnitude rather than an accurate quantification. Annex C.4.5 outlines the calculation and assumed parameters.

59 See also Annex C.4.4 which presents our assumptions on power production per unit area.

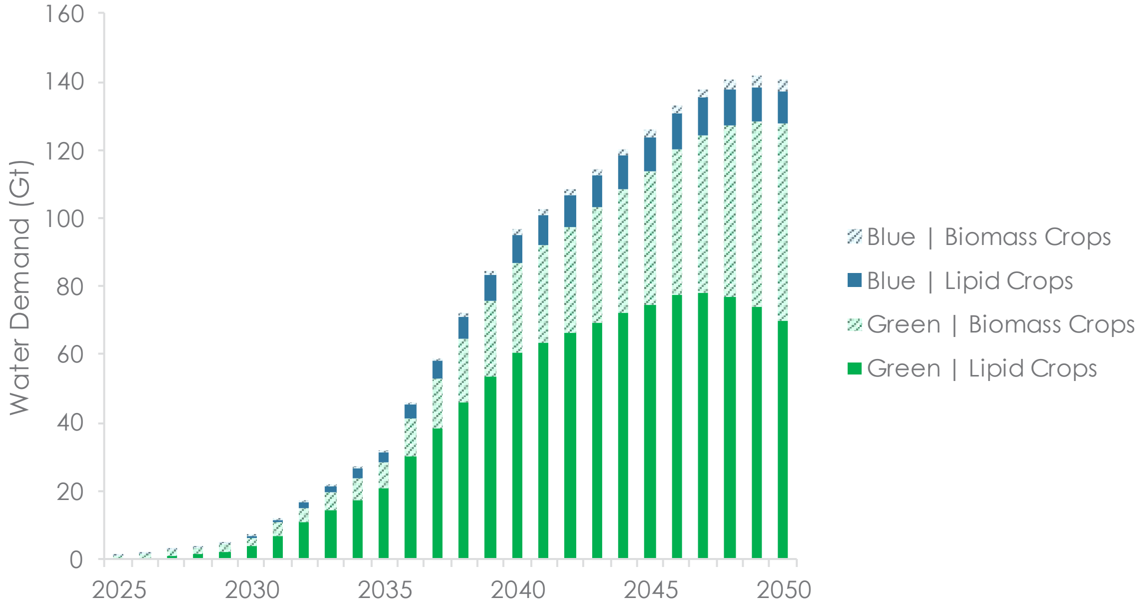


Figure 37. Modelled water demand for growing crops under the High RFNBO scenario

Note: 1 gigatonne (Gt) of water equates to a billion cubic metres.

Figure 38 compares the scenarios' electricity demand. At the high end, the 2050 consumption is comparable to the EU's current total renewable electricity supply[60], meaning that considerable new generation capacity will have to be built just to serve these segments. The carbon dioxide consumption implied by the scenarios increases approximately in line with electricity consumption, reaching into the tens of megatonnes per year by 2050 (see Annex C.6). This matches the proposed scale of EU ambition for carbon capture and sequestration: 50 Mt/year by 2050 (European Commission, 2023k).

60 In 2021 the EU generated about 550 TWh from the renewable sources wind, solar, and geothermal (Eurostat, 2024e).

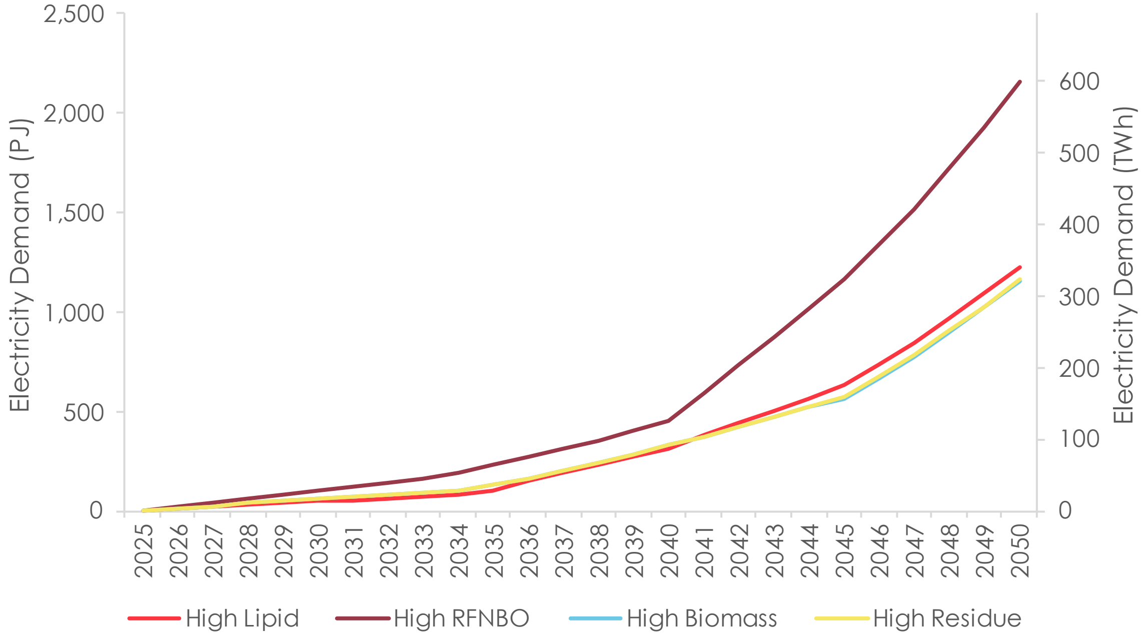


Figure 38. Annual consumption of electricity for battery charging and PtL production

Note: This does not include any electrolysis-derived hydrogen used for refining of other fuels. See Figure 51 in Annex C.6.

Requirements of other resources are discussed in Annex C.4.5; results are included in Annex C.6, as well as in the results tables in Chapter 8.

7.4.5. Exploring parameter ranges

This section explores the sensitivity of model results to some of our parameter assumptions. We consider three factors that can change the demand for land from the compliance scenarios:

1. the use of good- versus poor-quality agricultural land for biofuel feedstock production;
2. gains in crop yields; and
3. the potential for reductions in fuel consumption.

For the first analysis, we consider three 'sub-scenarios' for each of our four main scenarios. For all, the 'Standard' sub-scenario uses the same parameter settings as presented above and in Annex C.1, while in the other two sub-scenarios, feedstock is produced solely on good- or poor-quality agricultural land, with a commensurate yield advantage or penalty (Panoutsou et al., 2022).

The results shown in Figure 39 illustrate the obvious trade-off between quality of utilised land and the total area directly affected. Expanding on good, high-fertility agricultural land reduces the area needed, but is more likely to displace existing production systems and hence drive indirect land use changes. Bear in mind that one oft-cited advantage of second-generation biofuel feedstocks is that they can be grown on marginal land and hence avoid competition with food crops; but as discussed in Section 5.2.5, this is likely to conflict with biodiversity objectives where land identified as marginal is in fact semi-natural and of high biodiversity value. Thus, there may be cases where maximising the intensity of production may have biodiversity advantages.

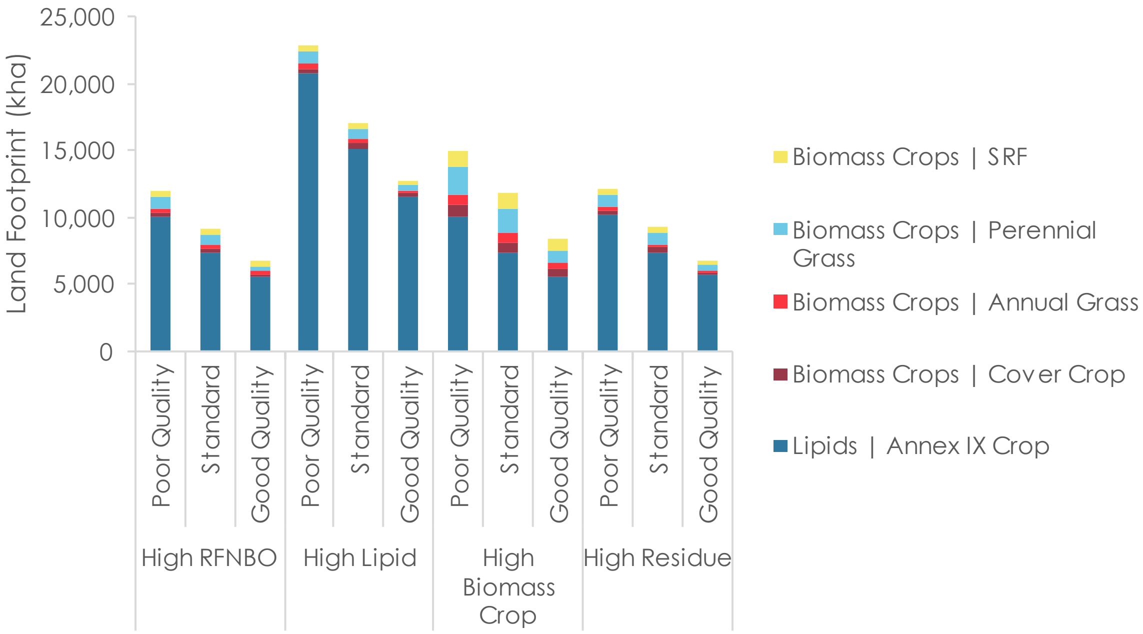


Figure 39. Affected land area for crop production in 2050 for all scenarios under three land quality assumptions

Note: Shown here is the land footprint – the total affected area discussed in Section 7.3.2. This could be broken down further to better reflect the particular ecological pressures exerted by additional land conversions and crop land intensification, as was done in Section 7.4.3.

Note: We do not include land harvested for cellulosic residues here as we assume that choices over where to locate the primary products (i.e. food crops and forest plantations) are not influenced by residue removal activities.

A related question is the extent to which boosting crop yields would be able to reduce land demand. Yield depends on the use of agricultural inputs and management strategies and selection from an evolving slate of crop varieties and can also be affected by land use change. It is uncertain how these factors will develop in future, and what their impact will be. For the purposes of this report, we consider an 'Optimistic' scenario in which we use the best-performing crop type within a given feedstock category as a proxy for all yields in that category; e.g. we use the relatively high-yielding rapeseed as the model Annex IX oilseed. In this sensitivity assessment the assumed geographical distribution and the balance between use of good- and poor-quality agricultural land is unchanged compared to the 'Standard' central versions of the scenarios.

As shown in Figure 40 for the High Lipids scenario, altering our yield assumptions significantly affects the land use results – a change of around 30% in 2050. For comparison, we also show the earlier results from Figure 39 on land quality. Figure 41 repeats the analysis for the High Biomass Crop scenario, where our higher yield assumption decreases land demand by 40%.

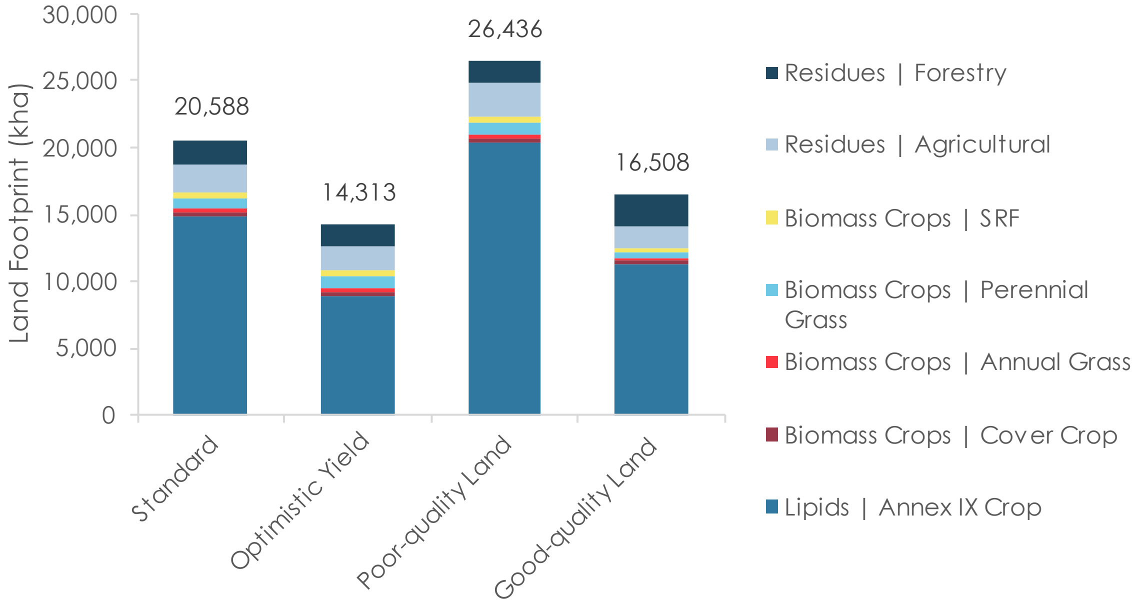


Figure 40. Land footprint in 2050 for the High Lipid scenario under different regimes of crop yield and land quality

Note: 'Standard' refers to the default scenario settings where a mix of crop and land types are used. 'Optimistic Yield' refers to a scenario where there are advances in crop yields. 'Poor-quality Land' and 'Good-quality Land' are as described in the previous analysis.

Note: For this graph we include residue collection in the affected land area.

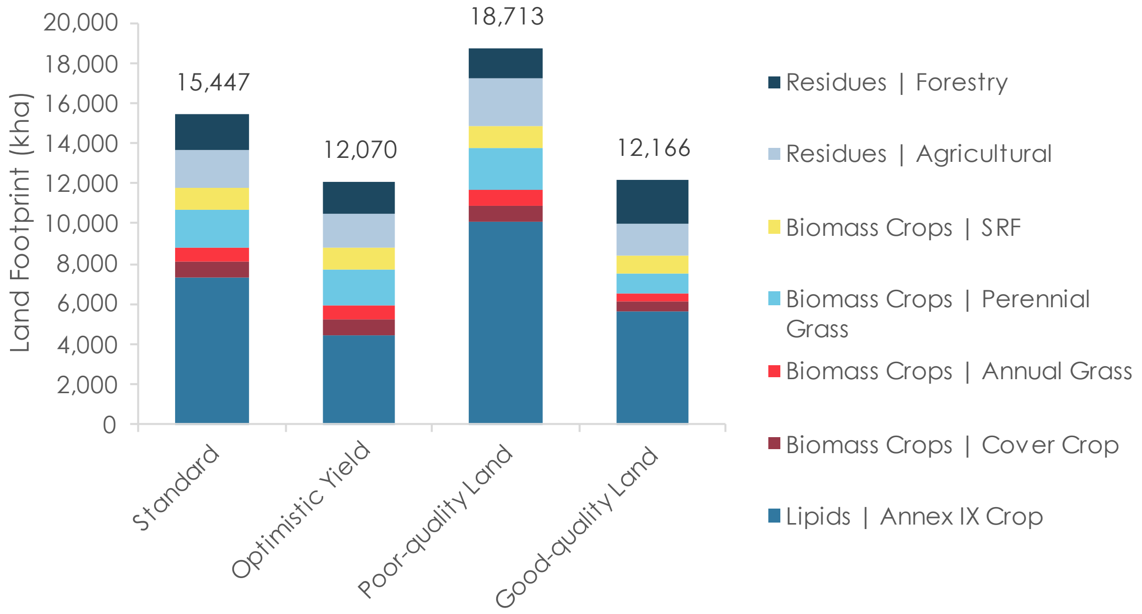


Figure 41. Land footprint in 2050 for the High Biomass Crop scenario under different regimes of crop yield and land quality

Note: See the note under Figure 40.

The third sensitivity analysis seeks to estimate the feedstock that could be saved and the land use that could be avoided if the EU were to lean a little more heavily on efficiency improvements and reductions in energy demand, going beyond what is envisaged in the projections underlying the four main scenarios (see Annex C.2). The parameters we consider are tabulated in Table 21.

There is evidence that each of these performance improvements would be achievable in principle; when stacked together, they give rise to a 33% reduction in aviation and maritime energy demand in 2050: over 1,400 PJ, as shown in Figure 42. This can be compared with the total 2050 energy demand from Figure 22 (about 1,860 PJ for aviation and 2,310 PJ for maritime), or the total biofuel demand (770 PJ and 1,610 PJ respectively in the High Lipid scenario, for example). Opportunities to reduce overall energy demand could in principle have implications for the land footprint of the modelled scenarios.

Table 21. Energy demand reduction parameters, with illustrative demand reduction factors (multiplicative) for 2050

Sector	Parameter	Reduction	Note
Aviation	Route optimisation	6%	Includes flight path, altitude, and speed optimisation[61]
	Air traffic volume	10%	Consumer behaviour changes in response to cost and loss of social acceptability
	Aircraft efficiency	11%	Fuel efficiency gains from improved materials, airframes, and jet engines[62]
Maritime	Slow steaming	21%	Slower speed cuts drag and fuel cost[63]
	Shipping volume	10%	Reduction in global demand for fossil fuels cuts shipping requirements[64]
	Vessel efficiency	8%	Improvements from the next generation of hull designs, drag control, and engines[65]
	Wind energy	2%	Enhanced use of modern sails substitutes fuel demand and reduces the emissions target

Note: The quoted parameters are multiplicative in the sense that if the original energy demand E and the reduction factor is x%, the final energy demand would be E×(100%–x).

61 Cf. Dallara (2011).

62 Cf. the scenarios in Owen et al. (2010). Note that efficiency improvements in recent decades (estimated at 39% between 2005-19) have relied in part on increasing the number of seats per aircraft and the seat occupancy, and there is limited scope for pushing this further (Esqué et al., 2022).

63 In an idealised system, the propulsive power required to maintain a steady speed in the presence of drag is proportional to the speed cubed, and the energy expended over the entirety of a journey is proportional to the speed squared. A small speed reduction can therefore have an outsized impact on fuel consumption in real-world voyages, as quoted in (Farkas et al., 2023). Here, we imagine a 10% average speed reduction in 2050. For aeroplanes the relationship between speed and drag is more complex.

64 It has been estimated that 20% of Europe's shipping is for fossil fuels (Abbasov et al., 2019).

65 (DNV Maritime, 2023, Figure 4-1)

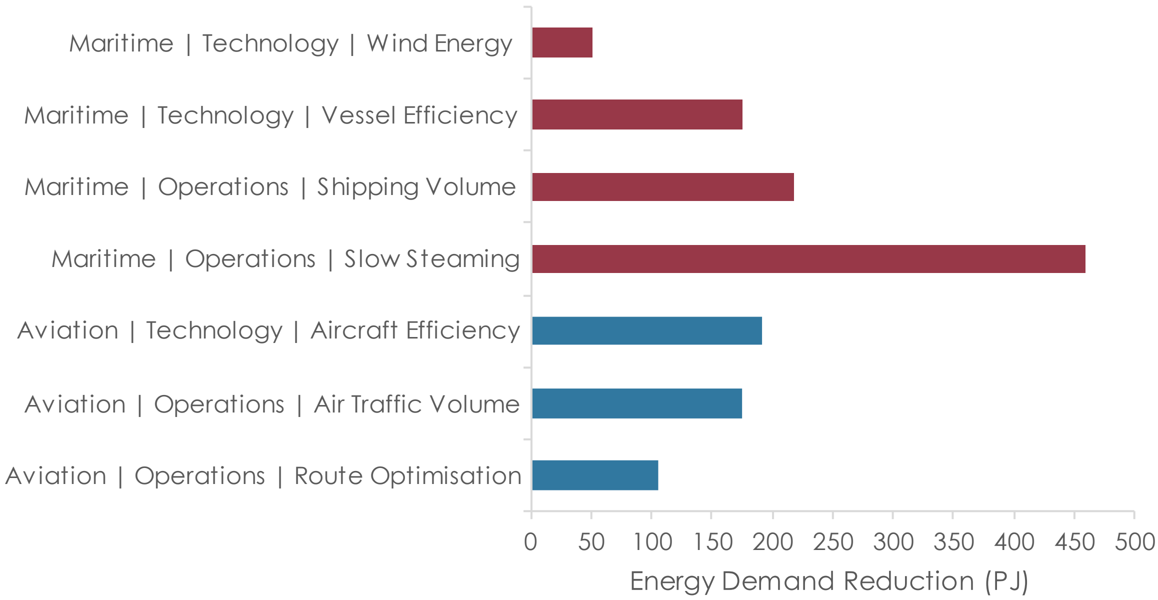


Figure 42. Reduction in energy use, attributed to the factors shown in Table 21

8. Connecting demand to risk

This section characterises the biodiversity risks associated with delivering the targets set by ReFuelEU Aviation and FuelEU Maritime under each of the four compliance model scenarios (as described in Table 16).

8.1. Risk categories

We assess and evaluate the expected biodiversity risk across a set of categories and rank them on a scale of 'Low' to 'Very High'. This system is used to consider the implications of the use of different feedstocks as part of the EU's fuel mix. Table 22 provides descriptions for each of the risk categories.

The risk-based approach allows us to evaluate the potential biodiversity impacts of different energy production pathways in a systematic and transparent manner. We recognise that biodiversity risks are not uniform and vary according to the type, scale, and intensity of the energy production methods used. Our approach helps to identify where the most significant risks lie, and which scenarios or practices may require more stringent management or mitigation measures to align with EU biodiversity goals. Given the complex interplay between various energy production practices and biodiversity, a risk-based framework allows for a nuanced understanding of potential threats and can help guide decision making toward pathways that minimise negative impacts.

The ranks for biodiversity risk are assigned as follows:

- Low – minimal risk, no significant tension with biodiversity goals, with little expected effect on biodiversity or the environment at the EU scale.
- Moderate – noticeable risk, in tension with biodiversity goals, with some potential effects on biodiversity and / or the environment that are manageable with proper practices.
- High – significant risk, likely to make biodiversity goals significantly more difficult to deliver, with potentially substantial effects on the environment or biodiversity, including species and habitats of particularly high nature conservation importance (e.g. those listed in Annexes I, II, IV and V of the Habitats Directive and Annex II of the Birds Directives) that require careful management to mitigate.
- Very High – severe risk, almost certain to make biodiversity goals significantly more difficult to deliver, with potential for profound and irreversible effects on the European environment and biodiversity, including species and habitats of particularly high nature conservation importance, that would be very difficult to mitigate.

Some risk categories have quantitative dimensions in their rank assignment. For instance, Table 23 provides examples of how biodiversity risks are assigned ranks for additional land demand (which drives land use change and habitat conversion), while Table 24 applies to land use intensification (which increases the pressure on land for instance through increased harvesting from existing systems). The severity of the assessed risk is dependent on scale, as changes in land use drive habitat degradation, which have the most significant overall impact on biodiversity. In practice, the impact will be dependent on both scale and on the adopted practices, but in the absence of legislation that would enforce the adoption of best practices for biodiversity protection we have treated a larger scale of operation as a higher risk. Description tables for ranks assignment for the other risk categories (as described in Table 22) can be found in Annex D.

Table 22. Biodiversity risk categories for bioenergy and renewable energy developments

Risk Category	Description	Relevance to Biodiversity
Additional land demand	The amount of land required for additional biomass cropping for the different energy production scenarios	Large-scale land uses have a major influence over ecosystems, landscapes, and habitat diversity, affecting species populations by causing habitat fragmentation and degradation.
Intensification of land use	The amount of land subjected to increased agricultural or forest management intensity through productive cover cropping or residue harvesting	Intensification often involves increased pressure on land, including increased harvesting and use of more inputs (such as fertilisers, pesticides and water), which can degrade habitat quality, decrease soil health and result in biodiversity loss due to decreased resource availability.
Pollution	Assesses the risk and extent of pollution resulting from energy production practices	Pollution from nutrient-rich agricultural runoff, pesticides, and herbicides can harm aquatic and terrestrial life, leading to declines in biodiversity.
Invasive species	Evaluates the likelihood of bioenergy crops or practices introducing invasive species	Introduction of non-native species can outcompete native species, leading to declines in biodiversity.
Soil health	Assesses the impact on overall soil health	Healthy soils are critical for supporting diverse plant and animal communities, degradation can reduce soil fertility and ecosystem functions.
Water demand	Measures the water requirements for energy production	Water is a crucial resource for plant and animal species, and high demand can exacerbate water scarcity issues, impacting biodiversity.
Fertiliser consumption	Evaluates the input of fertilisers required for bioenergy systems and their potential impacts	High fertiliser use can have consequences for species, and degrade soil and water quality, impacting biodiversity more broadly.
Pesticide consumption	Evaluates the input of pesticides required for bioenergy systems and their potential impacts	High pesticide use can degrade soil and water quality, with adverse consequences for species, and ecosystem health.
Indirect land use change	Evaluates the risk of secondary impacts on land use due to increased demand for crops or practices	Indirect land use change can lead to habitat loss and fragmentation, displacement of other land uses and competition for land resources, all of which can impact biodiversity.

For additional land demand (Table 23), our threshold values consider estimates of available marginal (Section 5.2.5) and agricultural lands that are likely to become abandoned (Section 5.2.4) in the EU, which could potentially be used for renewable energy generation. Allen et al. (2014) estimates that up to 1.5 Mha of marginal land could be further explored for energy production, though the authors acknowledge that their estimate may not capture some areas that are difficult to map. Additionally, an estimated 4.8 Mha of agricultural land is expected to be abandoned by 2030 (Perpiña Castillo et al., 2018), though only some of this is likely suitable for energy generation. Given the clear connection between additional land use and habitat loss, and the associated biodiversity impacts, we have set our 'very high' biodiversity risk threshold at over 3 Mha of additional land demand. The upper estimate of 1.5 Mha by Allen et al. (2014) follows a somewhat more precautionary approach and has been used as the threshold for 'high' biodiversity risk. This approach reflects the need to minimise land conversion and avoid driving further habitat loss and fragmentation in support of energy generation, which could significantly undermine the EU's biodiversity goals.

For land use intensification (Table 24), we base our threshold values on the combined total of the EU's utilised agricultural area (UAA), which was 161,000 kha in 2022 (Eurostat, 2024h), and the planted forest area, which is estimated at 53,000 kha (UN FAO, 2020a). Intensifying land use across 10% of this combined area (total of 214,000 kha) would pose substantial risks, including habitat degradation, reduction in resource availability, increased inputs of pesticides and fertilisers, and alterations to hydrological regimes. This integrated approach considers the full spectrum of risk posed by land use intensification, spanning both agricultural and forest lands. As such, we set out highest risk category for land use intensification at 10% of this total. This threshold also provides a precautionary indicator of biodiversity risk at a landscape scale.

Whilst modest increases in land demand for bioenergy crops and other feedstocks might be accommodated within existing agricultural systems, large-scale production will require widespread changes in crop type and is also likely to drive intensification. This would be highly detrimental for biodiversity if it leads to the loss of highly biodiverse and threatened semi-natural habitat types and species, including habitats and species protected under the Habitats and Birds Directives. Risks are particularly high where bioenergy crops are suited to marginal agricultural lands, resulting in direct habitat change. Although production in Natura 2000 sites should be constrained by their protection regime, this is not always the case in practice. Large areas of semi-natural habitat protected under the directives also occur outside the protected area network. There is also a risk of the loss of highly biodiversity habitats on marginal farmland due to indirect land use change, which could extend into Natura 2000 sites by driving incremental changes in farming systems and intensification that could be difficult to control and lead to significant cumulative habitat degradation.

Table 23. Ranking biodiversity risk based on additional land demand for bioenergy and renewable energy developments

Rank	Values (kha)	Description	Examples
Low	< 500	Limited additional land required; no significant change in land use patterns	Utilisation of existing intensive agricultural lands with slight modifications (e.g., reduced tillage, cover cropping) Use of existing intensive agricultural land for dual-purpose systems (e.g., agrivoltaics) Small-scale integration of bioenergy crops into existing intensive agricultural systems without the need for expansion Low-intensity agroforestry systems combining tree crops with intensive agricultural systems Use of urban and semi-urban areas, such as brownfields, for bioenergy and renewable energy generation
Moderate	501-1,500	Some additional land required, leading to noticeable land use change, with potential displacement of habitats	Conversion of some marginal agricultural lands of low biodiversity value to bioenergy crops Expansion of bioenergy crops into non-agricultural land of low biodiversity value Introduction of bioenergy crops in rotation with food crops, potentially leading to temporary displacement of existing uses
High	1,501-3,000	Significant additional land required, causing major changes in land use, with high risk of loss of biodiverse habitats	Significant conversion of arable land into energy crops resulting in ILUC. Significant conversion of semi-natural grasslands and other biodiverse habitats to bioenergy. Conversion of multi-use landscapes and diverse ecosystems into single-use bioenergy monocultures.
Very High	>3,001	Extensive additional land required, leading to profound changes in land use, with inevitable loss of habitats and biodiversity	Large-scale clearance of biodiverse habitats for biomass crops Large scale intensification of land use disrupting existing land uses and degrading biodiverse habitats and associated species

Table 24. Ranking biodiversity risk based on land use intensification for bioenergy and renewable energy developments

Rank	Values (kha)	Description	Examples
Low	< 1500	Limited intensification required, with minimal changes in management intensity.	Utilisation of existing intensive agricultural lands with slight modifications (e.g., reduced tillage, cover cropping) Introduction of dual-purpose systems on already intensively managed lands (e.g., intercropping with minimal impact) Maintaining low-intensity agroforestry or silvopastoral systems without significant increases in chemical or water inputs
Moderate	1501-7,500	Some intensification of land management practices, leading to moderate changes in management practices.	Conversion of some existing agricultural lands to more intensive cropping systems, including the introduction of high-yielding varieties Implementing more frequent harvesting or higher-density planting on existing lands to increase biomass production Introduction of bioenergy crops in rotation with food crops.
High	7,501-20,000	Significant intensification required, causing significant changes in land use management.	Shifting from low intensity grazing or traditional farming systems to intensive monoculture bioenergy plantations Intensification that leads to reduced crop diversity and habitat heterogeneity, affecting associated biodiversity
Very High	>20,001	Extensive intensification required, leading to extensive changes in management practices.	Large scale intensification of land use disrupting existing land uses degrading biodiverse habitats and associated species Intensification in sensitive areas, resulting in widespread degradation and loss of biodiversity

The underlying premise of this report is that the decarbonisation targets of ReFuelEU Aviation and FuelEU Maritime can be satisfied in a number of ways; each potential pathway will have its own benefits and pose its own set of challenges and degrees of biodiversity risk that would not exist in the absence of the EU regulations.

The findings of our assessments for the decarbonisation scenarios are presented in Sections 8.2 to 8.5. We consider biodiversity risks in the years 2030 and 2050, which are significant for many aspects of the EU's policy landscape for climate and biodiversity; particularly the EU's Biodiversity Strategy (Section 4.2.2) and Nature Restoration Regulation (Section 4.2.3). This analysis is done under the assumption that no additional governance measures are implemented beyond the current regulatory framework –improved governance could reduce biodiversity risk.

8.2. High RFNBO scenario

The High RFNBO scenario emphasises the deployment of liquid and gaseous RFNBOs based on renewable energy and leads to a substantial increase in renewable electricity demand. Table 25 shows that the contribution of RFNBOs to the total fuel energy mix increases from 45 PJ in 2030 to 1,492 PJ by 2050, with the relative contribution of RFNBOs to the overall fuel mix increasing from 1 to 36%. Biofuels made from lipids, biomass crops, and residues will also contribute, resulting in the increasing feedstock demand shown in Table 26.

Table 25. Consumption of each fuel type and percentage contribution to total energy supply in 2030 and 2050 under the High RFNBO scenario

Fuel Type	2030			2050		
	PJ	Mtoe	% of total	PJ	Mtoe	% of total
RFNBOs	45	1.1	1%	1,492	35.7	36%
Lipids	114	2.7	3%	644	15.4	15%
Biomass Crops	17	0.4	0%	475	11.3	11%
Residues	17	0.4	0%	440	10.5	11%

Note: Percentage is of total energy demand, including other alternative fuels and conventional fossil fuels.

Table 26. Biofuel feedstock demand in the High RFNBO scenario

Fuel Type	Unit	2030	2050	Increase 2030-50
Lipids	Mt	3.1	17.7	5.7x
Biomass Crops	Mt	1.3	34.5	27.3x
Residues	Mt	1.4	35.0	24.8x

Table 27 presents the biodiversity risk results for the modelled scenario. To support the increase in demand between 2030 and 2050, RFNBO production must increase 30-fold, reaching a land demand of 225 kha for new solar, wind, and geothermal installations – roughly the size of Luxembourg. A comparable amount of land is required for producing a relatively modest amount of electricity for direct supply to aeroplanes and ships; this is driven by the bioenergy component of the grid and renewables mix.

Although all this land must come from somewhere and could still impact habitats and species, the land required to support RFNBOs is far less (by an order of magnitude) than that affected by the biofuel feedstocks that are needed to supply a similar amount of energy in 2050: 17,138 kha, approaching the land area of Belarus. Of this, over 1,400 kha would need to come from additional land rather than intensification of activity on existing crop land and managed forests. In the EU and globally, additional cropland expansions are likely to encroach on biodiverse semi-natural grasslands and abandoned agricultural land: as a reference point, the GLOBIOM modelling concludes that agricultural expansion stimulated by production of biofuels from perennial grasses will be roughly one third from abandoned agricultural land and two thirds from natural land not classed as grassland (Valin et al., 2015). This land use change results in the 'High' land use impact reported in Table 27.

As a further comparison point, the EU-27's utilised agricultural area (UAA) in 2022 was about 161,000 kha (Eurostat, 2024h), and the planted forest area (PFA) was about 53,000 kha (UN FAO, 2020a)[66]. In the High RFNBO scenario in 2050, under our assumptions about average crop yield, about 0.9% of this UAA would be required for additional agricultural land[67]. Just under 5% of UAA would be affected by intermediate cropping, and 4.7% by crop residue collection, meanwhile 6.5% of PFA would have some form of residue collection (all contributing to land use intensification).

Table 27. Biodiversity risk assessment of High RFNBOs scenario

Risk Category	Quantity	2030	2050
Additional land demand (kha)	Electricity for RFNBOs	9	225
	Electricity for direct supply	104	228
	Additional agricultural land	37	1,474
	Risk	Low	High
Land use intensification (kha)	Crop intensification	719	6,133
	Residue harvesting	327	9,531
	Risk	Low	High
Pollution	Risk	Low	Moderate
Invasive species		Low	Moderate
Soil health		Low	Moderate
Water demand (Mt)	Total	6,839	140,532
	Risk	Moderate	High
Fertiliser consumption (kt)	Total	65	773
	Risk	Low	High
Pesticide consumption (kt)	Total	2	23
	Risk	Low	High
Indirect land use change	Risk	Low	Moderate

Note: Water demand for electrolysis and fuel conversion is small enough to be neglected; so, the reported water demand is for crop production.

66 We use the PFA as our comparison point rather than the total forest area (cf. Figure 35) in recognition of the fact that harvesting of ligno-cellulosic residues is likely to take place in more intensively managed areas close to transport infrastructure.

67 Recall from Table 18 that this includes new land needed for crops (perennial and annual grasses) and for SRF.

For this scenario, the risk of invasive species is low in 2030 and moderate by 2050. This is not due to the use of RFNBOs, which are non-biological by nature, but more characteristic of the use of biomass crops, which increase in scale to contribute to the overall fuel mix between 2030 and 2050, and for which several species pose invasive risk.

Total agricultural water demand increases from 6,839 Mt in 2030 to 140,532 Mt in 2050 (water demand for RFNBO production and fuel conversion is deemed negligible and is not reported). EU fertiliser consumption rises from around 65 kt in 2030 to 770 kt in 2050, with the risk to biodiversity moving from moderate to high. Pesticide use also increases from 2 kt in 2030 to 23 kt in 2050[68]. The environmental costs of increased fertiliser use include nutrient runoff and water pollution, as well as potential contamination of soil and water ecosystems for pesticides.

8.3. High Lipid scenario

The High Lipid scenario emphasises a significant increase in the use of lipids to meet energy targets. The approach significantly increases demand for waste and residual oils such as used cooking oil (UCO) and rendered animal fats, as well as the development of Annex IX compliant intermediate oilseed crops. Table 28 shows that in the High Lipid scenario, these will account for 30% of total aviation and maritime fuel consumption in 2050. Table 29 shows that demand for lipid feedstock grows to 4.1 Mt in 2030 and 34.3 Mt in 2050. Between 2030 and 2050, demand for other fuels increase too, as seen in Table 28: the fuel energy contribution of RFNBOs reach 10 PJ and 833 PJ in 2030 and 2050 respectively; 1.2 Mt and 37.9 Mt for biomass crops, and 1.3 Mt and 38.2 Mt for residues.

Table 28. Consumption of each fuel type and percentage contribution to total energy supply in 2030 and 2050 under the High Lipid scenario

Fuel Type	2030			2050		
	PJ	Mtoe	% of total	PJ	Mtoe	% of total
RFNBOs	10	0.2	0%	833	19.9	20%
Lipids	152	3.6	4%	1,240	29.6	30%
Biomass Crops	16	0.4	0%	522	12.5	12%
Residues	16	0.4	0%	482	11.5	11%

Note: Percentage is of total energy demand, including other alternative fuels and conventional fossil fuels.

68 Many bioenergy crops, such as miscanthus, have relatively low input requirements, and in cases where they replace more intensively-farmed crops on a given plot of land, one would expect pesticide and fertiliser use on that land to diminish. However, as discussed elsewhere, we assume that this would just move production of the original crop – and its commensurate input usage – elsewhere, so the global input usage can only increase because of renewable energy policy.

Table 29. Biofuel feedstock demand in the High Lipid scenario

Fuel Type	Unit	2030	2050	Increase 2030-50
Lipids	Mt	4.1	34.3	8.3x
Biomass Crops	Mt	1.2	37.9	32.2x
Residues	Mt	1.3	38.2	29.2x

The impact of the High Lipid scenario on land is substantial, much more so than the High RFNBO scenario we explored previously. A share of lipid fuel is made from residual oils and fats[69], but most of the increase in lipid feedstock must come from intermediate oilseeds which are presumptively going to be planted as off-season crops in productive, already-farmed areas. This means that land use change is not as large a concern as it will be in the High Biomass Crop scenario below, but there will be impacts from agricultural intensification. To support the increase in demand for lipids, the area of existing land use increases to 1,206 kha in 2030 and to 13,874 kha in 2050. This is a momentous increase, surpassing the land area of Greece. Nowadays, cover crops are generally grown for environmental reasons, however, the utilisation of these crops for bioenergy is likely to drive significant land use intensification, especially, as additional inputs are required to support productive intermediate crops in areas that are already farmed.

Using the same UAA/PFA comparison points as in the previous section, the High Lipid scenario in 2050 would need an additional 1.0% of present UAA for additional crop land. Nearly 10% of UAA would be affected by intensification (i.e. intermediate cropping), and just over 5% by crop residue collection. For forest residue harvesting, about 7.1% of PFA would be affected.

69 See Figure 25, which shows the relative contributions. Recall that pushing the import of residual oils consumption beyond existing levels risks further depriving existing markets of usable feedstock. Replacing the original feedstock with some alternative crop-based feedstocks will result in ILUC. At the same time, this scenario envisions a huge scale-up in Annex IX compliant intermediate oilseeds which is illustrative but not entirely realistic.

Table 30. Biodiversity risk assessment of High Lipids scenario

Risk Category	Quantity	2030	2050
Additional land demand (kha)	Electricity for RFNBOs	2	126
	Electricity for direct supply	104	228
	Additional agricultural land	34	1,617
	Risk	Low	High
Land use intensification (kha)	Crop intensification	1,206	13,874
	Residue harvesting	304	10,411
	Risk	Moderate	Very High
Pollution	Risk	Moderate	High
Invasive species		Low	Moderate
Soil health		Moderate	High
Water demand (Mt)	Total	9,665	231,428
	Risk	Moderate	Very High
Fertiliser consumption (kt)	Total	100	1,375
	Risk	Low	Very High
Pesticide consumption (kt)	Total	4	46
	Risk	Low	Very High
Indirect land use change	Risk	Moderate	High

The contribution of biomass crops to the overall fuel mix also grows; this will add to intensification pressure as well as agricultural expansion to new areas and will drive an increase in pollution risk from moderate in 2030 to high in 2050, due to likely increases in agricultural runoff from increased inputs and intensified practices.

The risk of invasive species is low in 2030 and moderate by 2050. Our research did not identify evidence of invasiveness risk for the candidate Annex IX lipid crops; the biomass crops in the fuel mix are more responsible for driving invasiveness risk in this scenario. This scenario also has significant demand for resources, with total water demand rising from 9,665 Mt in 2030 to 231,428 Mt in 2050. 10% of this demand will require irrigation. Oilseeds tend to require more careful cultivation than cellulosic crops, and so the additional fertiliser and pesticides used to produce feedstocks for aviation and maritime biofuels in this scenario are relatively high. Additional fertiliser reaches 100 kt in 2030 and 1,375 kt in 2050; pesticide reaches around 4 kt in 2030 and 46 kt in 2050 – double the values in the other scenarios. These results imply increased nutrient runoff and soil degradation, as well as environmental contamination and risks to non-target species populations.

8.4. High Biomass Crop scenario

The High Biomass Crop scenario focusses on the extensive use of cellulosic biomass material from energy crops: cover crops, annual crops, perennial grasses, and short rotation forestry. In this scenario, biomass crops contribute 28% of energy demand in 2050 (1,187 PJ), with a total feedstock demand of 4.2 Mt in 2030 to 86.3 Mt in 2050. This is shown in Table 31 and Table 32.

Table 31. Consumption of each fuel type and percentage contribution to total energy supply in 2030 and 2050 under High Biomass Crops scenario

Fuel Type	2030			2050		
	PJ	Mtoe	% of total	PJ	Mtoe	% of total
RFNBOs	19	0.5	0%	786	18.8	19%
Lipids	98	2.4	3%	648	15.5	15%
Biomass Crops	58	1.4	2%	1,187	28.4	28%
Residues	17	0.4	0%	442	10.6	11%

Note: Percentage is of total energy demand, including other alternative fuels and conventional fossil fuels.

Table 32. Biofuel feedstock demand in the High Biomass Crop scenario

Fuel Type	Unit	2030	2050	Increase 2030-50
Lipids	Mt	2.7	17.8	6.7x
Biomass Crops	Mt	4.2	86.3	20.3x
Residues	Mt	1.4	35.1	24.5x

To meet this demand, Table 33 shows that the additional land required for biomass crops increases from 124 kha in 2030 to 3,683 kha in 2050. This is the greatest new land requirement of any of the scenarios, equal roughly to the size of Belgium. This would likely stimulate the conversion of abandoned lands and lands farmed at lower intensity (considered to be High Nature Value farmland) to crop production[70], with the associated disruptions of on-site and neighbouring ecosystems and potential for indirect land use change when existing uses are displaced. Meanwhile, there is also a sizeable level of intensification on existing cropped land, rising to 554 kha in 2030 and 4,446 kha in 2050.

Using the same UAA/PFA comparison points as in the two preceding sections, the High Biomass Crop scenario in 2050 has heavier requirements for additional crop land, reaching 2.3% of present UAA in 2050. As with the High RFNBO scenario, about 5% apiece of UAA would be needed for crop intensification and residue collection; and 6.6% of PFA would be affected by forest residue harvesting.

70 We point once again to the GLOBIOM result that global agricultural expansion of perennial grasses is split with roughly one third coming from abandoned agricultural land and two thirds from natural land not classed as grassland (Valin et al., 2015).

Table 33. Biodiversity risk assessment of High Biomass Crop scenario

Risk Category	Quantity	2030	2050
Additional land demand (kha)	Electricity for RFNBOs	4	118
	Electricity for direct supply	104	228
	Additional agricultural land	124	3,683
	Risk	Low	Very High
Land use intensification (kha)	Crop intensification	554	4,446
	Residue harvesting	246	7,373
	Risk	Low	High
Pollution	Risk	Moderate	High
Invasive species		Moderate	Very high
Soil health		Moderate	High
Water demand (Mt)	Total	11,745	232,861
	Risk	High	Very High
Fertiliser consumption (kt)	Total	79	1,127
	Risk	Low	Very High
Pesticide consumption (kt)	Total	2	24
	Risk	Low	High
Indirect land use change	Risk	Moderate	High

It is important to note that not all biomass crops pose the same level of risk to soil health. Perennial grass crops, such as miscanthus and switchgrass, are likely to have a lower impact on soil health compared to annual grasses like sorghum. Perennial grasses have deep root systems that can improve soil structure and promote carbon sequestration, with less frequent soil disturbance than annual crops. Meanwhile, annual crops necessitate yearly replanting, more frequent tillage and / use of machinery, and higher input use (fertilisers, pesticides), which can accelerate soil degradation and increase habitat disruption. Therefore, the risks associated with the High Biomass Crop scenario are particularly pronounced for the annual grass components, where practices will be more intensive than with perennial grasses

Additionally, the crops favoured in this scenario pose the highest invasiveness risk: in our categorisation, this increases from high in 2030 to very high by 2050. Carboneras et al. (2018) identified several biomass crops with invasive risk in the EU, including giant reed (*Aundo donax*) – a perennial grass, sugar beet (*Beta vulgaris*) and biomass sorghum (*Sorghum bicolor*) – both used as annual energy crops, and several species of poplar (*Populus* spp.) and willow (*Salix* spp.) which are used in SRF.

Total demand for water (both blue and green) increases from 11,745 Mt in 2030 to 232,861 Mt by 2050. This substantial increase underscores the higher water requirements of biomass crops and may represent a strain on local water resources and the availability of water for local ecosystems. Meanwhile, fertiliser use rises from 79 kt in 2030 to over 1.1 Mt in 2050, with significant implications for soil and water quality. Pesticide use increases from under 2 kt in 2030 to 24 kt in 2050, also posing a significant risk to biodiversity.

8.5. High Residue scenario

The High Residue scenario focusses on the use of ligno-cellulosic residues and wastes from agriculture, forestry, and industry for bioenergy production. Table 34 shows residue-based biofuels accounting for 27% of energy consumption in aviation and maritime in 2050, while in Table 35 we see these sectors' residue feedstock demand increasing from 1.4 Mt in 2030 to 27.2 Mt in 2050. While some of this will come from industrial materials with a negligible land footprint, the scenario nevertheless necessitates a rapid scale-up of harvesting from existing land, covering 1,183 kha in 2030 and rising to 26,977 kha in 2050 – see Table 36. This is impacting an area larger than the UK, and while the utilisation of forest and agricultural residues and other biomass wastes does not trigger additional demand for land, significant areas of land will be affected by the intensification of management practices. The primary concern here is related to soil impacts and resulting habitat degradation rather than outright habitat loss, although this would have implications for resource availability.

Table 34. Consumption of each fuel type and percentage contribution to total energy supply in 2030 and 2050 under High Residue scenario

Fuel Type	2030			2050		
	PJ	Mtoe	% of total	PJ	Mtoe	% of total
RFNBOs	19	0.5	0%	789	18.9	19%
Lipids	98	2.4	3%	653	15.6	16%
Biomass Crops	17	0.4	0%	480	11.5	11%
Residues	58	1.4	2%	1,140	27.2	27%

Note: Percentage is of total energy demand, including other alternative fuels and conventional fossil fuels.

Table 35. Biofuel feedstock demand in the High Residue scenario

Fuel Type	Unit	2030	2050	Increase 2030-50
Lipids	Mt	2.7	18.0	6.7x
Biomass Crops	Mt	1.3	34.9	27.2x
Residues	Mt	4.7	90.5	19.2x

The other biofuel components of the fuel mix impose further land demands: 1,491 kha of additional crop land, and 6,254 kha of intensification on existing crop land in 2050. The former category – which reaches a similar level for all scenarios except the High Biomass Crop scenario where it is much greater – is as already discussed likely to impinge upon a variety of unused and lower-grade crop land which could drive the loss of biodiverse semi-natural habitats and associated species.

In terms of UAA and PFA, 12.1% of UAA and 16.9% of PFA would be affected by residue harvesting in this scenario. This takes the pressure off the other land uses, with only 0.9% of current UAA needed as additional agricultural area, and 4.8% of UAA being brought under intensified management.

Table 36. Biodiversity impact assessment of High Residue scenario

Risk Category	Quantity	2030	2050
Additional land demand (kha)	Electricity for RFNBOs	4	119
	Electricity for direct supply	104	228
	Additional agricultural land	38	1,491
	Risk	Low	High
Land use intensification (kha)	Crop intensification	494	6,254
	Residue harvesting	1,183	26,977
	Risk	Moderate	Very High
Pollution	Risk	Low	Low
Invasive species		Low	Moderate
Soil health		Moderate	Very High
Water demand (Mt)	Total	5,507	142,728
	Risk	Moderate	High
Fertiliser consumption (kt)	Total	48	785
	Risk	Low	High
Pesticide consumption (kt)	Total	2	23
	Risk	Low	High
Indirect land use change	Risk	Low	Low

Pollution risk remains low throughout both 2030 and 2050, as the scenario relies more heavily on existing agricultural and forestry systems. Similarly, the risk of invasive species is low in 2030, given the limited introduction of new species into the environment under this scenario. However, characteristic of the use of biomass crops, which increase in scale to contribute to the overall fuel mix between 2030 and 2050, and for which several species pose invasive risk, the risk increases to moderate in 2050. Additionally, there are significant implications for soil health due to the potential depletion of nutrients and carbon from residue removal. While the impacts are assessed as moderate in 2030, by 2050, this risk escalates to very high. This is due to increased residue harvesting, which can negatively affect long-term soil fertility, ecosystem health and soil biodiversity.

It is important to highlight that the long-term impacts on soil health from residue removal can extend beyond immediate nutrient loss. Continuous extraction of agricultural residues could lead to a decline in soil organic carbon stocks, which is critical for maintaining soil structure, water retention, and microbial activity. A decrease in soil organic carbon could also undermine the sustainability of farming systems by reducing crop productivity and resilience to environmental stresses. Further, declining soil carbon stocks could have significant implications for GHG emissions, as soils are a major carbon sink. If residue removal practices lead to a net loss of soil carbon, this could negate the carbon savings that biofuels are meant to achieve, thereby undermining the rationale for using residues for renewable energy.

This concern is compounded by the fact that soil carbon changes are not always accurately represented in national inventories or carbon accounting frameworks, such as those under the Land Use, Land Use Change, and Forestry (LULUCF) regulation. As a result, the negative impacts of soil carbon loss could be overlooked, allowing biofuels derived from residue removal to be marketed as a sustainable option despite their potentially detrimental effects on both soil health and GHG balances. For more detailed discussion on the limitations of current soil carbon accounting practices, please refer to Section 4.3.8.

Total water demand is lower than in the other biofuel-dominated scenarios: 5,507 Mt in 2030 and 142,728 Mt in 2050. This lower demand is primarily due to the expansion of the biomass crops, which contribute to the fuel mix. Residue use itself does not significantly impact water demand. Fertiliser consumption is 48 kt in 2030 and rises to 785 kt in 2050 – again lower than the other biofuel-dominated scenarios. This increase is tied to the intensification of agricultural practices needed to support higher yields for biomass and lipid crops. Pesticide consumption totals less than 2 kt in 2030, increasing to 23 kt by 2050. The rise in pesticide use is linked to the need to protect intensified biomass crop production from pests, but this also poses significant risks to non-target species and overall biodiversity.

9. Conclusions and recommendations

In this final section of the report, we draw together findings from the scenario analysis to consider the specific tensions between our scenarios and meeting targets set by the EU's decarbonisation policies for aviation and maritime and those for protecting biodiversity. We explore strategies to mitigate negative effects and deliver co-benefits, consider how future EU policy may influence these pathways and identify opportunities for stakeholders to engage with the key issues. Finally, we provide actionable recommendations to ensure that meeting the targets set by ReFuelEU Aviation and FuelEU Maritime can be compatible with biodiversity conservation, nature restoration and sustainable development.

9.1. Implications for EU biodiversity goals

Our analysis across the four scenarios reveals substantial and varied risk on biodiversity. This means that the extent to which the energy production pathways align or conflict with the EU's biodiversity goals varies too. The overarching ambition of the Biodiversity Strategy is to ensure biodiversity is on the road to recovery by 2030. However, our findings clearly indicate that none of the scenarios are readily compatible with meeting these targets. Significant biodiversity impacts are almost inevitable if the ReFuelEU Aviation and FuelEU Maritime targets are pursued without substantial additional mitigation measures.

The High RFNBO scenario (see Table 27 for the scenario summary) is most compatible with EU biodiversity goals, as renewable electricity production requires significantly less land than any of the bioenergy pathways. There is still some risk involving land use change, particularly if new infrastructure encroaches on protected areas, although these risks could be mitigated with careful planning in both marine and terrestrial areas, such as appropriate site selection and avoiding sensitive habitats. Conversely, the High Lipid and High Biomass Crop scenarios present considerable challenges due to land demand for cultivating crops, which drive land-use intensification of existing land use, land conversion, and potentially encroach on semi-natural habitats which are crucial for biodiversity. The expansion of bioenergy production, especially under the High Residue scenario, could intensify management practices that directly or indirectly impact semi-natural areas, including protected areas, thus posing significant challenges to meeting the objectives of the EU Biodiversity Strategy, the Birds and Habitats Directives, and the Nature Restoration Regulation.

To make these risks more explicit, the summary tables below use a colour-coded system to indicate the compatibility of each scenario against key EU biodiversity policy objectives for 2030 (Table 37) and 2050 (Table 38). The 2030 table highlights that while the High RFNBO scenario aligns relatively well with several EU biodiversity objectives, the High Lipids, High Biomass Crop, and High Residue scenarios already show emerging conflicts due to land-use intensification and increasing environmental pressures. Meanwhile, the 2050 table demonstrates that most scenarios are unlikely to align with EU biodiversity goals without substantial mitigation efforts, with significant incompatibilities particularly evident in the High Biomass Crop and High Lipids scenarios, which pose serious threats to habitat conservation, soil health, and ecosystem integrity.

Table 37. Compatibility of scenarios against key biodiversity policy objectives for 2030

Policy	Headline Objective	Compatibility for 2030			
		High RFNBO	High Lipid	High Biomass-Crop	High Residue
Biodiversity Strategy for 2030	Build a coherent Trans-Europe Nature Network w/30% EU land and sea protected	Low tension	High tension	Moderate tension	High tension
Birds Directive	To protect all naturally occurring wild bird species present in the EU and their most important habitats	Moderate tension	High tension	Moderate tension	High tension
Habitats Directive	Preserve the biodiversity of Europe's natural habitats and wildlife by ensuring that species and habitats are maintained or restored to a favourable conservation status	Moderate tension	High tension	High tension	High tension
Nature Restoration Regulation	Restore 20% of EU's degraded ecosystems by 2030 and all by 2050	Moderate tension	High tension	Moderate tension	High tension
Invasive Alien Species Regulation	Prevent, minimise and mitigate the adverse impacts posed by these species on native biodiversity and ecosystem services	Low tension	Low tension	High tension	Low tension
Water Framework Directive	Halt the deterioration of the status of EU water bodies and achieve good status for Europe's rivers, lakes and groundwater	Low tension	Moderate tension	Moderate tension	Low tension
Marine Strategy Framework Directive	Achieve good environmental status of the EU's marine waters and sustainably protect the resource base upon which marine-related economic and social activities depend	Low tension	Moderate tension	Moderate tension	Low tension
Soil Strategy for 2030	Achieve healthy and resilient soils by 2050	Low tension	Moderate tension	Moderate tension	Moderate tension
Forest Strategy for 2030	Improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience	Low tension	Moderate tension	Moderate tension	Moderate tension
Pollinators Initiative	Reverse the decline of pollinators by 2030	Low tension	Moderate tension	Moderate tension	Moderate tension

Key:

Low tension	The scenario aligns with the policy objective with minimal risk to biodiversity
Moderate tension	The scenario may require additional mitigation measures or management
High tension	The scenario poses substantial risk to the policy objective and biodiversity

Table 38. Compatibility of scenarios against key biodiversity policy objectives for 2050

Policy	Headline Objective	Compatibility for 2050			
		High RFNBO	High Lipid	High Biomass-Crop	High Residue
Biodiversity Strategy for 2030	Build a coherent Trans-Europe Nature Network w/30% EU land and sea protected				
Birds Directive	To protect all naturally occurring wild bird species present in the EU and their most important habitats				
Habitats Directive	Preserve the biodiversity of Europe's natural habitats and wildlife by ensuring that species and habitats are maintained or restored to a favourable conservation status				
Nature Restoration Regulation	Restore 20% of EU's degraded ecosystems by 2030 and all by 2050				
Invasive Alien Species Regulation	Prevent, minimise and mitigate the adverse impacts posed by these species on native biodiversity and ecosystem services				
Water Framework Directive	Halt the deterioration of the status of EU water bodies and achieve good status for Europe's rivers, lakes and groundwater				
Marine Strategy Framework Directive	Achieve good environmental status of the EU's marine waters and sustainably protect the resource base upon which marine-related economic and social activities depend				
Soil Strategy for 2030	Achieve healthy and resilient soils by 2050				
Forest Strategy for 2030	Improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience				
Pollinators Initiative	Reverse the decline of pollinators by 2030				

Biodiversity in Europe has been in decline for decades, primarily driven by land use change, agricultural intensification, and habitat loss. The growing demand for bioenergy, particularly in the aviation and maritime sectors, is likely to exacerbate these trends. This is especially true if demand for biofuel feedstocks triggers further land use change and agricultural intensification, as is highly likely under energy pathways heavily dependent on biofuels.

While all scenarios could theoretically align with the Nature Restoration Regulation's short-term goal of restoring 20% of ecosystems by 2030, the long-term goal of restoring "all ecosystems in need of restoration by 2050" would be difficult to achieve if significant portions of land are used for bioenergy production. This is demonstrated in Table 38, whereby, energy pathways which rely heavily on cellulosic materials for advanced biofuel production present high tension with many of the EU's biodiversity related policies and objectives by 2050. The High Biomass scenario, in particular shows significant risks to biodiversity due to large-scale land conversion and habitat degradation by 2050. In contrast, due to its lower land demand, the High RFNBO scenario is somewhat more compatible with these goals, particularly as the land needed for producing renewable electricity for RFNBOs is an order of magnitude less than that needed for bioenergy. Additionally, the High Lipids scenario shows moderate compatibility in the short term but could pose rising risks to biodiversity closer to 2050 due to agricultural intensification and increased input use.

In contrast, the High Lipid, High Biomass Crop, and High Residue scenarios would necessitate substantial levels of land conversion and / or land use intensification, likely resulting in habitat loss and degradation, and significant tension with the Birds and Habitats Directives. For example, the High Biomass Crop scenario, which requires over 3,600 kha of additional land by 2050, will directly undermine efforts to halt biodiversity loss under the Birds and Habitats Directives, the EU Biodiversity Strategy and the Nature Restoration Regulation, as it would lead to the loss and degradation of natural and semi-natural ecosystems. This large-scale conversion of land would make the 2050 goal, central to the Nature Restoration Regulation, very difficult to reach.

While the High Biomass Crop scenario presents significant risks to soil health by 2050, the risks by 2030 are likely to be moderate, particularly due to the role of perennial energy crops, such as miscanthus. These crops, with their deep root systems, can enhance soil structure, promote carbon sequestration, and reduce soil erosion, which mitigates the immediate risk to soil health. While there may be some tension with soil health due to the use of annual grass crops (e.g. sorghum) and their associated high input use, the tensions remain moderate in 2030. However, by 2050, as the cultivation of biomass crops, and particularly annual grass crops, becomes more widespread, the cumulative impacts of land conversion and intensification will escalate. Annual crops require frequent more frequent planting, tillage and higher input use (fertilisers and pesticides), all of which lead to nutrient depletion, soil compaction, and a greater risk of soil erosion. This means that the risks to soil health rise significantly by 2050, creating much greater tension with the objectives of the Soil Strategy.

A particularly significant point of tension is the expected use of fertilisers and pesticides for these bioenergy crops. The High Lipid scenario, which sees fertiliser consumption rise from 100 kt in 2030 to 1,375 kt in 2050, and pesticide use increasing from 4 kt to 46 kt, conflicts directly with the EU Biodiversity Strategy's goal of halving pesticide use by 2030 and reducing the use fertilisers by 20%. Similarly, the High Biomass Crop scenario implies a steep rise in pesticide use (up to 24 kt by 2050) to support intensified biomass crop production, which also exacerbates tensions with aims to reduce environmental contamination and protecting non-target species. Furthermore, increased use of inputs will exacerbate challenges in achieving improvements in the condition of Europe's rivers and waterbodies, as required by the Water Framework

Directive, and place additional pressures on coastal and marine ecosystems, as outlined in the Marine Strategy Framework Directive.

The High Lipid and High Residue scenarios also pose significant risk to biodiversity through intensification of existing agricultural lands and extensive residue harvesting, which can degrade soil health and water resources. By 2050, water demand, pollution and soil health risks, escalate under these scenarios further undermining EU biodiversity goals. While some mitigation measures could alleviate the pressure in the short term, significant policy interventions would be necessary to ensure these pathways could align with long-term biodiversity and restoration goals.

9.2. Reducing impact/delivering co-benefits

To align with EU biodiversity goals, it is crucial to minimise the negative impacts of energy demand and enhance co-benefits wherever possible. In 2026, Member States will be expected to fulfil obligations under the Nature Restoration Regulation and submit their own national restoration plans. These should include plans to restore habitats within their respective countries and identify new areas of land and sea for protection and restoration. Member States must also outline the designation of Renewable Acceleration Areas (RAAs) under the RED. These areas enable renewable energy projects to benefit from streamlined planning processes.

To support Member States with the designation of these areas, the JRC has developed a geospatial tool (JRC, 2023) which provides energy and environmental data, as well as areas that should be avoided, such as Natura 2000, peatlands, important areas for birds and other biodiversity, and ecologically or biologically significant marine areas. This tool will be essential when scaling up on renewable energy development towards 2050, when renewable energy sources are expected to have displaced the majority of fossil fuels in EU aviation and maritime.

To mitigate potential negative effects and enhance the opportunity for positive outcomes for biodiversity, several strategies can be employed to find 'win-win' solutions (as outlined in the Biodiversity Strategy). Firstly, it is crucial to utilise production systems which do not encroach upon areas of significant biodiversity. This means avoiding Nature 2000 sites and minimising human disturbance in these areas. A 'land sparing' approach to land use and management would concentrate human activities in already degraded and areas to avoid high-biodiversity regions. One example of this is to prioritise generating electricity in urban spaces, which already support the lowest levels of biodiversity.

Another approach is to establish multi-functional systems such as agrivoltaics, where solar panels are installed above crops or livestock. This method mitigates potential conflicts between food and energy production, and maximises the utility of existing agricultural land, thereby reducing pressure on biodiversity while supporting energy generation. This can also provide additional income for farmers and reduce the need to intensify practices or convert natural habitats, provided that the location, habitat, scale and other environmental considerations are appropriate.

However, the increased use of crop residues for bioenergy also needs careful consideration and management. While using residues can reduce the need for new cropland, excessive residue removal can deplete soil organic matter and reduce soil fertility, impacting both soil health and the ability of farmland to support diverse species. Therefore, best practices for residue management should be encouraged, including retaining sufficient residues to maintain soil carbon levels, promote soil biodiversity, and support other ecosystem services.

In bioenergy production systems, adopting sustainable land management practices is essential. This includes promoting mixed, diverse systems such as biodiversity-rich agroforestry, silvoarable systems and polyculture (Section 5.5). Though these systems could create conflict with the need to increase the use of crop residues, they offer alternatives to traditional monoculture models by integrating various crops and land-use practices that promote biodiversity through improved habitat complexity, diversity, and resource availability. Farmers and land managers can be supported through CAP measures to adopt such practices, which also enhance soil health and carbon sequestration.

It is equally crucial to consider the forest landscapes where bioenergy production may impact biodiversity. Encouraging sustainable forest management practices can reduce the negative impacts of increased demand for wood and residues for bioenergy. Practices such as selective harvesting, longer rotation periods, and maintaining a diversity of tree species and ages, and deadwood, help preserve the structural complexity and biodiversity of forest ecosystems. Additionally, integrating SRF into agroforestry systems can provide renewable energy while delivering co-benefits for soil protection, carbon sequestration, and biodiversity. Similar benefits could be delivered through utilising the phytoremediation potential of SRF and perennial grasses like miscanthus in areas of contaminated land (of which there an estimated 2.5 million sites across Europe).

Finally, rather than attempting to define marginal lands in a general sense, a more practical approach would be to develop systems that identify preferred lands for the development of biomass supply systems based on their current ecological functions and biodiversity values. This would involve evaluating potential bioenergy sites to ensure that the expansion of biomass production avoids areas of high ecological value, including High Nature Value farmland and habitats protected under the Birds and Habitats Directives. These lands often play a crucial role in supporting biodiversity, pollination, carbon sequestration, and water cycling, and must be safeguarded to align with the sustainability criteria in future iterations of the RED. Additionally, prioritising habitat restoration under the Nature Restoration Regulation should be a key consideration before utilising these lands for energy production. By developing a robust system for assessing and identifying suitable sites, bioenergy systems can be implemented more sustainably, minimising conflict with biodiversity and ecosystem services.

Habitat loss and degradation must be prevented within Natura 2000 and national protected area networks. However, it is important to recognise that large areas of habitat and species protected under the Birds and Habitats Directives occur outside the Natura 2000 network. Furthermore, the obligation on Member States to achieve favourable conservation status applies to the entire extent of the habitat and whole species population within their borders. Compliance would require thorough assessments of the biodiversity value and associated ecological functions of sites to be carried out before establishing new bioenergy production systems to ensure these practices do not undermine the conservation status of the habitats and species protected by the Directives, as well as national laws.

Incentivising best practices through policy support, such as CAP measures, is essential for achieving bioenergy systems that minimise harm to biodiversity and contribute to its recovery wherever possible. Effective mechanisms can promote diverse cropping systems which enhance yields without expanding land. Smart farming techniques, such as precision agriculture, can optimise resource use and crop productivity, reducing the need for additional land. These approaches, coupled with sustainable forest management practices, can support the efficient use of existing agricultural and forest landscapes, reducing the impact on natural habitats.

9.3. Future Policy

Our modelling scenarios assumed no additional policy change takes place; however, climate and renewable energy policy are likely to continue to evolve. Future policy shifts could significantly impact energy production systems and biodiversity in the EU. These shifts could range from adjustments to existing policies to increased ambition levels for proposed and developing policies, as well as new policies beyond the current legislative horizon. The proposed soil and forest monitoring laws, for instance, are still under development, and there is opportunity to ensure they include robust provisions to prevent biomass production from contributing to soil and forest degradation. Failure to integrate such provisions could undermine the EU's goal of 'putting nature on the path to recovery'.

Both the soil and forest monitoring laws propose stringent requirements for Member States to monitor and report on the state of their soils and forests. This can help to track the environmental impacts of land management practices. Currently, information about residue harvesting rates in both forestry and agriculture is scarce, making it difficult to identify ecological impacts and best practices.

Another way to ensure that future policy could support both energy and biodiversity goals is by addressing existing points of tension. For instance, while the CAP supports SRF as a renewable energy source, it should include provisions to ensure SRF is implemented in ways that are ecologically appropriate (i.e., not replacing features with higher biodiversity value). A target for at least 10% of farms to be placed under high diversity landscape features or ecological focus areas under the proposed Nature Restoration Law, was eroded to a non-binding target of 4% in its final adopted text. The shift weakens incentives for farmers to maintain areas specifically for biodiversity and could favour the establishment of economically productive landscape elements over features like hedgerows or riparian buffers which provide higher biodiversity value.

A major challenge in balancing biodiversity conservation lies in the insufficient recognition and valuation of ecosystem services provided by biodiversity. Future policies could address this by explicitly recognising and compensating ecosystem services, such as pollinators or carbon sequestration. For instance, conservation policies targeting pollinators could incentivize practices that protect these species, such as payment schemes to farmers for maintaining forage-rich marginal lands.

Moreover, future policies should consider the risk of invasiveness associated with bioenergy crops and fast-growing trees used in SRF, such as willows and poplars, which can become invasive if they spread beyond cultivation areas. These species are often selected for their adaptability and fast growth, which can lead to unintended consequences if they spread into natural habitats. The Invasive Alien Species Regulation could be amended to include stricter measures for assessing invasiveness before species are introduced for bioenergy production and to establish monitoring systems to control the unintended spread of bioenergy crops into natural ecosystems.

9.4. Opportunity for policymakers & other stakeholders

Policymakers play a crucial role in shaping the intersection between biodiversity and climate policy. Their role is involves developing, implementing and enforcing robust sustainability criteria that balance energy needs with biodiversity conservation. Legislation like RED III, and the Nature Restoration Regulation must be comprehensive and effectively enforced, with clear guidelines for sustainable bioenergy production, rigorous environmental impact assessments (EIAs) and accountability measures for non-compliance. Policymakers can also foster cross-sector collaboration to ensure that renewable energy policies do not undermine biodiversity objectives. By integrating biodiversity considerations into all stages of policy development and implementation, they can create more resilient energy landscapes.

Businesses, particularly in the renewable energy and bioenergy sectors, are key to developing and adopting best practices. Companies can drive innovation by investing in biodiversity-friendly practices, such as mixed cropping systems, agroforestry, and the use of marginal lands that do not compromise critical habitats. By demonstrating the feasibility and benefits of such practices, businesses can influence policy makers to adopt supporting policies. Additionally, understanding biodiversity risk and contributing to biodiversity conservation is becoming increasingly significant in terms of company reputation and marketability, offering a competitive advantage to early movers who contribute to broader environmental goals.

Investors have the power to drive change at scale by prioritising investments in companies and projects which adhere to rigorous environmental standards. Sustainable finance instruments, like the EU's Sustainable Finance Taxonomy, help channel funds towards renewable energy projects which also support biodiversity protection. Investors can also encourage companies to improve transparency and accountability in their practices, ensuring that investment portfolios contribute positively to both biodiversity and climate goals.

Finally, the biodiversity impacts of aviation and maritime energy demand are closely tied to the overall energy demand. While technological innovations – such as more efficient engines, lighter materials, and optimised flight and shipping paths – can reduce fuel use and emissions per unit of transport, these measures alone are likely to be insufficient to offset the environmental and biodiversity impacts of projected demand growth. Given the significant environmental implications of high demand projections, including the findings in this report's biodiversity risk assessments, it is crucial to consider whether demand reduction measures should be part of the solution. Policy discussions around reducing demand, particularly in sectors with rapid growth, could provide a lower-cost and more effective way to mitigate biodiversity and environmental impacts compared to relying solely on bioenergy solutions.

For instance, policy measures aimed at curbing frequent flying, reducing business travel, or discouraging the use of private jets could play a role in reducing the overall demand for energy in aviation. Airlines and shipping operators may have the flexibility to pass through the costs of such measures to consumers, creating an opportunity to influence demand by adjusting pricing structures. These strategies would not require asking the public to stop flying altogether but could focus on targeted reductions in high-impact areas of travel, which may provide a more cost-effective approach to reducing energy demand and biodiversity risk.

9.5. Future research

The urgency of addressing biodiversity loss while advancing decarbonisation efforts in the aviation and maritime sector necessitates a holistic approach. This approach should 'think in terms of biodiversity' and consider the complexity of ecosystems and foster systems that provide opportunities for a wide range of species and habitats to coexist and function. Several key areas of research could provide further context on how to support decarbonisation efforts while minimising the risk to biodiversity and aligning with the EU's biodiversity goals and nature restoration targets.

While biomass for bioenergy will remain crucial for reaching renewable energy targets and supporting the phase out of fossil fuels, it is essential to develop methodologies for long term monitoring of biodiversity impacts associated with bioenergy production. Current research often provides comparative analysis between conventional cropping systems and bioenergy, focussing on immediate and near-term impacts. However, these studies frequently examine landscapes over relatively short time scales, potentially failing to capture the extent and complexity of changes in biodiversity and ecosystems over the long term. Longitudinal studies that monitor biodiversity over decades are essential to understand the true ecological impacts of biomass production.

Further to this, most research that highlights the potential biodiversity benefits of bioenergy systems has focused on comparisons with existing arable systems. These studies often show that crops like miscanthus and SRF can improve soil health, carbon sequestration, and biodiversity relative to intensive agricultural practices. In some instances, comparisons have been made between different biomass crop types. However, our review of the literature found little research that assesses how these benefits change when marginal lands or semi-natural habitats are converted to bioenergy production. Given the high biodiversity value of many of these lands, further research is needed to determine whether bioenergy crops offer ecological advantages over the conservation of these ecosystems.

Innovation in bioenergy cropping systems can offer pathways to enhance biodiversity while producing biomass. Mixed cropping systems, agroforestry, and other innovative practices can create more complex habitats that support a wider range of species. Research should focus on identifying and quantifying the biodiversity benefits for these systems. For instance, intercropping bioenergy crops with native species or incorporating buffer zones of natural vegetation can provide habitats for pollinators and other wildlife, enhancing ecosystem services while maintaining or potentially improving biomass yields.

Additionally, future research should address the non-CO_2 impacts of both conventional and alternative fuels, which were beyond the scope of this study. These include emissions such as contrails and nitrogen oxides (NO_x), which can have significant climate and environmental effects. Considering these factors might alter the relative benefits of different fuels. For example, the land demand for CO_2 for synthetic fuels, such as methanol or e-kerosene, whether obtained via Direct Air Capture (DAC) or from biogenic sources, needs to be considered (as noted in Section 6.1.8 and Annex C.4.3). These aspects could significantly impact the overall evaluation of each scenario's compatibility with biodiversity goals.

Research should also explore the impacts of climate change – the very threat that decarbonisation policies are trying to address – on energy production systems and on biodiversity. Climate change poses risks such as altered precipitation patterns, increased frequency of extreme weather events (such as fires or flooding), and shifts in growing seasons. These changes can affect biomass yields and the efficiency of solar and wind energy systems. In some novel cropping systems, the impacts of heat stress and water scarcity could reduce yields in drought-affected regions, potentially increasing the need for irrigation and raising both costs and demand for resources like water. This could lead to other environmental impacts, for instance if stressed crops are more prone to pest outbreaks and require higher chemical usage.

Climate change can exacerbate pest and disease pressures on biomass crops, increasing vulnerability and potentially reducing yields. Higher temperatures and altered precipitation patterns can create favourable conditions for pests and diseases, necessitating increased chemical inputs for crop protection. Biodiverse systems generally offer better resilience to these threats, making it essential to consider that efforts to conserve biodiversity now will support the viability of future production systems. Identifying climate-resilient crops and optimising management practices such as water and nutrient requirements will be critical to ensuring that renewable energy systems can adapt to changing conditions and support climate resilience without compromising biodiversity.

9.6. Recommendations

There is a need to balance the targets set out in the EU's aviation and maritime decarbonisation policies with the need to protect and restore biodiversity. In line with the EU's call for 'win-win solutions for energy generation', we provide the following recommendations:

- **Develop RFNBO technologies**: Renewable Fuels of Non-Biological Origin (RFNBOs) present the lowest tension pathway for meeting existing biodiversity targets due to their lower pressures on land compared to bioenergy pathways. However, a significant portion of the necessary infrastructure, such as electrolysers and renewable electricity generation, is currently lacking, and the associated costs of scaling up are high. Delaying investment in RFNBO infrastructure risks increasing future costs significantly, akin to other climate mitigation challenges where delays lead to higher costs and stranded assets. At the same time, it is critical to ensure that this infrastructure is designed to monitor and minimise hydrogen leaks which could undermine the climate advantages of electrolysis-based fuels.
- **Reduce the overall demand in the aviation and maritime sectors:** The pressures on land, sea and biodiversity are already immense due to existing demands for agriculture, urban development and conservation needs. As the most recent UN SDGs report highlighted, EU lifestyles are characterised by high energy consumption, and the EU's aviation and maritime sectors, both significant contributors to greenhouse gas emissions, are poised for expansion under current energy scenarios. Delaying demand reduction measures will only exacerbate constraints on land and marine ecosystems, making it costlier and more challenging to achieve climate and biodiversity goals in the future. Implementing overall demand reduction strategies, such as enhancing energy efficiency, incentivising shifts towards lower-impact travel, and reducing frequent flying, business travel, and the use of private jets, can collectively reduce energy demand and help align the EU's biodiversity and climate goals.

- **Identify and protect marginal land of high biodiversity value**: The concept of marginal land presents both opportunities and challenges for bioenergy production. These lands, often deemed unsuitable for productive and profitable conventional agriculture, are promoted for producing bioenergy crops without significant reductions in food production. However, these lands are often significant for biodiversity, overlapping considerably with semi-natural habitats and their associated species protected under EU law. Development and implementation of ecological assessments would help stakeholders to understand the biodiversity values and ecological functions of these lands before conversion. Additional strategies, such as guidelines for biodiversity-friendly mixed energy cropping, agroforestry, and adaptive management, could also help mitigate negative impacts and enhance positive outcomes.
- **Incorporate soil carbon monitoring**: Soil carbon remains a blind spot in EU greenhouse gas emissions accounting policies, such as the Land Use, Land Use Change and Forestry (LULUCF) Regulation. Current policies do not mandate the inclusion of soil carbon unless it is a net source of emissions, resulting in insufficient monitoring and reporting. Without proper oversight, practices like residue harvesting may continue to degrade soil carbon stocks, undermining climate mitigation efforts. The EU's proposed soil monitoring law should strive to align with renewable energy targets by encouraging Member States to adopt forest and agricultural residue removal thresholds for key soil types. Effective monitoring and management of soil carbon is crucial since soils are the largest terrestrial carbon store, support 25% of biodiversity, and play a vital role in the sustainability of energy and food production.
- **Protect and expand habitats and other landscape features that support biodiversity in productive forestry and agricultural systems**: including remaining patches of semi-natural habitat, fallow land, native trees, hedgerows, ponds, ditches etc, some of which may be maintained as Ecological Focus Areas (EFAs) or under other agri-environmental measures of the Common Agricultural Policy (CAP). Such areas and features are essential for supporting biodiversity within agricultural landscapes, serving as refuges for wildlife, enhancing habitat connectivity, and providing ecosystem services such as pollination, natural pest control and water purification.

10. References

Abbasov, F. (2024). Analysis on interaction of CII with GFS: Calibrating IMO energy efficiency and fuels targets. *Transport and Environment (T&E)*. https://www.transportenvironment.org/uploads/files/202401_CII_GFS_EE_targets_for_IMO-3.pdf

Abbasov, F., Earl, T., & Afonso, F. (2019). *EU shipping's climate record*. https://www.transportenvironment.org/articles/european-shippings-climate-record

Acreman, M., Casier, R., & Salathe, T. (2022). Evidence-based Risk Assessment of Ecological Damage due to Groundwater Abstraction; the Case of Doñana Natural Space, Spain. *Wetlands*, *42*(7). https://doi.org/10.1007/s13157-022-01570-6

Ahlgren, S., & Di Lucia, L. (2016). Erratum to: Indirect land use changes of biofuel production – a review of modelling efforts and policy developments in the European Union. *Biotechnology for Biofuels*, 9(1), 1–10. https://doi.org/10.1186/s13068-016-0459-4

Allen, B., Kretschmer, B., Baldock, D., Menadue, H., Nanni, S., & Tucker, G. (2014). *Space for energy crops – assessing the potential contribution to Europe's energy future*. https://www.transportenvironment.org/uploads/files/IEEP_2014_Space_for_Energy_Crops.pdf

Aminian-Biquet, J., Gorjanc, S., Sletten, J., Vincent, T., Laznya, A., Vaidianu, N., Claudet, J., Young, J., & Horta e Costa, B. (2024). Over 80% of the European Union's marine protected area only marginally regulates human activities. *One Earth*. https://doi.org/10.1016/j.oneear.2024.07.010

Andersson, C., Johansson, A. T., Genell, A., & Winroth, J. (2024). Fully electric ship propulsion reduces airborne noise but not underwater noise. *Ocean Engineering*, *302*, 117616. https://doi.org/10.1016/j.oceaneng.2024.117616

Arrigoni, A., & Bravo Diaz, L. (2022). *Hydrogen emissions from a hydrogen economy and their potential global warming impact*. https://op.europa.eu/en/publication-detail/-/publication/918b0980-21c7-11ed-8fa0-01aa75ed71a1/language-en

Arrowsmith, S., Lee, D. S., Owen, B., Faber, J., van Wijngaarden, L., Boucher, O., Celikel, A., Deransy, R., Fuglestvedt, J., Laukia, J., Lund, M. T., Sausen, R., Schaefer, M., Skowron, A., Stromatas, S., & Watt, A. (2000). *Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)*. https://www.easa.europa.eu/en/document-library/research-reports/report-commission-european-parliament-and-council

Arrowsmith, S., Lee, D. S., Owen, B., Faber, J., van Wijngaarden, L., Boucher, O., Celikel, A., Deransy, R., Fuglestvedt, J., Laukia, J., Lund, M. T., Sausen, R., Schaefer, M., Skowron, A., Stromatas, S., & Watt, A. (2020). Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4). European Union Aviation Safety (EASA), MOVE/E1/SER/2019-475/SI2.81706, Köln. In *European Commission*. https://www.easa.europa.eu/sites/default/files/dfu/201119_report_com_ep_council_updated_analysis_non_CO_2_climate_impacts_aviation.pdf

Ash, N., Davies, A., & Newton, C. (2020). Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels Investigating supply-side constraints to decarbonising the transport sector in the European. https://te-cdn.ams3.cdn.digitaloceanspaces.com/files/2020_Report_RES_to_decarbonise_transport_in_EU.pdf

Augusto, L., Bakker, M. R., & Meredieu, C. (2008). Wood ash applications to temperate forest ecosystems—potential benefits and drawbacks. *Plant and Soil*, *306*(1–2), 181–198. https://doi.org/10.1007/s11104-008-9570-z

Baldock, D., Beaufoy, G., Bennett, G., & Clark, J. (1993). Nature conservation and new directions in the EC common agricultural policy.

Ballogh, A. (2021). The rise and fall of monoculture farming. *Horizon*. https://projects.research-and-innovation.ec.europa.eu/en/horizon-magazine/rise-and-fall-monoculture-farming

Balvanera, P., Calderón-Contreras, R., Castro, A. J., Felipe-Lucia, M. R., Geijzendorffer, I. R., Jacobs, S., Martín-López, B., Arbieu, U., Speranza, C. I., Locatelli, B., Harguindeguy, N. P., Mercado, I. R., Spierenburg, M. J., Vallet, A., Lynes, L., & Gillson, L. (2017). Interconnected place-based social–ecological research can inform global sustainability. In *Current Opinion in Environmental Sustainability* (Vol. 29, pp. 1–7). Elsevier B.V. https://doi.org/10.1016/j.cosust.2017.09.005

Barker, B. , Hodgson, P. , Hyde, D. , Miller, R. , & Rapeanu, M. (2022). *Target True Zero: Unlocking Sustainable Battery and Hydrogen-Powered Flight*. https://www.weforum.org/publications/target-true-zero-unlocking-sustainable-battery-and-hydrogen-powered-flight/

Barney, J. N., & DiTomaso, J. M. (2010). *Invasive Species Biology, Ecology, Management and Risk Assessment: Evaluating and Mitigating the Invasion Risk of Biofuel Crops* (pp. 263–284). https://doi.org/10.1007/978-3-642-13440-1_9

Baroni, D., Korpimäki, E., Selonen, V., & Laaksonen, T. (2020). Tree cavity abundance and beyond: Nesting and food storing sites of the pygmy owl in managed boreal forests. *Forest Ecology and Management*, *460*, 117818. https://doi.org/10.1016/j.foreco.2019.117818

Barredo, J., Brailescu, C., Teller, A., Sabatini, F. M., Mauri, A., & Janouskova, K. (2021). Mapping and assessment of primary and old-growth forests in Europe. In *EU Joint Research Centre*. https://publications.jrc.ec.europa.eu/repository/handle/JRC124671

Basile, M., Krištín, A., Mikusiński, G., Thorn, S., Żmihorski, M., Pasinelli, G., & Brockerhoff, E. G. (2022). Salvage Logging Strongly Affects Woodpecker Abundance and Reproduction: a Meta-analysis. *Current Forestry Reports*, *9*(1), 1–14. https://doi.org/10.1007/s40725-022-00175-w

Basma, H., & Rodríguez, F. (2023). *A total cost of ownership comparison of truck decarbonization pathways in Europe*. https://theicct.org/publication/total-cost-ownership-trucks-europe-nov23/

Baum, C., Leinweber, P., Weih, M., Lamersdorf, N. P., & Dimitriou, I. (2009). Effects of short rotation coppice with willows and poplar on soil ecology. *Landbauforschung Volkenrode*, *59*, 183–196. https://api.semanticscholar.org/CorpusID:38047723

Baylin-Stern, A., Beck, L., Beuttler, C., Bolesta, C., Dailey, M. D. , T., Edwards, R., Gauvin, C., Hancu, D., Holmes, G., Karimjee, A., Kawakami, H., Kemper, J., Khan, A., Pilorgé, H., Sakwa-Novak, M., Scott, V., Uzor, L., & Weir, J. (2022). *Direct Air Capture: A key technology for net zero*. https://www.iea.org/reports/direct-air-capture-2022

Beaufoy, G., & Marsden, K. (2010). *CAP reform 2013: last chance to stop the decline of Europe's High Nature Value farming?* https://wwfeu.awsassets.panda.org/downloads/cap_reform_2013.pdf

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochar's potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, *159*(12), 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, *27*(19), 4697–4710. https://doi.org/10.1111/gcb.15747

Bell, G. P. (1997). ECOLOGY AND MANAGEMENT OF ARUNDO DONAX, AND APPROACHES TO RIPARIAN HABITAT RESTORATION IN SOUTHERN CALIFORNIA. *Environmental Science*. https://www.desertfishes.org/cuatroc/literature/pdf/Bell_1997_Arundo_ecology_management.pdf

Bellamy, P. E., Croxton, P. J., Heard, M. S., Hinsley, S. A., Hulmes, L., Hulmes, S., Nuttall, P., Pywell, R. F., & Rothery, P. (2009). The impact of growing miscanthus for biomass on farmland bird populations. *Biomass and Bioenergy*, *33*(2), 191–199. https://doi.org/10.1016/j.biombioe.2008.07.001

Bellassen, V., Angers, D., Kowalczewski, T., & Olesen, A. (2022). Soil carbon is the blind spot of European national GHG inventories. *Nature Climate Change*, *12*(4), 324–331. https://doi.org/10.1038/s41558-022-01321-9

Bengtsson, J., Ahnström, J., & Weibull, A.-C. (2005). The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology*, *42*(2), 261–269. https://doi.org/10.1111/j.1365-2664.2005.01005.x

Benjamins, S., Williamson, B., Billing, S.-L., Yuan, Z., Collu, M., Fox, C., Hobbs, L., Masden, E. A., Cottier-Cook, E. J., & Wilson, B. (2024). Potential environmental impacts of floating solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, *199*, 114463. https://doi.org/10.1016/j.rser.2024.114463

Bennett, H., & O'Connell, S. (2022). *Preparing for take off—Speeding up the switch to sustainable aviation fuel*. https://green-alliance.org.uk/wp-content/uploads/2022/05/Preparing-for-take-off.pdf

Bennun, L., van Bochove, J., Ng, C., Fletcher, C., Wilson, D., Phair, N., & Carbone, G. (2021). Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers. In *Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/iucn.ch.2021.04.en

Bieker, G. (2021). *A GLOBAL COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF COMBUSTION ENGINE AND ELECTRIC PASSENGER CARS*. https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/

BiofuelWatch. (2024). *TREES FROM CLEARCUTTING IN PORTUGUESE NATURE RESERVE FOUND TO HAVE GONE TO DRAX PELLET SUPPLIER*. https://www.biofuelwatch.org.uk/2024/drax-pinewells-pr/

Blanco-Canqui, H. (2016). Growing Dedicated Energy Crops on Marginal Lands and Ecosystem Services. *Soil Science Society of America Journal*, *80*(4), 845–858. https://doi.org/10.2136/sssaj2016.03.0080

Blanco-Canqui, H., & Lal, R. (2009°). Crop Residue Removal Impacts on Soil Productivity and Environmental Quality. *Critical Reviews in Plant Sciences*, *28*(3), 139–163. https://doi.org/10.1080/07352680902776507

Blanco-Canqui, H., & Lal, R. (2009b). Crop Residue Removal Impacts on Soil Productivity and Environmental Quality. *Critical Reviews in Plant Sciences*, *28*(3), 139–163. https://doi.org/10.1080/07352680902776507

Blanco-Canqui, H., & Lal, R. (2015). *Crop Residue Management and Soil Carbon Dynamics* (pp. 291–309). https://doi.org/10.2136/sssaspecpub57.2ed.c17

Bolinder, M. A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., Tits, M., Tóth, Z., & Kätterer, T. (2020). The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change*, *25*(6), 929–952. https://doi.org/10.1007/s11027-020-09916-3

Booth, M. S. (2018). Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. *Environmental Research Letters*, *13*(3). https://doi.org/10.1088/1748-9326/aaac88

Boothroyd-Roberts, K., Gagnon, D., & Truax, B. (2013). Can hybrid poplar plantations accelerate the restoration of forest understory attributes on abandoned fields? *Forest Ecology and Management*, *287*, 77–89. https://doi.org/10.1016/j.foreco.2012.09.021

Bota, G., Morales, M. B., Mañosa, S., & Camprodon, J. (2005). *Ecology and Conservation of Steppe-Land Birds*. Lynx Edicions & Centre Tecnològic Forestal de Catalunya. https://www.researchgate.net/profile/Jordi-Camprodon/publication/233792351_Ecology_and_Conservation_of_Steppe-Land_Birds/links/0f31753ac891d65224000000/Ecology-and-Conservation-of-Steppe-Land-Birds.pdf

Bowers, C., Toews, M. D., & Schmidt, J. M. (2021). Winter cover crops shape early-season predator communities and trophic interactions. *Ecosphere*, *12*(7). https://doi.org/10.1002/ecs2.3635

Bowman, G., Burg, V., Erni, M., Lemm, R., Thees, O., & Björnsen Gurung, A. (2021). How much land does bioenergy require? An assessment for land-scarce Switzerland. *GCB Bioenergy*, *13*(9), 1466–1480. https://doi.org/10.1111/gcbb.12869

Bowyer, C., Tucker, G., Underwood, E., & et al. (2020). *Potential impacts of bioenergy developments on habitats and species protected under the Birds and Habitats Directives*. https://op.europa.eu/en/publication-detail/-/publication/53b80f77-02cb-11eb-8919-01aa75ed71a1

Brack, D., Birdsey, R., & Walker, W. (2021). Greenhouse gas emissions from burning US-sourced woody biomass in the EU and UK. *Chatham House*. https://www.chathamhouse.org/2021/10/greenhouse-gas-emissions-burning-us-sourced-woody-biomass-eu-and-uk

Brooker, R. W., George, T. S., Homulle, Z., Karley, A. J., Newton, A. C., Pakeman, R. J., & Schöb, C. (2021). Facilitation and biodiversity–ecosystem function relationships in crop production systems and their role in sustainable farming. *Journal of Ecology*, *109*(5), 2054–2067. https://doi.org/10.1111/1365-2745.13592

Brown, S., & Jones, D. (2024). *European Electricity Review 2024*. https://ember-climate.org/insights/research/european-electricity-review-2024/#supporting-material

Brunner, P. H., & Rechberger, H. (2015). Waste to energy – key element for sustainable waste management. *Waste Management*, *37*, 3–12. https://doi.org/10.1016/j.wasman.2014.02.003

Burland, A., & von Cossel, M. (2023a). Towards Managing Biodiversity of European Marginal Agricultural Land for Biodiversity-Friendly Biomass Production. *Agronomy*, *13*(6). https://doi.org/10.3390/agronomy13061651

Burland, A., & von Cossel, M. (2023b). Towards Managing Biodiversity of European Marginal Agricultural Land for Biodiversity-Friendly Biomass Production. *Agronomy*, *13*(6), 1651. https://doi.org/10.3390/agronomy13061651

CABI. (2019). *Salix fragilis (crack willow)*. CABI Digital Library. https://doi.org/10.1079/cabicompendium.48577

Camia, A., Giuntoli, Jonsson, J., & Robert, R. (2021). The use of woody biomass for energy purposes in the EU. In *Publications Office of the European Union, Luxembourg, JRC122719*. https://doi.org/10.2760/831621

Camia, A., Robert, N., Jonsson, K. , P. R., Garcia Condado, S., Lopez Lozano, R., Van Der Velde, M., Ronzon, T., Gurria Albusac, P., M'barek, R., Tamosiunas, S., Fiore, G., Dos Santos Fernandes De Araujo, R., Hoepffner, N., Marelli, L., & Giuntoli, J. (2018). *Biomass production, supply, uses and flows in the European Union: First results from an integrated assessment*. https://publications.jrc.ec.europa.eu/repository/handle/JRC109869

Campagnaro, T., Trentanovi, G., Iacopino, S., Squartini, A., Simonelli, F. G., Alterio, E., Bertoldo, G., Concheri, G., Grigolato, S., Portaccio, A., Rizzi, A., Rizzieri Masin, R., Stevanato, P., Tasinazzo, S., & Sitzia, T. (2023). Sweet chestnut forests under black locust invasion threat and different management: An assessment of stand structure and biodiversity. *Forest Ecology and Management*, *537*(February), 120907. https://doi.org/10.1016/j.foreco.2023.120907

Carboneras, C., Genovesi, P., Vilà, M., Blackburn, T. M., Carrete, M., Clavero, M., D'hondt, B., Orueta, J. F., Gallardo, B., Geraldes, P., González-Moreno, P., Gregory, R. D., Nentwig, W., Paquet, J., Pyšek, P., Rabitsch, W., Ramírez, I., Scalera, R., Tella, J. L., … Wynde, R. (2018). A prioritised list of invasive alien species to assist the effective implementation of EU legislation. *Journal of Applied Ecology*, *55*(2), 539–547. https://doi.org/10.1111/1365-2664.12997

Carboneras, C., Genovesi, P., Vilà, M., Blackburn, T. M., Carrete, M., Clavero, M., D'hondt, B., Orueta, J. F., Gallardo, B., Geraldes, P., González-Moreno, P., Gregory, R. D., Nentwig, W., Paquet, J. Y., Pyšek, P., Rabitsch, W., Ramírez, I., Scalera, R., Tella, J. L., … Wynde, R. (2018). A prioritised list of invasive alien species to assist the effective implementation of EU legislation. *Journal of Applied Ecology*, *55*(2), 539–547. https://doi.org/10.1111/1365-2664.12997

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., MacE, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. In *Nature* (Vol. 486, Issue 7401, pp. 59–67). Nature Publishing Group. https://doi.org/10.1038/nature11148

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). NONPOINT POLLUTION OF SURFACE WATERS WITH PHOSPHORUS AND NITROGEN. *Ecological Applications*, *8*(3). https://esajournals.onlinelibrary.wiley.com/doi/10.1890/1051-0761%281998%29008%5B0559%3ANPOSWW%5D2.0.CO%3B2

Cazzaniga, N., Jonsson, K., Pilli, R., & Camia, A. (2019). Wood resource balances of EU-28 and Member States. *Publications Office of the European Union*. https://publications.jrc.ec.europa.eu/repository/handle/JRC114889

Chambers, P. A., Meissner, R., Wrona, F. J., Rupp, H., Guhr, H., Seeger, J., Culp, J. M., & Brua, R. B. (2006). Changes in nutrient loading in an agricultural watershed and its effects on water quality and stream biota. *Hydrobiologia*, *556*(1), 399–415. https://doi.org/10.1007/s10750-005-1202-5

Chambers, P. A., Vis, C., Brua, R. B., Guy, M., Culp, J. M., & Benoy, G. A. (2008). Eutrophication of agricultural streams: defining nutrient concentrations to protect ecological condition. *Water Science and Technology*, *58*(11), 2203–2210. https://doi.org/10.2166/wst.2008.815

Chatzipanagi, A., Taylor, N., & Jaeger-Waldau. (2023). *Overview of the Potential and Challenges for Agri-Photovoltaics in the European Union*. https://doi.org/10.2760/208702

Cheilari, A. (2023). *Strict protection in the context of Biodiversity Strategy targets*. https://biogeoprocess.net/wp-content/uploads/2023/11/Session-3_Strict-protection-BS2030.pdf

Chen, M., Jiang, S., Han, A., Yang, M., Tkalich, P., & Liu, M. (2024). Bunkering for change: Knowledge preparedness on the environmental aspect of ammonia as a marine fuel. *Science of The Total Environment*, *907*, 167677. https://doi.org/10.1016/j.scitotenv.2023.167677

Chu, Y., & Cui, H. (2023). Annual update on the global transition to electric vehicles: 2022. *International Council on Clean Transportation*. https://theicct.org/publication/global-transition-electric-vehicles-update-jun23/

Ciucci, M. (2024). *Renewable Energy*. https://www.europarl.europa.eu/erpl-app-public/factsheets/pdf/en/FTU_2.4.9.pdf

Clapham, S. J., & Slater, F. (2008). The biodiversity of established biomass grass crops. *Aspects of Applied Biology*, *90*.

Comer, B., & Carvalho, F. (2023). IMO's newly revised GHG strategy: What it means for shipping and the Paris Agreement. *The International Council on Clean Transportation*. https://theicct.org/marine-imo-updated-ghg-strategy-jul23/

Comer, B., O'Malley, J., Osipova, L., & Pavlenko, N. (2022). COMPARING THE FUTURE DEMAND FOR, SUPPLY OF, AND LIFE-CYCLE EMISSIONS FROM BIO, SYNTHETIC, AND FOSSIL LNG MARINE FUELS IN THE EUROPEAN UNION. https://theicct.org/wp-content/uploads/2022/09/Renewable-LNG-Europe_report_FINAL.pdf

Cong, W., Hoffland, E., Li, L., Six, J., Sun, J., Bao, X., Zhang, F., & Van Der Werf, W. (2015). Intercropping enhances soil carbon and nitrogen. *Global Change Biology*, *21*(4), 1715–1726. https://doi.org/10.1111/gcb.12738

Cremer, K. W. (2003). Introduced willows can become invasive pests in Australia. *Biodiversity*, *4*(4), 17–24. https://doi.org/10.1080/14888386.2003.9712705

Crosti, R., Agrillo, E., Ciccarese, L., Guarino, R., Paris, P., & Testi, A. (2016). Assessing escapes from short rotation plantations of the invasive tree species Robinia pseudoacacia L. in Mediterranean ecosystems: A study in central Italy. *IForest*, 9(5), 822–828. https://doi.org/10.3832/ifor1526-009

Crowley, J. (2024). Drax: UK power station still burning rare forest wood. *BBC News*. https://www.bbc.co.uk/news/science-environment-68381160

Cunningham, H. M., Chaney, K., Bradbury, R. B., & Wilcox, A. (2004). Non-inversion tillage and farmland birds: a review with special reference to the UK and Europe. *Ibis*, *146*(s2), 192–202. https://doi.org/10.1111/j.1474-919X.2004.00354.x

Czyrnek-Delêtre, M. M., Chiodi, A., Murphy, J. D., & Ó Gallachóir, B. P. (2016). Impact of including land-use change emissions from biofuels on meeting GHG emissions reduction targets: the example of Ireland. *Clean Technologies and Environmental Policy*, *18*(6), 1745–1758. https://doi.org/10.1007/s10098-016-1145-8

Dabney, S. M., Delgado, J. A., & Reeves, D. W. (2001). USING WINTER COVER CROPS TO IMPROVE SOIL AND WATER QUALITY. *Communications in Soil Science and Plant Analysis*, *32*(7–8), 1221–1250. https://doi.org/10.1081/CSS-100104110

Dalin, P., Kindvall, O., & Björkman, C. (2009). Reduced Population Control of an Insect Pest in Managed Willow Monocultures. *PLoS ONE*, *4*(5), e5487. https://doi.org/10.1371/journal.pone.0005487

Dallara, E. S. (2011). *AIRCRAFT DESIGN FOR REDUCED CLIMATE IMPACT* [Stanford University]. https://stacks.stanford.edu/file/druid:yf499mg3300/thesis_online_final-augmented.pdf

Dauber, J., Jones, M. B., & Stout, J. C. (2010). The impact of biomass crop cultivation on temperate biodiversity. *GCB Bioenergy*, *2*(6), 289–309. https://doi.org/10.1111/j.1757-1707.2010.01058.x

DAUBER, J., JONES, M. B., & STOUT, J. C. (2010). The impact of biomass crop cultivation on temperate biodiversity. *GCB Bioenergy*, *2*(6), 289–309. https://doi.org/10.1111/j.1757-1707.2010.01058.x

Dawson, L., Ware, J., & Vest, L. (2022). *Ammonia at sea: studying the potential impact of ammonia as a shipping fuel on marine ecosystems*. https://www.ricardo.com/media/cq0hbh0x/ammonia_environmental_impact_study-2.pdf

de Vries, F. T., & Wallenstein, M. D. (2017). Below-ground connections underlying above-ground food production: a framework for optimising ecological connections in the rhizosphere. In *Journal of Ecology* (Vol. 105, Issue 4, pp. 913–920). Blackwell Publishing Ltd. https://doi.org/10.1111/1365-2745.12783

Derouaux, A. , Verbelen, D., Devos, K., & Paquet, J.-Y. (2020). *Reducing the risk of bird collisions with high-voltage power lines in Belgium through sensitivity mapping: 2020 update*. https://www.elia.be/-/media/project/elia/elia-site/sustainability/environement/biodiverity-and-rehabilitation-of-natural-habitats/20201214_elia_c208748146444_risk_map_for_belgium_update2020_report_final_en.pdf?la=en

Desrochers, V., Frenette-Dussault, C., Guidi Nissim, W., Brisson, J., & Labrecque, M. (2020). Using willow microcuttings for ecological restoration: An alternative method for establishing dense plantations. *Ecological Engineering*, *151*, 105859. https://doi.org/10.1016/j.ecoleng.2020.105859

Dhavle, J., Boshell, F., & Roesch, R. (2024). *Floating offshore wind outlook*. https://www.irena.org/Publications/2024/Jul/Floating-offshore-wind-outlook

Di Gruttola, F., & Borello, D. (2021). Analysis of the EU Secondary Biomass Availability and Conversion Processes to Produce Advanced Biofuels: Use of Existing Databases for Assessing a Metric Evaluation for the 2025 Perspective. *Sustainability*, *13*(14), 7882. https://doi.org/10.3390/su13147882

Di Lucia, L., Ahlgren, S., & Ericsson, K. (2012). The dilemma of indirect land-use changes in EU biofuel policy - An empirical study of policy-making in the context of scientific uncertainty. *Environmental Science and Policy*, *16*, 9–19. https://doi.org/10.1016/j.envsci.2011.11.004

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., … Zayas, C. N. (2019). REVIEW SUMMARY Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* . https://doi.org/10.1126/science.aaw3100

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., … Zayas, C. N. (2019). *Global Assessment Report on Biodiversity and Ecosystem Services*. https://doi.org/10.5281/zenodo.3553579

Dickmann, D. (2001). *Poplar Culture in North America*. NRC Research Press. https://books.google.co.uk/books?id=GRtdQYO_ejUC

Dickson, B., Miles, L., Thornton, H., & O'Connell, E. (2021). *Becoming #GenerationRestoration: Ecosystem Restoration for People, Nature and Climate*. https://wedocs.unep.org/bitstream/handle/20.500.11822/36251/ERPNC.pdf

DNV Maritime. (2023). Energy Transition Outlook 2023 – Maritime Forecast to 2050.

Dobbelaere, D. (2022). *Statistical Overview of the Animal By Products Industry in the EU in 2022*. https://efpra2023naples.eu/wp-content/uploads/2023/07/DIRK-STAS-NAPOLI.pdf

Dobor, L., Hlásny, T., Rammer, W., Zimová, S., Barka, I., & Seidl, R. (2020). Is salvage logging effectively dampening bark beetle outbreaks and preserving forest carbon stocks? *Journal of Applied Ecology*, *57*(1), 67–76. https://doi.org/10.1111/1365-2664.13518

Donald, P. F., Green, R. E., & Heath, M. F. (2001). Agricultural Intensification and the Collapse of Europe's Farmland Bird Populations. *Proceedings: Biological Sciences*, *268*(1462). https://www.jstor.org/stable/3067728

Donald, P. F., Sanderson, F. J., Burfield, I. J., & van Bommel, F. P. J. (2006). Further evidence of continent-wide impacts of agricultural intensification on European farmland birds, 1990–2000. *Agriculture, Ecosystems & Environment*, *116*(3–4), 189–196. https://doi.org/10.1016/j.agee.2006.02.007

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., Harding, H. R., Havlik, M. N., Meekan, M., Merchant, N. D., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., … Juanes, F. (2021). The soundscape of the Anthropocene ocean. *Science*, *371*(6529). https://doi.org/10.1126/science.aba4658

E3MLab, ECORYS, EFI, Eurocare, IUNG, WIP, & Renewable Energies. (2017). Research and Innovation perspective of the mid-and long-term Potential for Advanced Biofuels in Europe | D1.4 Forecast of feedstock availability generated from residues/waste. https://op.europa.eu/en/publication-detail/-/publication/5d857ff6-063a-11e8-b8f5-01aa75ed71a1/language-en

Earth Insight. (2024). Anything But Natural: Liquefied Natural Gas (LNG) Infrastructure Expansion Threats to Coastal & Marine Ecosystems.

EASA. (2022). *Current landscape and future of SAF industry*. European Aviation Environmental Report. https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/current-landscape-future-saf-industry#production-capacity-and-demand-2020-to-2030

EASAC. (2017). Multi-functionality and sustainability in the European Union's forests. In *EASAC Policy Report: Volume 32* (Issue April). https://easac.eu/publications/details/multi-functionality-and-sustain-ability-in-the-european-unions-forests/

ECJ. (2016). Judgment of the Court (Fifth Chamber) of 24 November 2016 | European Commission v Kingdom of Spain | Case C-461/14. *European Court of Justice*. https://curia.europa.eu/juris/liste.jsf?num=C-461/14

ECJ. (2021). Judgment of the Court (First Chamber) of 24 June 2021 | European Commission v Kingdom of Spain | Case C-559/19. *European Court of Justice*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A62019CJ0559

EEA. (2012). *Proportion of endemic species in Annex II to the Habitats Directive*. European Environment Agency. https://www.eea.europa.eu/data-and-maps/figures/proportion-of-endemic-species-in

EEA. (2019). *Land cover and change accounts 2000-2018*. European Environment Agency. https://www.eea.europa.eu/data-and-maps/dashboards/land-cover-and-change-statistics

EEA. (2020). *State of nature in the EU: Results from reporting under the nature directives 2013-2018*. https://www.eea.europa.eu/publications/state-of-nature-in-the-eu-2020

EEA. (2022a). Natura 2000 Barometer. *European Environment Agency*. https://www.eea.europa.eu/data-and-maps/dashboards/natura-2000-barometer

EEA. (2022b). *Natura 2000 sites designated under the EU Habitats and Birds Directives*. European Environment Agency. https://www.eea.europa.eu/en/analysis/indicators/natura-2000-sites-designated-under

EEA. (2023a). *European forest ecosystems: key allies in sustainable development*. European Environment Agency. https://www.eea.europa.eu/publications/european-forest-ecosystems-key-allies

EEA. (2023b). *Marine protected areas in Europe's seas*. European Environment Agency. https://www.eea.europa.eu/en/analysis/indicators/marine-protected-areas-in-europes-seas

EEA. (2023c). *Monitoring report on progress towards the 8th EAP objectives 2023 edition*. https://www.eea.europa.eu/publications/european-union-8th-environment-action-programme

EEA. (2023d). *Terrestrial protected areas in Europe*. European Environment Agency. https://www.eea.europa.eu/en/analysis/indicators/terrestrial-protected-areas-in-europe

EEA. (2024a). *Biodiversity: state of habitats and species*. European Environment Agency. https://www.eea.europa.eu/en/topics/in-depth/biodiversity

EEA. (2024b). *EEA greenhouse gases — data viewer*. European Environment Agency. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

EEA. (2024c). *Harvest*. European Environment Agency Forest Information System for Europe. https://forest.eea.europa.eu/topics/forest-management/harvest

EEA. (2024d). *Post-disturbance forest management*. European Environment Agency Forest Information System for Europe. https://forest.eea.europa.eu/topics/forest-management/post-disturbance-forest-management

EFSA. (2013). Guidance on the risk assessment of plant protection products on bees (Apis mellifera, Bombus spp. and solitary bees). *European Food Safety Authority Journal*, *11*(7). https://doi.org/10.2903/j.efsa.2013.3295

EIP-AGRI. (2021). *Sustainable industrial crops*. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_industrial_crops_final_report_2021_en.pdf

Element Energy. (2022). *The Role of Aviation Demand Reduction in UK Decarbonisation*. https://www.aef.org.uk/uploads/2022/05/The-Role-of-Aviation-Demand-in-Decarbonisation-Full-Report.pdf

Elowson, S. (1999). Willow as a vegetation filter for cleaning of polluted drainage water from agricultural land. *Biomass and Bioenergy*, *16*(4), 281–290. https://doi.org/10.1016/S0961-9534(98)00087-7

Entrekin, S., Evans-White, M., Johnson, B., & Hagenbuch, E. (2011). Rapid expansion of natural gas development poses a threat to surface waters. *Frontiers in Ecology and the Environment*, *9*(9), 503–511. https://doi.org/10.1890/110053

Esqué, A., Fuchs, G., & Riedel, R. (2022). Fuel efficiency: Why airlines need to switch to more ambitious measures. *Future Air Mobility Blog*. https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/fuel-efficiency-why-airlines-need-to-switch-to-more-ambitious-measures

Essl, F., Lenzner, B., Bacher, S., Bailey, S., Capinha, C., Daehler, C., Dullinger, S., Genovesi, P., Hui, C., Hulme, P. E., Jeschke, J. M., Katsanevakis, S., Kühn, I., Leung, B., Liebhold, A., Liu, C., MacIsaac, H. J., Meyerson, L. A., Nuñez, M. A., … Roura-Pascual, N. (2020). Drivers of future alien species impacts: An expert-based assessment. *Global Change Biology*, *26*(9), 4880–4893. https://doi.org/10.1111/gcb.15199

EU Innovation Fund. (2024). *Methodology for GHG Emission Avoidance Calculation*. https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/innovfund/guidance/ghg-emission-avoidance-methodology_innovfund_en.pdf

European Commission. (2018a). Commission notice: Energy transmission infrastructure and EU nature legislation. *Official Journal of the European Union*, *2018/C*(213/02). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2018.213.01.0062.01.ENG

European Commission. (2018b). Commission notice: 'Guidance document on the requirements for hydropower in relation to EU nature legislation.' *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2018.213.01.0001.01.ENG

European Commission. (2018c). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE

OF THE REGIONS EU Pollinators Initiative. *COM/2018/395 Final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1528213737113&uri=CELEX:52018DC0395

European Commission. (2020a). *A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system (COM 2020 381 final)*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381

European Commission. (2020b). *Bringing nature back into our lives | EU 2030 Biodiversity Strategy*. https://ec.europa.eu/commission/presscorner/api/files/attachment/865560/factsheet-EU-biodiversity-strategy_en.pdf

European Commission. (2020c). Commission Staff Working Document Accompanying the document "Report from the Commission 2019 Annual Report on CO_2 Emissions from Maritime Transport." *SWD(2020) 82 Final* . https://climate.ec.europa.eu/system/files/2020-05/swd_2020_82_en.pdf

European Commission. (2020d). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Biodiversity Strategy for 2030 Bringing nature back into our lives | COM/2020/380 final. *EUR-Lex*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380

European Commission. (2020°). *EU Reference Scenario 2020*. Directorate General for Energy. https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

European Commission. (2020f). *Guidance document on wind energy developments and EU nature legislation*. https://data.europa.eu/doi/10.2779/457035

European Commission. (2021a). EU Soil Strategy for 2030. Reaping the benefits of healthy soils for people, food, nature and climate. COM(2021) 699 final. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*, 1–26. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0699

European Commission. (2021b). Impact Assessment accompanying the Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport | SWD(2021) 635 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2021:635:FIN

European Commission. (2021c). Proposal for a Council directive restructuring the Union framework for the taxation of energy products and electricity (recast EU ETD). 0213.

European Commission. (2021d). *Sustainable & Smart Mobility Strategy*. https://transport.ec.europa.eu/document/download/be22d311-4a07-4c29-8b72-d6d255846069_en?filename=2021-mobility-strategy-and-action-plan.pdf

European Commission. (2021[e]). *Zero Pollution Action Plan*. Directorate-General for Environment. https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en

European Commission. (2022). *Criteria and guidance for protected areas designations - Staff Working Document*. https://environment.ec.europa.eu/publications/criteria-and-guidance-protected-areas-designations-staff-working-document_en

European Commission. (2023a). *Approved 28 CAP Strategic Plans (2023-2027)* . https://agriculture.ec.europa.eu/document/download/7b3a0485-c335-4e1b-a53a-9fe3733ca48f_en?filename=approved-28-cap-strategic-plans-2023-27.pdf

European Commission. (2023b). Commission Delegated Regulation on the production of RFNBOs. *Commission Delegated Regulation (EU) 2023/1184*. https://energy.ec.europa.eu/publications/delegated-regulation-union-methodology-rfnbos_en

European Commission. (2023c). COMMISSION STAFF WORKING DOCUMENT accompanying the Fourth Annual Report from the European Commission on CO_2 Emissions from Maritime Transport (period 2018-2021). *SWD(2023) 54 Final*. https://climate.ec.europa.eu/system/files/2023-03/swd_2023_54_en.pdf

European Commission. (2023d). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE

OF THE REGIONS Revision of the EU Pollinators Initiative A new deal for pollinators. *COM/2023/35 Final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A35%3AFIN&qid=1674555285177

European Commission. (2023e). *GHG emissions of all world countries*. EDGAR - Emissions Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/report_2023

European Commission. (2023f). *Guidelines for Defining, Mapping, Monitoring and Strictly Protecting EU Primary and Old-Growth Forests*. https://environment.ec.europa.eu/publications/guidelines-defining-mapping-monitoring-and-strictly-protecting-eu-primary-and-old-growth-forests_en

European Commission. (2023g). *Guidelines for Defining, Mapping, Monitoring and Strictly Protecting EU Primary and Old-Growth Forests*. https://environment.ec.europa.eu/publications/guidelines-defining-mapping-monitoring-and-strictly-protecting-eu-primary-and-old-growth-forests_en

European Commission. (2023h). *Guidelines on Biodiversity-Friendly Afforestation, Reforestation and Tree Planting*. https://environment.ec.europa.eu/publications/guidelines-biodiversity-friendly-afforestation-reforestation-and-tree-planting_en

European Commission. (2023i). Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law) COM(2023) 416 final. https://doi.org/10.1016/b978-0-12-822974-3.00131-2

European Commission. (2023j). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on a monitoring framework for resilient European forests. *COM/2023/728 Final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A728%3AFIN

European Commission. (2023k). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act). *COM(2023) 161 Final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN

European Commission. (2023l). *What is the EU ETS?* Directorate-General for Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/what-eu-ets_en

European Commission. (2024a). Annex to the Commission Delegated Directive (EU) amending Annex IX to Directive (EU) 2018/2001 of the European Parliament and of the Council, as regards adding feedstock for the production of biofuels and biogas. https://ec.europa.eu/info/law/better-regulation/

European Commission. (2024b). *Cereals statistics*. Directorate-General for Agriculture and Rural Development. https://agriculture.ec.europa.eu/data-and-analysis/markets/overviews/market-observatories/crops/cereals-statistics_en

European Commission. (2024c). Guidance on designating renewables acceleration areas. Commission Recommendation on Speeding up Permit-Granting Procedures for Renewable Energy and Related Infrastructure Projects, SWD(2024) 333 final. https://energy.ec.europa.eu/publications/guidance-designating-renewables-acceleration-areas_en

European Commission. (2024d). *Methane emissions*. Directorate-General for Energy. https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/methane-emissions_en

European Commission. (2024e). *National energy and climate plans*. Directorate-General for Climate Action. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

European Commission. (2024f). *National energy and climate plans*. Energy and Climate Governance and Reporting. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en#documents

European Commission. (2024g). *Natural or other area-specific constraints*. Directorate-General for Agriculture and Rural Development. https://agriculture.ec.europa.eu/common-agricultural-policy/income-support/additional-schemes/anc-payment_en

European Commission. (2024h). *Oilseeds and protein crops statistics*. Directorate-General for Agriculture and Rural Development. https://agriculture.ec.europa.eu/data-and-analysis/markets/overviews/market-observatories/crops/oilseeds-and-protein-crops_en

European Commission. (2024i, January 31). Commission proposes to allow EU farmers to derogate for one year from certain agricultural rule. *Press Release*. https://ec.europa.eu/commission/presscorner/detail/en/ip_24_582

European Commission Joint Research Centre. (2023). *ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials*. Joint Research Centre Data Catalogue. https://data.jrc.ec.europa.eu/collection/id-00138

European Council. (2024). *Where does the EU's gas come from?* https://www.consilium.europa.eu/en/infographics/eu-gas-supply/

European Environment Agency. (2021). *Ecological status of surface waters in Europe*. EEA. https://www.eea.europa.eu/en/analysis/indicators/ecological-status-of-surface-waters

European Environment Agency. (2022). *Water abstraction by source and economic sector in Europe*. Analysis and Data. https://www.eea.europa.eu/en/analysis/indicators/water-abstraction-by-source-and

European Environment Agency. (2024). *Endemism of EU native species — amphibians, reptiles, mammals, dragonflies and butterflies*. https://www.eea.europa.eu/en/analysis/maps-and-charts/endemism-of-eu-native-species

European Environmental Bureau. (2024). *EEB's response to the European Commission's call for evidence: Guidance on designating renewables acceleration areas*. https://eeb.org/wp-content/uploads/2024/02/EEB-response-to-EC-call-for-evidence-on-RAA-designation_20240223.pdf

European Hydrogen Observatory. (2023). *The European hydrogen market landscape*. https://observatory.clean-hydrogen.europa.eu/sites/default/files/2023-11/Report%2001%20-%20November%202023%20-%20The%20European%20hydrogen%20market%20landscape.pdf

European Parliament. (2023). *The European Union and forests*. The Common Agricultural Policy (CAP). https://www.europarl.europa.eu/factsheets/en/sheet/105/the-european-union-and-forests

European Union. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Union*. http://data.europa.eu/eli/dir/2000/60/oj

European Union. (2001). Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment. *Official Journal of the European Union*. http://data.europa.eu/eli/dir/2001/42/oj

European Union. (2008a). Consolidated text: Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy. *Official Journal of the European Union*. http://data.europa.eu/eli/dir/2008/105/2013-09-13

European Union. (2008b). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). *Official Journal of the European Union*, *164*(19). http://data.europa.eu/eli/dir/2008/56/oj

European Union. (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. *Official Journal of the European Union*, *140*, 16–62. https://doi.org/10.3000/17252555.L_2009.140.eng

European Union. (2013). Consolidated text: Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. https://eur-lex.europa.eu/eli/dir/1992/43/2013-07-01

European Union. (2014a). Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment Text with EEA relevance. *Official Journal of the European Union*. http://data.europa.eu/eli/dir/2014/52/oj

European Union. (2014b). Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R1143&from=EN

European Union. (2018a). Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, *L 328*, 82–209. https://eur-lex.europa.eu/eli/dir/2018/2001/2018-12-21

European Union. (2018b). Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending | LULUCF Regulation. *Official Journal of the European Union*, *May*, Art. EU 2018/841. https://eur-lex.europa.eu/eli/reg/2018/841/oj

European Union. (2021). CAP Strategic Plan 2021 | Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021. *Official Journal of the European Union*, *2021*(November), 435/1-435/186. https://eur-lex.europa.eu/eli/reg/2021/2115/oj

European Union. (2023a). Consolidated text: Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport | ReFuelEU Aviation. *EUR-Lex*. https://eur-lex.europa.eu/eli/reg/2023/2405

European Union. (2023b). Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council. *Official Journal of the European Union*, *2413*(401), 1–77. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413&qid=1699364355105

European Union. (2023c). Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. https://eur-lex.europa.eu/eli/reg/2023/1805/oj

European Union. (2024). REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on nature restoration. *European Parliament*. https://data.consilium.europa.eu/doc/document/PE-74-2023-INIT/en/pdf

Eurostat. (2023). *Use of renewables for transport*. Energy Statistics Nrg_ind_urtd. https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_urtd/default/table?lang=en

Eurostat. (2024a). *Agri-environmental indicator - consumption of pesticides*. Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_consumption_of_pesticides

Eurostat. (2024b). *Greenhouse gas emissions by source sector*. Air Emission Inventories. https://doi.org/10.2908/ENV_AIR_GGE

Eurostat. (2024c). *Gross and net production of electricity and derived heat by type of plant and operator*. Energy Statistics Nrg_ind_peh. https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_peh/default/table?lang=en

Eurostat. (2024d). *Pesticide use in agriculture*. Aei_pestuse. https://ec.europa.eu/eurostat/databrowser/view/aei_pestuse/

Eurostat. (2024e). *Simplified energy balances*. Energy Statistics Nrg_bal_s. https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_s__custom_11915732/default/table?lang=en

Eurostat. (2024f). Use of fertilisers in EU agriculture down 10% in 2022. *Eurostat News Articles*. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240628-1

Eurostat. (2024g). *Use of renewables for transport (2024) | nrg_ind_urtd*. https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_urtd/default/table?lang=en&category=nrg.nrg_quant.nrg_quanta.nrg_ind_share

Eurostat. (2024h). *Utilised agricultural area by categories*. Apro_cpsh1. https://doi.org/10.2908/TAG00025

EWABA. (2021). *EWABA Position paper on the ReFuelEU Aviation proposal* . https://www.ewaba.eu/_uploads/resources/Position-Papers/EWABAResponseReFuelEUconsultation.pdf

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B. E., van der Loeff, W. S., Smith, T., Zhang, Y., Kosaka, H., Adachi, M., Bonello, J.-M., Galbraith, C., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D. S., Liu, Y., Lucchesi, A., … Xing, H. (2021). *Fourth IMO GHG Study*. https://greenvoyage2050.imo.org/wp-content/uploads/2021/07/Fourth-IMO-GHG-Study-2020-Full-report-and-annexes_compressed.pdf

Faber, J., Huigen, T., & Nelissen, D. (2017). *Regulating speed: a short-term measure to reduce maritime GHG emissions*. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7L90_Regulating_speed_DEF.pdf

Faber, J., Nelissen, D., Ahdour, S., Harmsen, J., Toma, T., & Layla Lebesque. (2017). Study on the Completion of an EU Framework on LNG-fuelled Ships and its Relevant Fuel Provision Infrastructure.

Faber, J., 't Hoen, M., Vergeer, R., & Calleya, J. (2016). *Study of historical trends in ship design efficiency*. https://www.transportenvironment.org/uploads/files/2016_CE_Delft_Historical_Trends_in_Ship_Design_Efficiency.pdf

FAO. (2022). State of Knowledge of Soil Biodiversity. Intergovernmental Technical Panel on Initiative, Global Soil Biodiversity Diversity, Convention on Biological Commission, European. In *Soil in the Environment*.

FAOstat. (2024). *Crops and livestock products*. QCL. https://www.fao.org/faostat/en/#data/QCL

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, *319*(5867), 1235–1238. https://doi.org/10.1126/science.1152747

Farkas, A., Degiuli, N., Martić, I., & Mikulić, A. (2023). Benefits of slow steaming in realistic sailing conditions along different sailing routes. *Ocean Engineering*, *275*, 114143. https://doi.org/10.1016/j.oceaneng.2023.114143

Fayet, C. M. J., Reilly, K. H., Van Ham, C., & Verburg, P. H. (2022a). The potential of European abandoned agricultural lands to contribute to the Green Deal objectives: Policy perspectives. *Environmental Science and Policy*, *133*, 44–53. https://doi.org/10.1016/j.envsci.2022.03.007

Fayet, C. M. J., Reilly, K. H., Van Ham, C., & Verburg, P. H. (2022b). What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe. *Land Use Policy*, *112*, 105833. https://doi.org/10.1016/j.landusepol.2021.105833

FERN. (2021, July). *Forest Strategy: encouraging but too timid to face up to the challenge*. FERN News. https://www.fern.org/publications-insight/forest-strategy-encouraging-but-too-timid-to-face-up-to-the-challenge-2373/

Fernando, A. L., Rettenmaier, N., Soldatos, P., & Panoutsou, C. (2018). Sustainability of Perennial Crops Production for Bioenergy and Bioproducts. In *Perennial Grasses for Bioenergy and Bioproducts* (pp. 245–283). Elsevier. https://doi.org/10.1016/B978-0-12-812900-5.00008-4

Ferrer, M., Alloing, A., Baumbush, R., & Morandini, V. (2022). Significant decline of Griffon Vulture collision mortality in wind farms during 13-year of a selective turbine stopping protocol. *Global Ecology and Conservation*, *38*. https://doi.org/10.1016/j.gecco.2022.e02203

Ferrer, M., Morandini, V., Baumbusch, R., Muriel, R., De Lucas, M., & Calabuig, C. (2020). Efficacy of different types of "bird flight diverter" in reducing bird mortality due to collision with transmission power lines. *Global Ecology and Conservation*, *23*. https://doi.org/10.1016/j.gecco.2020.e01130

Findlay, C. R., Rojano-Doñate, L., Tougaard, J., Johnson, M. P., & Madsen, P. T. (2023). Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals. *Science Advances*, *9*(25). https://doi.org/10.1126/sciadv.adf2987

Fischer, C. ;, Smit, T. ;, Michalski, J. ;, Yearwood, J. ;, van Nuffel, L. ;, & De Vita, A. (2020). *Impact of the use of the biomethane and hydrogen potential on trans-European infrastructure*. https://op.europa.eu/en/publication-detail/-/publication/10e93b15-8b56-11ea-812f-01aa75ed71a1/language-en

Ford, J. S., Bale, C. S. E., & Taylor, P. G. (2024). The factors determining uptake of energy crop cultivation and woodland creation in England: Insights from farmers and landowners. *Biomass and Bioenergy*, *180*(December 2023), 107021. https://doi.org/10.1016/j.biombioe.2023.107021

Foster, W. A., Snaddon, J. L., Turner, E. C., Fayle, T. M., Cockerill, T. D., Farnon Ellwood, M. D., Broad, G. R., Chung, A. Y. C., Eggleton, P., Khen, C. V., & Yusah, K. M. (2011). Establishing the evidence base for maintaining biodiversity and ecosystem function in the oil palm landscapes of South East Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*(1582), 3277–3291. https://doi.org/10.1098/rstb.2011.0041

Fritz, B., Horváth, G., Hünig, R., Pereszlényi, Á., Egri, Á., Guttmann, M., Schneider, M., Lemmer, U., Kriska, G., & Gomard, G. (2020). Bioreplicated coatings for photovoltaic solar panels nearly eliminate light pollution that harms polarotactic insects. *PLoS ONE*, *15*(12 December). https://doi.org/10.1371/journal.pone.0243296

Gabriel, D., Sait, S. M., Hodgson, J. A., Schmutz, U., Kunin, W. E., & Benton, T. G. (2010). Scale matters: the impact of organic farming on biodiversity at different spatial scales. *Ecology Letters*, *13*(7), 858–869. https://doi.org/10.1111/j.1461-0248.2010.01481.x

Gális, M., Ševčík, M., Brndiar, J., Cibula, P., Csepányiová, D., Drahovský, V., Hapl, E., Jarošíková, M., Kňazovičová, L., Laboš, P., Lőbbová, D., Majdanová, L., Petluš, P., Petlušová, V., Ratičák, J., Riflik, Z., Slobodník, R., Šmídt, J., Szabo, M., … Zemko, M. (2020). Monitoring of effectiveness of bird flight diverters in preventing bird mortality from powerline collisions in Slovakia. *Raptor Journal*, *13*(1). https://doi.org/10.2478/srj20190005

Gallop, P. (2023). *TOWARDS A RENEWABLES SCALE-UP THAT WORKS FOR NATURE*. https://feps-europe.eu/wp-content/uploads/2023/06/Towards-a-renewables-scale-up-that-works-for-nature.pdf

Galparsoro, I., Menchaca, I., Seeger, I., Nurmi, M., Mcdonald, H., Garmendia, M., Pouso, S., & Borja, Á. (2022). *Mapping potential environmental impacts of offshore renewable energy*. https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm-reports/etc-icm-report-2-2022-mapping-potential-environmental-impacts-of-offshore-renewable-energy

García-Nieto, A. P., García-Llorente, M., Iniesta-Arandia, I., & Martín-López, B. (2013). Mapping forest ecosystem services: From providing units to beneficiaries. *Ecosystem Services*, *4*, 126–138. https://doi.org/10.1016/j.ecoser.2013.03.003

Gardi, C., Jeffery, S., & Saltelli, A. (2013). An estimate of potential threats levels to soil biodiversity in EU. *Global Change Biology*, *19*(5), 1538–1548. https://doi.org/10.1111/gcb.12159

Gasparatos, A., Doll, C. N. H., Esteban, M., Ahmed, A., & Olang, T. A. (2017). Renewable energy and biodiversity: Implications for transitioning to a Green Economy. In *Renewable and Sustainable Energy Reviews* (Vol. 70, pp. 161–184). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.08.030

Gaston, K. J. (2000). *Global patterns in biodiversity*. www.nature.com

Gaveau, D. L. A., Locatelli, B., Salim, M. A., Husnayaen, Manurung, T., Descals, A., Angelsen, A., Meijaard, E., & Sheil, D. (2022). Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices. *PLoS ONE*, *17*(3 March), 1–19. https://doi.org/10.1371/journal.pone.0266178

Gavin, G. (2024, April 24). EU countries dilute fuel tax hike as green anger mounts. *Politico*. https://www.politico.eu/article/european-union-fuel-tax-energy-taxation-directive/

Geiger, F., Bengtsson, J., Berendse, F., Weisser, W. W., Emmerson, M., Morales, M. B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L. W., Dennis, C., Palmer, C., Oñate, J. J., … Inchausti, P. (2010). Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic and Applied Ecology*, *11*(2), 97–105. https://doi.org/10.1016/j.baae.2009.12.001

Genell, A., Johansson, T., Andersson, C. , Glebe, D., & Krång, A. S. (2023). *Measuring noise from ships underway* . https://fudinfo.trafikverket.se/fudinfoexternwebb/Publikationer/Publikationer_007501_007600/Publikation_007588/SHIPNOISE%20slutrapport.pdf

Gensch, L., Jantke, K., Rasche, L., & Schneider, U. A. (2024). Pesticide risk assessment in European agriculture: Distribution patterns, ban-substitution effects and regulatory implications. *Environmental Pollution*, *348*, 123836. https://doi.org/10.1016/j.envpol.2024.123836

Gerwin, W., Repmann, F., Galatsidas, S., Vlachaki, D., Gounaris, N., Baumgarten, W., Volkmann, C., Keramitzis, D., Kiourtsis, F., & Freese, D. (2018). Assessment and quantification of marginal lands for biomass production in Europe using soil-quality indicators. *Soil*, *4*(4), 267–290. https://doi.org/10.5194/soil-4-267-2018

Gherasim, C. (2024). Illegal logging plagues Romania. *EUreporter*. https://www.eureporter.co/world/romania/2024/05/07/illegal-logging-plagues-romania/

Ghosh, A. (2023). A comprehensive review of water based PV: Flotavoltaics, under water, offshore & canal top. *Ocean Engineering*, *281*, 115044. https://doi.org/10.1016/j.oceaneng.2023.115044

Giannelos, G., Humphris-Bach, A., Davies, A., Baxter, B., Cames, M., Kasten, P., Siskos, P., Tsiropoulos, I., Kalokyris, T., & Statharas, S. (2021). *Study supporting the impact assessment of the ReFuelEU Aviation initiative*.

Gibon, T., Menacho, Á. H., & Guiton, M. (2022). *Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources*. https://unece.org/sites/default/files/2022-04/LCA_3_FINAL%20March%202022.pdf

Godard, C., Boissy, J., & Gabrielle, B. (2013). Life-cycle assessment of local feedstock supply scenarios to compare candidate biomass sources. *GCB Bioenergy*, *5*(1), 16–29. https://doi.org/10.1111/j.1757-1707.2012.01187.x

Gordalla, B. C., Ewers, U., & Frimmel, F. H. (2013). Hydraulic fracturing: a toxicological threat for groundwater and drinking-water? *Environmental Earth Sciences*, *70*(8), 3875–3893. https://doi.org/10.1007/s12665-013-2672-9

Goulson, D. (2013). REVIEW: An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*, *50*(4), 977–987. https://doi.org/10.1111/1365-2664.12111

Grady, K., & Nleya, T. (2010). Camelina Production. *Extension Extra (South Dakota State University)*. https://agresearch.montana.edu/wtarc/producerinfo/agronomy-nutrient-management/Camelina/SDSUFactSheet.pdf

Grass, I., Batáry, P., & Tscharntke, T. (2021). *Combining land-sparing and land-sharing in European landscapes* (pp. 251–303). https://doi.org/10.1016/bs.aecr.2020.09.002

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., Tiede, J., Udy, K., Westphal, C., Wurz, A., & Tscharntke, T. (2019). Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People and Nature*, *1*(2), 262–272. https://doi.org/10.1002/pan3.21

Grassi, G., Fiorese, G., Pilli, R., Jonsson, K., Blujdea, V., Korosuo, A., & Vizzarri, M. (2021). *Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution*. 1–16. https://publications.jrc.ec.europa.eu/repository/handle/JRC124374

Gulli, C., Heid, B., Noffsinger, J., Waardenburg, M., & Wilthaner, M. (2024). *Global Energy Perspective 2023: Hydrogen outlook*. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-hydrogen-outlook

Gurr, G. M., Wratten, S. D., & Luna, J. M. (2003). Multi-function agricultural biodiversity: pest management and other benefits. *Basic and Applied Ecology*, *4*(2), 107–116. https://doi.org/10.1078/1439-1791-00122

Gustafsson, K., Sadegh-Vaziri, R., Grönkvist, S., Levihn, F., & Sundberg, C. (2021). BECCS with combined heat and power: Assessing the energy penalty. *International Journal of Greenhouse Gas Control*, *108*, 103248. https://doi.org/10.1016/j.ijggc.2020.103248

Gustafsson, L., Kouki, J., & Sverdrup-Thygeson, A. (2010). Tree retention as a conservation measure in clear-cut forests of northern Europe: a review of ecological consequences. *Scandinavian Journal of Forest Research*, *25*(4), 295–308. https://doi.org/10.1080/02827581.2010.497495

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., Lovejoy, T. E., Sexton, J. O., Austin, M. P., Collins, C. D., Cook, W. M., Damschen, E. I., Ewers, R. M., Foster, B. L., Jenkins, C. N., King, A. J., Laurance, W. F., Levey, D. J., Margules, C. R., … Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, *1*(2). https://doi.org/10.1126/sciadv.1500052

Haeler, E., Stillhard, J., Hindenlang Clerc, K., Pellissier, L., & Lachat, T. (2024). Dead wood distributed in different-sized habitat patches enhances diversity of saproxylic beetles in a landscape experiment. *Journal of Applied Ecology*, *61*(2), 316–327. https://doi.org/10.1111/1365-2664.14554

Hangs, R. D., Schoenau, J. J., Van Rees, K. C. J., Bélanger, N., & Volk, T. (2014). Leaf Litter Decomposition and Nutrient-Release Characteristics of Several Willow Varieties Within Short-Rotation Coppice Plantations in Saskatchewan, Canada. *BioEnergy Research*, *7*(4), 1074–1090. https://doi.org/10.1007/s12155-014-9431-y

Harrison, P., Malins, C., Searle, S. Y., Baral, A., Turley, D., & Hopwood, L. (2014). *Wasted: Europe's untapped resource*. European Climate Foundation.

Haughton, A. J., Bohan, D. A., Clark, S. J., Mallott, M. D., Mallott, V., Sage, R., & Karp, A. (2016). Dedicated biomass crops can enhance biodiversity in the arable landscape. *GCB Bioenergy*, *8*(6), 1071–1081. https://doi.org/10.1111/gcbb.12312

Haughton, A. J., Bond, A. J., Lovett, A. A., Dockerty, T., Sünnenberg, G., Clark, S. J., Bohan, D. A., Sage, R. B., Mallott, M. D., Mallott, V. E., Cunningham, M. D., Riche, A. B., Shield, I. F., Finch, J. W., Turner, M. M., & Karp, A. (2009). A novel, integrated approach to assessing social, economic and environmental implications of changing rural land-use: a case study of perennial biomass crops. *Journal of Applied Ecology*, *46*(2), 315–322. https://doi.org/10.1111/j.1365-2664.2009.01623.x

Haye, S., Panchaksharam, Y., Raphael, E., Liu, L., Howes, J., Bauen, A., Searle, S. Y., Zhou, Y., Casey, K., O'Malley, J., Malins, C., Alberici, S., Hardy, M., Research, W., Elbersen, W., Gursel, I. V., Elbersen, B., Rudolf, M., Hall, N., & Armentrout, B. (2021). Assessment of the potential for new feedstocks for the production of advanced biofuels. In *European Comission* (Issue October). European Commission. https://op.europa.eu/en/publication-detail/-/publication/ec9c1003-76a7-11ed-9887-01aa75ed71a1/language-en

Henry, M., Leung, B., Cuthbert, R. N., Bodey, T. W., Ahmed, D. A., Angulo, E., Balzani, P., Briski, E., Courchamp, F., Hulme, P. E., Kouba, A., Kourantidou, M., Liu, C., Macêdo, R. L., Oficialdegui, F. J., Renault, D., Soto, I., Tarkan, A. S., Turbelin, A. J., … Haubrock, P. J. (2023). Unveiling the hidden economic toll of biological invasions in the European Union. *Environmental Sciences Europe*, *35*(1), 43. https://doi.org/10.1186/s12302-023-00750-3

Heroldová, M., Šipoš, J., Suchomel, J., & Zejda, J. (2021). Interactions between common vole and winter rape. *Pest Management Science*, *77*(2), 599–603. https://doi.org/10.1002/ps.6050

Hintze, M. (2021). *Total Cost of Ownership Model for Decarbonization of Vessels* (v1.5). Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. https://www.zerocarbonshipping.com/publications/calculate-total-cost-of-ownership-tco-for-decarbonization-of-vessels/

Hochkirch, A., Bilz, M., Ferreira, C. C., Danielczak, A., Allen, D., Nieto, A., Rondinini, C., Harding, K., Hilton-Taylor, C., Pollock, C. M., Seddon, M., Vié, J. C., Alexander, K. N. A., Beech, E., Biscoito, M., Braud, Y., Burfield, I. J., Buzzetti, F. M., Cálix, M., … Zuna-Kratky, T. (2023). A multi-taxon analysis of European Red Lists reveals major threats to biodiversity. *PLoS ONE*, *18*(11 November), 1–13. https://doi.org/10.1371/journal.pone.0293083

Hoffland, E., Kuyper, T. W., Comans, R. N. J., & Creamer, R. E. (2020). Eco-functionality of organic matter in soils. *Plant and Soil*, *455*(1–2), 1–22. https://doi.org/10.1007/s11104-020-04651-9

Holland, J. M. (2004). The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agriculture, Ecosystems & Environment*, *103*(1), 1–25. https://doi.org/10.1016/j.agee.2003.12.018

Hooper, D. U., Adair, E. C., Cardinale, B. J., Byrnes, J. E. K., Hungate, B. A., Matulich, K. L., Gonzalez, A., Duffy, J. E., Gamfeldt, L., & Connor, M. I. (2012). A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature*, *486*(7401), 105–108. https://doi.org/10.1038/nature11118

Horváth, G., Blahó, M., Egri, Á., Kriska, G., Seres, I., & Robertson, B. (2010). Reducing the maladaptive attractiveness of solar panels to polarotactic insects. *Conservation Biology*, *24*(6), 1644–1653. https://doi.org/10.1111/j.1523-1739.2010.01518.x

Horwath, S., Hassrick, J., Grismala, R., & Diller, E. (2020). *Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations* . https://www.boem.gov/sites/default/files/documents/environment/Wind-Turbine-Foundations-White%20Paper-Final-White-Paper.pdf

Hussain, F. (2024). UK SAF mandate approved by House of Commons. *SAF Investor*. https://www.safinvestor.com/news/145858/uk/

Hydrogen Europe. (2019). *Hydrogen Roadmap Europe*. https://doi.org/10.2843/249013

IATA. (2024). *CORSIA Fact sheet*. https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---corsia/

Iboyi, J. E., Mulvaney, M. J., Leon, R. G., Balkcom, K. S., Bashyal, M., Devkota, P., & Small, I. M. (2023). Double-cropping effects of Brassica carinata and summer crops: I. Effects of summer cropping history on carinata production. *Industrial Crops and Products*, *194*. https://doi.org/10.1016/j.indcrop.2023.116364

ICAO. (2016). *European Advanced Biofuels Flight Path*. Initiatives & Projects. https://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=9

ICAO. (2024). *Conversion processes*. International Civil Aviation Authority. https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

ICCT. (2023). *THE STEEP DESCENT TO NET-ZERO AVIATION*. International Council on Clean Transportation. https://theicct.org/stack/net-zero-aviation-mar22/

IEA. (2024). *Global EV Outlook 2024*. https://www.iea.org/reports/global-ev-outlook-2024

Inspectie Leefomgeving en Transport. (2019). Fraud with sustainable biodiesel certification. *NL Ministerie van Infrastructuur En Waterstaat*. https://www.ilent.nl/documenten/leefomgeving-en-wonen/product-labels--markeringen-en-energiemaatregelen/voertuigen-en-verkeersproducten/signaalrapportages/fraude-met-certificering-duurzame-biodiesel

IPBES. (2018a). Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for Europe and Central Asia of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (M. Fischer, M. Rounsevell, A. T. M. Rando, A. Mader, A. Church, M. Elbakidze, V. Elias, T. Hahn, P. A. Harrison, J. Hauck, B. M. López, I. Ring, C. Sandström, I. S. Pinto, P. Visconti, N. E. Zimmermann, & M. Christie, Eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3237467

IPBES. (2018b). *The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia* (M. Rounsevell, M. Fischer, A. T. M. Rando, & A. Mader, Eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3237428

IPBES. (2019). Report of the plenary of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on the work of its seventh session. Addendum: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of. *Report of the Plenary*, *7*(1), 56.

ISCC. (2023). *ISCC EU 202-1: AGRICULTURAL BIOMASS: ISCC PRINCIPLE 1*. https://www.iscc-system.org/certification/iscc-documents/iscc-system-documents/

Isebrands, J. G., & Richardson, J. (2014). *Poplars and willows: trees for society and the environment*. https://openknowledge.fao.org/server/api/core/bitstreams/a34b3e72-733a-41ea-9e70-5e57e7f89a89/content

IUCN. (2018). *European Red List of saproxylic beetles*. https://portals.iucn.org/library/node/47296

Ivanov, K. (2022). *Uprooting state credibility in Bulgaria's logging sector*. Global Initiative against Transnational Organized Crime. https://globalinitiative.net/analysis/bulgarias-logging-sector-ocindex/

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinen, K., & Byrne, K. A. (2007). How strongly can forest management influence soil carbon sequestration? *Geoderma*, *137*(3–4), 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003

Johnston, C. (2024). Case Study: Biofiltration blocks of Short Rotation Coppice willow used for riparian protection to reduce nutrient run-off into the water environment. https://www.biomassconnect.org/wp-content/uploads/2024/08/AFBI-Case-Study.pdf

Jones, N. F., & Pejchar, L. (2013). Comparing the ecological impacts of wind and oil & gas development: A landscape scale assessment. *PLoS ONE*, *8*(11). https://doi.org/10.1371/journal.pone.0081391

Jones, N. F., Pejchar, L., & Kiesecker, J. M. (2015). The energy footprint: How oil, natural gas, and wind energy affect land for biodiversity and the flow of ecosystem services. *BioScience*, *65*(3), 290–301. https://doi.org/10.1093/biosci/biu224

JRC. (2023). *Energy and Industry Geography Lab*. European Commission Joint Research Centre. https://energy-industry-geolab.jrc.ec.europa.eu/

Kahle, P., & Janssen, M. (2020). Impact of short-rotation coppice with poplar and willow on soil physical properties. *Journal of Plant Nutrition and Soil Science*, *183*(2), 119–128. https://doi.org/10.1002/jpln.201900443

Kanchiralla, F. M., Brynolf, S., Olsson, T., Ellis, J., Hansson, J., & Grahn, M. (2023). How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study. *Applied Energy*, *350*, 121773. https://doi.org/10.1016/j.apenergy.2023.121773

Karlen, D. L. (2011). Potential Soil Quality Impact of Harvesting Crop Residues for Biofuels. *Agrociencia*, *15*(2), 120–127. https://doi.org/10.31285/AGRO.15.600

Kati, V., Kassara, C., Vrontisi, Z., & Moustakas, A. (2021). The biodiversity-wind energy-land use nexus in a global biodiversity hotspot. *Science of the Total Environment*, *768*. https://doi.org/10.1016/j.scitotenv.2020.144471

Keenleyside, C., Beaufoy, G., Tucker, G., & Jones, G. (2014). High Nature Value farming throughout EU-27 and its financial support under the CAP.

Kiesel, A., von Cossel, M., Clifton-Brown, J., & Lewandowski, I. (2023). Valorisation of marginal agricultural land in the bioeconomy. *GCB Bioenergy*, *15*(12), 1418–1423. https://doi.org/10.1111/gcbb.13105

Kinšt, J., & Jakobsen, B. (2016). *The EU system for the certification of sustainable biofuels*. https://www.eca.europa.eu/Lists/ECADocuments/SR16_18/SR_BIOFUELS_EN.pdf

Kleinbauer, I., Dullinger, S., Peterseil, J., & Essl, F. (2010). Climate change might drive the invasive tree Robinia pseudacacia into nature reserves and endangered habitats. *Biological Conservation*, *143*(2), 382–390. https://doi.org/10.1016/j.biocon.2009.10.024

Klenke, R. A., Frey, B., & Zarzycka, A. (2017). Case study 5: The effects of increased rape and maize cropping on agricultural biodiversity. In G. Siriwardena & G. Tucker (Eds.), *Service contract to support follow-up actions to the mid-term review of the EU biodiversity strategy to 2020 in relation to target*

3A – Agriculture (Final Report). EU Law and Publications, Directorate-General for Environment. https://op.europa.eu/en/publication-detail/-/publication/cd1c6a81-969e-11e7-b92d-01aa75ed71a1/language-en

Kletty, F., Rozan, A., & Habold, C. (2023). Biodiversity in temperate silvoarable systems: A systematic review. *Agriculture, Ecosystems & Environment*, *351*, 108480. https://doi.org/10.1016/j.agee.2023.108480

Klopp, H. W., & Blanco-Canqui, H. (2022). Implications of crop residue removal on soil physical properties: A review. *Soil Science Society of America Journal*, *86*(4), 979–1001. https://doi.org/10.1002/saj2.20418

Koh, L. P., & Ghazoul, J. (2008). Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. *Biological Conservation*, *141*(10), 2450–2460. https://doi.org/10.1016/j.biocon.2008.08.005

Kokkoris, I. P., Skuras, D., Maniatis, Y., & Dimopoulos, P. (2023). Natura 2000 public awareness in EU: A prerequisite for successful conservation policy. *Land Use Policy*, *125*. https://doi.org/10.1016/j.landusepol.2022.106482

Korosuo, A., Vizzarri, M., Pilli, R., Fiorese, G., Colditz, R., Abad-Viñas, R., Rossi, S., & Grassi, G. (2021). *Forest reference levels under Regulation (EU) 2018/841 for the period 2021 – 2025*. https://doi.org/10.2760/0521

Kowalczewska, K., van Aardenne, J., Iversen, P., & Petersen, J.-E. (2023). *The European biomass puzzle Challenges, opportunities and trade-offs around biomass production and use in the EU*. https://doi.org/10.2800/834565

Kunz, T. H., Braun de Torrez, E., Bauer, D., Lobova, T., & Fleming, T. H. (2011). Ecosystem services provided by bats. *Annals of the New York Academy of Sciences*, *1223*(1), 1–38. https://doi.org/10.1111/j.1749-6632.2011.06004.x

Kuresoo, S., Kuresoo, L., Lilleväli, U., & Kerus, V. (2020). Hidden inside a wood pellet: Intensive logging impacts in Estonian and Latvian forests.

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, *31*(4), 575–584. https://doi.org/10.1016/j.envint.2004.09.005

Lamb, A., Weers, B., McKinley, B., Rooney, W., Morgan, C., Marshall-Colon, A., & Mullet, J. (2022). Bioenergy sorghum's deep roots: A key to sustainable biomass production on annual cropland. *GCB Bioenergy*, *14*(2), 132–156. https://doi.org/10.1111/gcbb.12907

Lampkin, N., & Pearce, B. (2021). *Organic Farming and Biodiversity*. IFOAM Organics Europe. https://read.organicseurope.bio/publication/organic-farming-and-biodiversity/pdf/

Landälv, I., Waldheim, L., & Maniatis, K. (2018). *Technology status and reliability of the value chains: 2018 Update*. https://artfuelsforum.eu/news-articles/updated-sgab-report-technology-status-and-reliability-of-the-value-chains/

Larsen, B. M. (2018). Emitted noise in harbors – Effect of shore power. *Baltic-Nordic Acoustics Meeting*. https://admin.artegis.com/urlhost/artegis/customers/1571/.lwtemplates/layout/default/events_public/12612/Papers/2024559_Larsen_BNAM2018.pdf

Laursen, R., Barcarolo, D., Patel, H., Dowling, M., Penfold, M., Faber, J., Király, J., van der Ven, R., Pang, E., & van Grinsven, A. (2022). *Potential of Ammonia as Fuel in Shipping*. https://www.emsa.europa.eu/newsroom/latest-news/download/7322/4833/23.html

Laursen, R. ;, Patel, H. ;, Sofiadi, D. ;, Zhu, R. ;, Nelissen, D. ;, Van Seters, D. ;, & Pang, E. (2023). *Potential of Wind-Assisted Propulsion for Shipping*. https://safety4sea.com/wp-content/uploads/2023/11/EMSA-Report-potential-of-wind-assisted-propulsion-for-shipping_2023_11.pdf

Lavelle, P., Decaëns, T., Aubert, M., Barot, S., Blouin, M., Bureau, F., Margerie, P., Mora, P., & Rossi, J.-P. (2006). Soil invertebrates and ecosystem services. *European Journal of Soil Biology*, *42*, S3–S15. https://doi.org/10.1016/j.ejsobi.2006.10.002

Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J. L., Qin, Z., McNamara, N. P., Zinn, Y. L., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E.,

& Hillier, J. (2020). Changes in soil organic carbon under perennial crops. *Global Change Biology*, *26*(7), 4158–4168. https://doi.org/10.1111/gcb.15120

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., … Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

Lee, J. S. H., Garcia-Ulloa, J., & Koh, L. P. (2011). Impacts of Biofuel Expansion in Biodiversity Hotspots. In *Biodiversity Hotspots* (pp. 277–293). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-20992-5_15

Lewandowski, I., Clifton-Brown, J., Kiesel, A., Hastings, A., & Iqbal, Y. (2018). Miscanthus. In *Perennial Grasses for Bioenergy and Bioproducts* (pp. 35–59). Elsevier. https://doi.org/10.1016/B978-0-12-812900-5.00002-3

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M. J., & Marchetti, M. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, *259*(4), 698–709. https://doi.org/10.1016/j.foreco.2009.09.023

Link, S., Stephan, A., Speth, D., & Plötz, P. (2024). Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification. In *Nature Energy*. Nature Research. https://doi.org/10.1038/s41560-024-01531-9

Livingstone, D., Smyth, B. M., Lyons, G., Foley, A. M., Murray, S. T., & Johnston, C. (2022). Life cycle assessment of a short-rotation coppice willow riparian buffer strip for farm nutrient mitigation and renewable energy production. *Renewable and Sustainable Energy Reviews*, *158*(May 2021), 112154. https://doi.org/10.1016/j.rser.2022.112154

López-Mondéjar, R., Brabcová, V., Štursová, M., Davidová, A., Jansa, J., Cajthaml, T., & Baldrian, P. (2018). Decomposer food web in a deciduous forest shows high share of generalist microorganisms and importance of microbial biomass recycling. *The ISME Journal*, *12*(7), 1768–1778. https://doi.org/10.1038/s41396-018-0084-2

Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). Land-use intensity of electricity production and tomorrow's energy landscape. *PLoS ONE*, *17*(7 July). https://doi.org/10.1371/journal.pone.0270155

Lowell, D., Bradley, M., Haifeng Wang, A., & Lutsey, N. (2013). *Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping*. https://theicct.org/wp-content/uploads/2021/06/ICCTwhitepaper_MarineLNG_130513.pdf

MAGIC. (2023). *The MAGIC Project*. Horizon 2020. https://magic-h$_2$020.eu/

Malins, C. (2017). *What role is there for electrofuel technologies in European transport's low carbon future?* Cerulogy. https://www.cerulogy.com/wp-content/uploads/2022/10/Cerulogy_What-role-electrofuels_November2017_v1_3.pdf

Malins, C. (2019). *Risk management - Identifying high and low ILUC-risk biofuels under the recast Renewable Energy Directive* (Issue January). http://www.cerulogy.com/palm-oil/risk-management/

Malins, C. (2020). Biofuel to the Fire. *Rainforest Foundation Norway*, *FEBRUARY*, 40–42.

Malins, C. (2023). *The fat of the land: The impact of biofuel demand on the European market for rendered animal fats*. https://www.transportenvironment.org/wp-content/uploads/2023/05/Cerulogy_Fat-of-the-land_May_23.pdf

Malins, C., Searle, S., & Baral, A. (2014). A Guide for the Perplexed to the Indirect Effects of Biofuels Production. *Icct*, 1–166.

Maniatis, K., Heuvel, E. van den, & Kalligero, S. (2017). Building up the Future: Cost of Biofuel. *Sustainable Transport Forum Sub Group on Advanced Biofuels*, 1–71.

Marshall, E. J. P., & Moonen, A. C. (2002). Field margins in northern Europe: their functions and interactions with agriculture. *Agriculture, Ecosystems & Environment*, *89*(1–2), 5–21. https://doi.org/10.1016/S0167-8809(01)00315-2

Martín, J. M., Rafael, J., López, G., Sousa, H. C., & Barrios, V. (2022). Wildlife and power lines: Guidelines for preventing and mitigating wildlife mortality associated with electricity distribution networks. https://portals.iucn.org/library/sites/library/files/documents/2022-043-En.pdf

Material Economics. (2021). *EU Biomass Use in a Net-Zero Economy*. https://www.climate-kic.org/wp-content/uploads/2021/06/MATERIAL-ECONOMICS-EU-BIOMASS-USE-IN-A-NET-ZERO-ECONOMY-ONLINE-VERSION.pdf

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural Intensification and Ecosystem Properties. *Science*, *277*(5325), 504–509. https://doi.org/10.1126/science.277.5325.504

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution*, *10*(16), 8927–8935. https://doi.org/10.1002/ece3.6592

Mayer, P. M., Reynolds, S. K., McCutchen, M. D., & Canfield, T. J. (2007). Meta-Analysis of Nitrogen Removal in Riparian Buffers. *Journal of Environmental Quality*, *36*(4), 1172–1180. https://doi.org/10.2134/jeq2006.0462

McLeod, K., Reed, M., & Nelson, E. (2001). Influence of a willow canopy on tree seedling establishment for wetland restoration. *Wetlands*, *21*. https://link.springer.com/article/10.1672/0277-5212(2001)021[0395:IOAWCO]2.0.CO;2

Meijaard, E., Brooks, T. M., Carlson, K. M., Slade, E. M., Garcia-Ulloa, J., Gaveau, D. L. A., Lee, J. S. H., Santika, T., Juffe-Bignoli, D., Struebig, M. J., Wich, S. A., Ancrenaz, M., Koh, L. P., Zamira, N., Abrams, J. F., Prins, H. H. T., Sendashonga, C. N., Murdiyarso, D., Furumo, P. R., … Sheil, D. (2020). The environmental impacts of palm oil in context. *Nature Plants*, *6*(12), 1418–1426. https://doi.org/10.1038/s41477-020-00813-w

Metz, B., Davidson, O., Bosch, P., Rutu, D., & Meyer, L. (2007). *AR4 Climate Change 2007: Mitigation of Climate Change*. https://www.ipcc.ch/report/ar4/wg3/

Ministerial Conference on the Protection of Forests in Europe - FOREST EUROPE. (2020). State of Forests. *State of Europe's Forests*, 394.

MMMCZCS. (2024). *Global Availability of Biogenic CO_2 and Implications for Maritime Decarbonization*. https://www.zerocarbonshipping.com/publications/global-availability-of-biogenic-CO_2-and-implications-for-maritime-decarbonization/

Moffat, A., Nisbet, T., & Nicoll, B. (2011). Environmental effects of stump and root harvesting. *Forestry Commission Research Note*, *September*, 1–12.

Mohammed, Y. A., Chen, C., & Afshar, R. K. (2017). Nutrient Requirements of Camelina for Biodiesel Feedstock in Central Montana. *Agronomy Journal*, *109*(1). https://doi.org/10.2134/agronj2016.03.0163

Mola-Yudego, B., & Aronsson, P. (2008). Yield models for commercial willow biomass plantations in Sweden. *Biomass and Bioenergy*, *32*(9), 829–837. https://doi.org/10.1016/j.biombioe.2008.01.002

Møller, A. P., Czeszczewik, D., Flensted-Jensen, E., Erritzøe, J., Krams, I., Laursen, K., Liang, W., & Walankiewicz, W. (2021). Abundance of insects and aerial insectivorous birds in relation to pesticide and fertilizer use. *Avian Research*, *12*(1), 43. https://doi.org/10.1186/s40657-021-00278-1

Montag, H., Parker, G., & Tom, C. (2016). *THE EFFECTS OF SOLAR FARMS ON LOCAL BIODIVERSITY: A COMPARATIVE STUDY*. https://www.farminguk.com/content/knowledge/Effects-of-Solar-Farms-on-Local-Biodiversity(4654-8780-3868-4254).pdf

Monti, A., & Zatta, A. (2009). Root distribution and soil moisture retrieval in perennial and annual energy crops in Northern Italy. *Agriculture, Ecosystems & Environment*, *132*(3–4), 252–259. https://doi.org/10.1016/j.agee.2009.04.007

Mukhopadhaya, J., & Rutherford, D. (2022). Performance Analysis Of Evolutionary Hydrogen-Powered Aircraft. In *The International Council on Clean Transportation* (Issue January). https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/

Mulumba, L. N., & Lal, R. (2008). Mulching effects on selected soil physical properties. *Soil and Tillage Research*, *98*(1), 106–111. https://doi.org/10.1016/j.still.2007.10.011

Mundia, C. W., Secchi, S., Akamani, K., & Wang, G. (2019). A Regional Comparison of Factors Affecting Global Sorghum Production: The Case of North America, Asia and Africa's Sahel. *Sustainability*, *11*(7), 2135. https://doi.org/10.3390/su11072135

Naeem, S., Chazdon, R., Duffy, J. E., Prager, C., & Worm, B. (2016). Biodiversity and human well-being: An essential link for sustainable development. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1844). https://doi.org/10.1098/rspb.2016.2091

Naeem, S., Duffy, J. E., & Zavaleta, E. (2012). The functions of biological diversity in an age of extinction. *Science*, *336*(6087), 1401–1406. https://doi.org/10.1126/science.1215855

National Center for Biotechnology Information. (2024). PubChem Compound Summary for CID 222, Ammonia. *PubChem Compound Summary*. https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia

Naumann, S., Noebel, R., Gaudillat, Z., Stein, U., Röschel, L., Ittner, S., Davis, M., Staneva, A., Rutherford, C., & Romão, C. (2020). *State of nature in the EU: Results from reporting under the nature directives 2013-2018*. https://www.eea.europa.eu/publications/state-of-nature-in-the-eu-2020

Nunes, F. C., de Jesus Alves, L., de Carvalho, C. C. N., Gross, E., de Marchi Soares, T., & Prasad, M. N. V. (2020). Soil as a complex ecological system for meeting food and nutritional security. In *Climate Change and Soil Interactions*. LTD. https://doi.org/10.1016/b978-0-12-818032-7.00009-6

Ocko, I. B., & Hamburg, S. P. (2022). Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, *22*(14), 9349–9368. https://doi.org/10.5194/acp-22-9349-2022

OECD. (2017). OECD Studies on Water Diffuse Pollution, Degraded Waters Emerging Policy Solutions. In *OECD Studies on Water Diffuse Pollution, Degraded Waters Emerging Policy Solutions*. https://www.proquest.com/books/oecd-studies-on-water-diffuse-pollution-degraded/docview/2474601339/se-2?accountid=206735

Oksuz, D. P., & Correia, R. A. (2023). Wood-pasture abandonment changes bird functional diversity and composition with potential drawbacks to pest regulation. *Community Ecology*, *24*(1), 9–20. https://doi.org/10.1007/s42974-022-00129-z

O'Malley, J., & Baldino, C. (2024). *AVAILABILITY OF WASTE FATS AND OILS USED COOKING OIL*. https://doi.org/10.2784/8525

Oppermann, R. , Beaufoy, G., & Jones, G. (Eds.). (2012). *High Nature Value Farming in Europe*. Verlag Regionalkultur.

Orgiazzi, A., Panagos, P., Yigini, Y., Dunbar, M. B., Gardi, C., Montanarella, L., & Ballabio, C. (2016). A knowledge-based approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity. *Science of the Total Environment*, *545–546*, 11–20. https://doi.org/10.1016/j.scitotenv.2015.12.092

Owen, B., Lee, D. S., & Lim, L. (2010). Flying into the Future: Aviation Emissions Scenarios to 2050. *Environmental Science & Technology*, *44*(7), 2255–2260. https://doi.org/10.1021/es902530z

PAC. (2020). *The PAC Scenario - Technical Summary of Key Elements*. https://www.pac-scenarios.eu/pac-scenario/scenario-development.html

Panoutsou, C., Giarola, S., Ibrahim, D., Verzandvoort, S., Elbersen, B., Sandford, C., Malins, C., Politi, M., Vourliotakis, G., Zita, V. E., Vásáry, V., Alexopoulou, E., Salimbeni, A., & Chiaramonti, D. (2022). Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe. *Applied Sciences 2022, Vol. 12, Page 4623*, *12*(9), 4623. https://doi.org/10.3390/APP12094623

Panoutsou, C., & Maniatis, K. (2021). Sustainable Biomass Availability in the EU to 2050. In *Concawe*. https://doi.org/10.32964/tj20.8

Panteleit, J., Horgan, F. G., Türke, M., Schmidt, A., Schädler, M., Bacht, M., Brandl, R., & Hotes, S. (2018). Effects of detritivorous invertebrates on the decomposition of rice straw: evidence from a microcosm experiment. *Paddy and Water Environment*, *16*(2), 279–286. https://doi.org/10.1007/s10333-017-0625-8

Paracchini, M.-L., Petersen, J.-E., Hoogeveen, Y., Bamps, C., Burfield, I., & Van Swaay, C. (2009). High Nature Value Farmland in Europe - An Estimate of the Distribution Patterns on the Basis of Land Cover and Biodiversity Data. https://doi.org/10.2788/8891

Pardo, I., Zabalza, S., Berastegi, A., Ripoll-Bosch, R., & Astrain, C. (2024). Assessment of determinants of high nature value (HNV) farmland at plot scale in Western Pyrenees. *Journal of Environmental Management*, *349*, 119516. https://doi.org/10.1016/j.jenvman.2023.119516

Paredes, I., Ramírez, F., Aragonés, D., Bravo, M. Á., Forero, M. G., & Green, A. J. (2021). Ongoing anthropogenic eutrophication of the catchment area threatens the Doñana World Heritage Site (South-west Spain). *Wetlands Ecology and Management*, *29*(1), 41–65. https://doi.org/10.1007/s11273-020-09766-5

Pavlenko, N., & Searle, S. (2018). *A Comparison of Induced Land-Use Change Emissions Estimates From Energy Crops*. *February*, 44. https://theicct.org/wp-content/uploads/2021/06/ILUC-energy-crops_ICCT-White-Paper_06022018_vF1.pdf

Perpiña Castillo, C., Kavalov, B., Diogo, V., Jacobs, C., Batista E Silva, F., & Lavalle, C. (2018). *Agricultural Land Abandonment in the EU within 2015-2030*. https://joint-research-centre.ec.europa.eu/publications/agricultural-land-abandonment-eu-within-2015-2030_en

Perttu, K. L. (1999). Environmental and hygienic aspects of willow coppice in Sweden. *Biomass and Bioenergy*, *16*(4), 291–297. https://doi.org/10.1016/S0961-9534(98)00012-9

Perttu, K. L., & Kowalik, P. J. (1997). Salix vegetation filters for purification of waters and soils. *Biomass and Bioenergy*, *12*(1), 9–19. https://doi.org/10.1016/S0961-9534(96)00063-3

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., & Blair, R. (1995). Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science*, *267*(5201), 1117–1123. https://doi.org/10.1126/science.267.5201.1117

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

Ponisio, L. C., M'Gonigle, L. K., Mace, K. C., Palomino, J., de Valpine, P., & Kremen, C. (2015). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1799), 20141396. https://doi.org/10.1098/rspb.2014.1396

Potter, H. K., Yacout, D. M. M., & Henryson, K. (2023). Climate Assessment of Vegetable Oil and Biodiesel from Camelina Grown as an Intermediate Crop in Cereal-Based Crop Rotations in Cold Climate Regions. *Sustainability*, *15*(16). https://doi.org/10.3390/su151612574

Poupinha, C., & Dornoff, J. (2024). The bigger the better? How battery size affects real-world energy consumption, cost of ownership, and life-cycle emissions of electric vehicles. https://theicct.org/publication/bev-battery-size-energy-consumption-cost-ownership-lca-ev-apr24/

Powlson, D. S., Riche, A. B., Coleman, K., Glendining, M. J., & Whitmore, A. P. (2008). Carbon sequestration in European soils through straw incorporation: Limitations and alternatives. *Waste Management*, *28*(4), 741–746. https://doi.org/10.1016/j.wasman.2007.09.024

Prangel, E., Kasari-Toussaint, L., Neuenkamp, L., Noreika, N., Karise, R., Marja, R., Ingerpuu, N., Kupper, T., Keerberg, L., Oja, E., Meriste, M., Tiitsaar, A., Ivask, M., & Helm, A. (2023). Afforestation and abandonment of semi-natural grasslands lead to biodiversity loss and a decline in ecosystem services and functions. *Journal of Applied Ecology*, *60*(5), 825–836. https://doi.org/10.1111/1365-2664.14375

Pywell, R. F., Heard, M. S., Woodcock, B. A., Hinsley, S., Ridding, L., Nowakowski, M., & Bullock, J. M. (2015). Wildlife-friendly farming increases crop yield: evidence for ecological intensification. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1816), 20151740. https://doi.org/10.1098/rspb.2015.1740

Q ENERGY. (2023). Q ENERGY starts construction of Europe's largest floating solar farm.

Rajala, T., Tuomivirta, T., Pennanen, T., & Mäkipää, R. (2015). Habitat models of wood-inhabiting fungi along a decay gradient of Norway spruce logs. *Fungal Ecology*, *18*, 48–55. https://doi.org/10.1016/j.funeco.2015.08.007

Ramachandra, T. V., Bharath, S., & Gupta, N. (2018). Modelling landscape dynamics with LST in protected areas of Western Ghats, Karnataka. *Journal of Environmental Management*, *206*, 1253–1262. https://doi.org/10.1016/j.jenvman.2017.08.001

Ramírez, L., Fraile, D., Brindley, G., & O'Sullivan, R. (2020). *Offshore Wind in Europe*. https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/

Raptor Protection of Slovakia. (2021). *Electrocutions & Collisions of Birds in EU Countries*. https://www.birdlife.org/wp-content/uploads/2022/10/Electrocutions-Collisions-Birds-Best-Mitigation-Practices-NABU.pdf

Renewables Grid Initiative. (2024). *RGI Statement on Renewables Acceleration Areas*. https://renewables-grid.eu/fileadmin/user_upload/Nature/RGI_statement_on_the_renewables_acceleration_areas.pdf

Richardson, D. M., & Rejmánek, M. (2011). Trees and shrubs as invasive alien species – a global review. *Diversity and Distributions*, *17*(5), 788–809. https://doi.org/10.1111/j.1472-4642.2011.00782.x

Ritchie, H. (2022). *How does the land use of different electricity sources compare?* Our World In Data. https://ourworldindata.org/land-use-per-energy-source

Rodrigues, A., Gonçalves, A. B., Casquilho, M., & Gomes, A. A. (2020). A GIS-based evaluation of the potential of woody short rotation coppice (SRC) in Portugal aiming at co-firing and decentralized co-generation. *Biomass and Bioenergy*, *137*(March), 105554. https://doi.org/10.1016/j.biombioe.2020.105554

Rouet-Leduc, J., Pe'er, G., Moreira, F., Bonn, A., Helmer, W., Shahsavan Zadeh, S. A. A., Zizka, A., & van der Plas, F. (2021). Effects of large herbivores on fire regimes and wildfire mitigation. *Journal of Applied Ecology*, *58*(12), 2690–2702. https://doi.org/10.1111/1365-2664.13972

Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B. S., Brosowski, A., & Thrän, D. (2019). ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379. https://doi.org/10.1016/j.esr.2019.100379

Rytter, R.-M., Rytter, L., & Högbom, L. (2015). Carbon sequestration in willow (Salix spp.) plantations on former arable land estimated by repeated field sampling and C budget calculation. *Biomass and Bioenergy*, *83*, 483–492. https://doi.org/10.1016/j.biombioe.2015.10.009

SafeLines4Birds. (2023). *Reducing bird mortality caused by power lines*. EU Life Project. https://www.safelines4birds.eu/

Sage, R., Cunningham, M., & Boatman, N. (2006). Birds in willow short-rotation coppice compared to other arable crops in central England and a review of bird census data from energy crops in the UK. *Ibis*, *148*(s1), 184–197. https://doi.org/10.1111/j.1474-919X.2006.00522.x

Sand, M., Skeie, R. B., Sandstad, M., Krishnan, S., Myhre, G., Bryant, H., Derwent, R., Hauglustaine, D., Paulot, F., Prather, M., & Stevenson, D. (2023). A multi-model assessment of the Global Warming Potential of hydrogen. *Communications Earth & Environment*, *4*(1), 203. https://doi.org/10.1038/s43247-023-00857-8

Sandford, C., Malins, C., Vourliotakis, G., & Panoutsou, C. (2024). 'Low ILUC-Risk' as a Sustainability Standard for Biofuels in the EU. *Energies*, *17*(10), 2365. https://doi.org/10.3390/en17102365

Sapkota, T. B. (2012). *Conservation Tillage Impact on Soil Aggregation, Organic Matter Turnover and Biodiversity* (pp. 141–160). https://doi.org/10.1007/978-94-007-4113-3_6

Sarnocińska, J., Teilmann, J., Balle, J. D., van Beest, F. M., Delefosse, M., & Tougaard, J. (2020). Harbor Porpoise (Phocoena phocoena) Reaction to a 3D Seismic Airgun Survey in the North Sea. *Frontiers in Marine Science*, 6. https://doi.org/10.3389/fmars.2019.00824

Savilaakso, S., Garcia, C., Garcia-Ulloa, J., Ghazoul, J., Groom, M., Guariguata, M. R., Laumonier, Y., Nasi, R., Petrokofsky, G., Snaddon, J., & Zrust, M. (2014). Systematic review of effects on biodiversity from oil palm production. *Environmental Evidence*, *3*(1). https://doi.org/10.1186/2047-2382-3-4

Scanlon, B. R., Jolly, I., Sophocleous, M., & Zhang, L. (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research*, *43*(3). https://doi.org/10.1029/2006WR005486

Schmidt, P., Weindorf, W., Roth, A., Batteiger, V., & Riegel, F. (2016). *Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*. https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf

Schneider, L., & Wissner, N. (2022). *Fit for purpose? Key issues for the first review of CORSIA*. https://www.oeko.de/fileadmin/oekodoc/Key-issues-for-first-review-of-CORSIA.pdf

Searle, S. Y., & Malins, C. J. (2014). Will energy crop yields meet expectations? *Biomass and Bioenergy*, *65*, 3–12. https://doi.org/10.1016/j.biombioe.2014.01.001

Searle, S. Y., & Malins, C. J. (2016). Waste and residue availability for advanced biofuel production in EU Member States. *Biomass and Bioenergy*, *89*, 2–10. https://doi.org/10.1016/j.biombioe.2016.01.008

Secretariat of the Convention on Biological Diversity. (2020). *Global Biodiversity Outlook 5*. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

Seidl, R., Schelhaas, M.-J., Rammer, W., & Verkerk, P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change*, *4*(9), 806–810. https://doi.org/10.1038/nclimate2318

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A., & Reyer, C. P. O. (2017). Forest disturbances under climate change. *Nature Climate Change*, *7*(6), 395–402. https://doi.org/10.1038/nclimate3303

Semere, T., & Slater, F. (2007a). Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus×giganteus) and reed canary-grass (Phalaris arundinacea) fields. *Biomass and Bioenergy*, *31*(1), 20–29. https://doi.org/10.1016/j.biombioe.2006.07.001

Semere, T., & Slater, F. (2007b). Invertebrate populations in miscanthus (Miscanthus×giganteus) and reed canary-grass (Phalaris arundinacea) fields. *Biomass and Bioenergy*, *31*(1), 30–39. https://doi.org/10.1016/j.biombioe.2006.07.002

Sereda, E., Wolters, V., & Birkhofer, K. (2015). Addition of crop residues affects a detritus-based food chain depending on litter type and farming system. *Basic and Applied Ecology*, *16*(8), 746–754. https://doi.org/10.1016/j.baae.2015.07.005

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*(7397), 229–232. https://doi.org/10.1038/nature11069

Shipley, J. R., Frei, E. R., Bergamini, A., Boch, S., Schulz, T., Ginzler, C., Barandun, M., Bebi, P., Bolliger, J., Bollmann, K., Delpouve, N., Gossner, M. M., Graham, C., Krumm, F., Marty, M., Pichon, N., Rigling, A., & Rixen, C. (2024). Agricultural practices and biodiversity: Conservation policies for semi-natural grasslands in Europe. *Current Biology*, *34*(16), R753–R761. https://doi.org/10.1016/j.cub.2024.06.062

Siitonen, J. (2001). Forest Management, Coarse Woody Debris and Saproxylic Organisms: Fennoscandian Boreal Forests as an Example. *Ecological Bulletins*. https://www.jstor.org/stable/20113262

Sil, Â., Fernandes, P. M., Rodrigues, A. P., Alonso, J. M., Honrado, J. P., Perera, A., & Azevedo, J. C. (2019). Farmland abandonment decreases the fire regulation capacity and the fire protection ecosystem service in mountain landscapes. *Ecosystem Services*, *36*, 100908. https://doi.org/10.1016/j.ecoser.2019.100908

Siol, C., Thrän, D., & Majer, S. (2023). Utilizing residual biomasses from agriculture and forestry: Different approaches to set system boundaries in environmental and economic life-cycle assessments. *Biomass and Bioenergy*, *174*, 106839. https://doi.org/10.1016/j.biombioe.2023.106839

Smith, R. G., Gross, K. L., & Robertson, G. P. (2008). Effects of Crop Diversity on Agroecosystem Function: Crop Yield Response. *Ecosystems*, *11*(3), 355–366. https://doi.org/10.1007/s10021-008-9124-5

Smith, V. H., Tilman, G. D., & Nekola, J. C. (1999). Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, *100*(1–3), 179–196. https://doi.org/10.1016/S0269-7491(99)00091-3

Smulders, M. J. M., Cottrell, J. E., Lefèvre, F., van der Schoot, J., Arens, P., Vosman, B., Tabbener, H. E., Grassi, F., Fossati, T., Castiglione, S., Krystufek, V., Fluch, S., Burg, K., Vornam, B., Pohl, A., Gebhardt, K., Alba, N., Agúndez, D., Maestro, C., … Boerjan, W. (2008). Structure of the genetic diversity in black poplar (Populus nigra L.) populations across European river systems: Consequences for conservation and restoration. *Forest Ecology and Management*, *255*(5–6), 1388–1399. https://doi.org/10.1016/j.foreco.2007.10.063

Soares-Ramos, E. P. P., de Oliveira-Assis, L., Sarrias-Mena, R., & Fernández-Ramírez, L. M. (2020). Current status and future trends of offshore wind power in Europe. *Energy*, *202*, 117787. https://doi.org/10.1016/j.energy.2020.117787

Song, X. P., Hansen, M. C., Potapov, P., Adusei, B., Pickering, J., Adami, M., Lima, A., Zalles, V., Stehman, S. V., Di Bella, C. M., Conde, M. C., Copati, E. J., Fernandes, L. B., Hernandez-Serna, A., Jantz, S. M., Pickens, A. H., Turubanova, S., & Tyukavina, A. (2021). Massive soybean expansion in South America since 2000 and implications for conservation. *Nature Sustainability*, *4*(9), 784–792. https://doi.org/10.1038/s41893-021-00729-z

Soquet-Boissy, A., Koster, M., Simone, F. De, Vion, M., & Saint-Supéry. (2024). *Overview of biofuels policies and markets across the EU* (Issue January). https://www.epure.org/wp-content/uploads/2023/02/230227-DEF-REP-Overview-of-biofuels-policies-and-markets-across-the-EU-February-2023-1.pdf

Soubly, K., & Riefer, D. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. *McKinsey & Company*, 43. https://www.mckinsey.com/~/media/mckinsey/industries/travel transport and logistics/our insights/scaling sustainable aviation fuel today for clean skies tomorrow/clean-skies-for-tomorrow.pdf

Sovacool, B. K. (2013). The avian benefits of wind energy: A 2009 update. *Renewable Energy*, *49*, 19–24. https://doi.org/10.1016/j.renene.2012.01.074

Springer, A., Earl, T., & Abbasov, F. (2023). *The impact of FuelEU Maritime on European shipping*. https://www.transportenvironment.org/articles/the-impact-of-fueleu-maritime

Sun, T., Shrestha, E., Hamburg, S. P., Kupers, R., & Ocko, I. B. (2024). Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales. *Environmental Science & Technology*, *58*(12), 5299–5309. https://doi.org/10.1021/acs.est.3c09030

Suzan, S. (2023). *Biofuels: From unsustainable crops to dubious waste?* https://www.transportenvironment.org/wp-content/uploads/2023/12/202312_TE_biofuels_update_report.pdf

Tallamy, D. W., & Shriver, W. G. (2021). Are declines in insects and insectivorous birds related? *Ornithological Applications*, *123*(1). https://doi.org/10.1093/ornithapp/duaa059

Tarimo, R. (2011). Going Underground: European Transmission Practices. *Power Grid International*. https://www.power-grid.com/td/going-underground-european-transmission-practices/

The Nature Conservancy. (2024). Statement: The Nature Conservancy Welcomes EU Guidance to Accelerate the Renewable Energy Rollout - Now, Implementation is Key. *The Nature Conservancy Newsroom*. https://www.nature.org/en-us/newsroom/statement-the-nature-conservancy-eu-guidance-acclerate-renewable-energy-rollout/

Thompson, E. P., Bombelli, E. L., Shubham, S., Watson, H., Everard, A., D'Ardes, V., Schievano, A., Bocchi, S., Zand, N., Howe, C. J., & Bombelli, P. (2020). Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland. *Advanced Energy Materials*, *10*(35). https://doi.org/10.1002/aenm.202001189

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671–677. https://doi.org/10.1038/nature01014

Tilman, D., Isbell, F., & Cowles, J. M. (2014). Biodiversity and ecosystem functioning. *Annual Review of Ecology, Evolution, and Systematics*, *45*, 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917

Tilman, D., Reich, P. B., & Isbell, F. (2012). Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(26), 10394–10397. https://doi.org/10.1073/pnas.1208240109

Titus, B. D., Brown, K., Helmisaari, H. S., Vanguelova, E., Stupak, I., Evans, A., Clarke, N., Guidi, C., Bruckman, V. J., Varnagiryte-Kabasinskiene, I., Armolaitis, K., de Vries, W., Hirai, K., Kaarakka, L., Hogg, K., & Reece, P. (2021). Sustainable forest biomass: a review of current residue harvesting guidelines. *Energy, Sustainability and Society*, *11*(1), 1–32. https://doi.org/10.1186/s13705-021-00281-w

Torralba, M., Fagerholm, N., Burgess, P. J., Moreno, G., & Plieninger, T. (2016). Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture, Ecosystems & Environment*, *230*, 150–161. https://doi.org/10.1016/j.agee.2016.06.002

Tougaard, J., Henriksen, O. D., & Miller, L. A. (2009). Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals. *The Journal of the Acoustical Society of America*, *125*(6), 3766–3773. https://doi.org/10.1121/1.3117444

Transport and Environment. (2024). *EV Market Dashboard*. https://www.transportenvironment.org/topics/cars/ev-market

Trentadue, G., Lucas, A., Otura, M., Pliakostathis, K., Zanni, M., & Scholz, H. (2018). Evaluation of Fast Charging Efficiency under Extreme Temperatures. *Energies*, *11*(8), 1937. https://doi.org/10.3390/en11081937

Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C., & Batáry, P. (2021). Beyond organic farming – harnessing biodiversity-friendly landscapes. *Trends in Ecology & Evolution*, *36*(10), 919–930. https://doi.org/10.1016/j.tree.2021.06.010

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., & Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. *Ecology Letters*, *8*(8), 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K., Hemerik, L., de Vries, F. T., Bardgett, R. D., Brady, M. V., Bjornlund, L., Jørgensen, H. B., Christensen, S., Hertefeldt, T. D., Hotes, S., Gera Hol, W. H., Frouz, J., Liiri, M., Mortimer, S. R., … Hedlund, K. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biology*, *21*(2), 973–985. https://doi.org/10.1111/gcb.12752

Tsiropoulos, I., Nijs, W., Tarvydas, D., & Ruiz, P. (2020). Towards net-zero emissions in the EU energy system by 2050 insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal. https://op.europa.eu/en/publication-detail/-/publication/94aab140-8378-11ea-bf12-01aa75ed71a1/language-en

Tuck, S. L., Winqvist, C., Mota, F., Ahnström, J., Turnbull, L. A., & Bengtsson, J. (2014). Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. *Journal of Applied Ecology*, *51*(3), 746–755. https://doi.org/10.1111/1365-2664.12219

Tucker, G. M., Hart, K., Farmer, A., Dunn, E., & Baldock, D. (2023). Nature conservation policy, legislation and funding in the EU. In G. M. Tucker (Ed.), *Nature conservation in Europe: approaches and lessons*. Cambridge University Press.

Tuomisto, H. L., Hodge, I. D., Riordan, P., & Macdonald, D. W. (2012). Does organic farming reduce environmental impacts? – A meta-analysis of European research. *Journal of Environmental Management*, *112*, 309–320. https://doi.org/10.1016/j.jenvman.2012.08.018

Turney, D., & Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 6, pp. 3261–3270). Elsevier Ltd. https://doi.org/10.1016/j.rser.2011.04.023

UK Department for Transport. (2022). Jet Zero Strategy: Delivering net zero aviation by 2050. July, 83.

UK Department for Transport. (2024a). *Supporting the transition to Jet Zero: Creating the UK SAF Mandate*. *April*. https://assets.publishing.service.gov.uk/media/662938db3b0122a378a7e722/creating-the-UK-saf-mandate-consultation-response.pdf

UK Department for Transport. (2024b). *Sustainable Aviation Fuel Mandate: Final Stage Cost Benefit Analysis*. *April*. https://www.gov.uk/government/consultations/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate

UN. (2006). *Multi Dimensional Issues in International Electric Power Grid Interconnections*. https://www.un.org/esa/sustdev/publications/energy/interconnections.htm

UN FAO. (2020ª). *Data Dashboard*. Global Forest Resources Assessment 2020. https://fra-data.fao.org/assessments/fra/2020/EU27/home/overview

UN FAO. (2020b). *Global Forest Resources Assessment 2020*. FAO. https://doi.org/10.4060/ca9825en

UN International Maritime Organisation. (2023). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf

UNECE. (2013). *Forest Products Annual Market Review 2012-2013*. https://unece.org/DAM/timber/publications/FPAMR2013.pdf

U.S. Department of Energy. (2024). *GREET*. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/greet

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., & Hamelinck, C. (2015). The land use change impact of biofuels in the EU: Quantification of area and greenhouse gas impacts. *August*, 261. https://pure.iiasa.ac.at/id/eprint/12310/

van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. In *Journal of Power Sources* (Vol. 327, pp. 345–364). Elsevier B.V. https://doi.org/10.1016/j.jpowsour.2016.07.007

van der Winden, J., van Vliet, ., Patterson, A., & Lane, B. (2015). *Renewable Energy Technologies and Migratory Species: Guidelines for sustainable deployment*. https://tethys.pnnl.gov/sites/default/files/publications/van-der-Winden-et-al-2015.pdf

van Dyk, S., & Saddler, J. (2021). *Progress in Commercialization of Biojet / Sustainable Aviation Fuels (SAF): Technologies, potential and challenges*. IEA Task 39. https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf

van Grinsven, A., Bettina Kampman, Cor Leguijt, Emiel van den Toorn, Isabel Nieuwenhuijse, Joeri Vendrik, Martijn Broeren, & Reinier van der Veen. (2020). *Bio-Scope: use and availability of sustainable biomass*. https://cedelft.eu/publications/bio-scope-use-and-availability-of-sustainable-biomass/

Van Veldhuizen, B., Van Biert, L., Aravind, P. V., & Visser, K. (2023). Solid Oxide Fuel Cells for Marine Applications. *International Journal of Energy Research*, *2023*. https://doi.org/10.1155/2023/5163448

van Veldhuizen, B., van Biert, L., Aravind, P. V., & Visser, K. (2023). Solid Oxide Fuel Cells for Marine Applications. In *International Journal of Energy Research* (Vol. 2023). Wiley-Hindawi. https://doi.org/10.1155/2023/5163448

Vanbeveren, S. P. P., & Ceulemans, R. (2019). Biodiversity in short-rotation coppice. *Renewable and Sustainable Energy Reviews*, *111*, 34–43. https://doi.org/10.1016/j.rser.2019.05.012

Vanden Broeck, A., Villar, M., Van Bockstaele, E., & Van Slycken, J. (2005). Natural hybridization between cultivated poplars and their wild relatives: Evidence and consequences for native poplar populations. *Annals of Forest Science*, *62*(7), 601–613. https://doi.org/10.1051/forest:2005072

Vervaeke, P., Luyssaert, S., Mertens, J., Meers, E., Tack, F. M. G., & Lust, N. (2003). Phytoremediation prospects of willow stands on contaminated sediment: a field trial. *Environmental Pollution*, *126*(2), 275–282. https://doi.org/10.1016/S0269-7491(03)00189-1

Viant, M. (2009). The fat of the land. *Planet Earth*, *SPRING*, 14–15. https://doi.org/10.7748/ns.18.41.21.s29

Vítková, M., Müllerová, J., Sádlo, J., Pergl, J., & Pyšek, P. (2017). Black locust (Robinia pseudoacacia) beloved and despised: A story of an invasive tree in Central Europe. *Forest Ecology and Management*, *384*, 287–302. https://doi.org/10.1016/j.foreco.2016.10.057

Vizzarri, M., Pilli, R., Korosuo, A., Blujdea, V. N. B., Rossi, S., Fiorese, G., Abad-Viñas, R., Colditz, R. R., & Grassi, G. (2021). Setting the forest reference levels in the European Union: overview and challenges. *Carbon Balance and Management*, *16*(1), 1–16. https://doi.org/10.1186/s13021-021-00185-4

Voigt, C. C. (2021). Insect fatalities at wind turbines as biodiversity sinks. *Conservation Science and Practice*, *3*(5). https://doi.org/10.1111/csp2.366

Volk, T. A., Verwijst, T., Tharakan, P. J., Abrahamson, L. P., & White, E. H. (2004). Growing fuel: a sustainability assessment of willow biomass crops. *Frontiers in Ecology and the Environment*, *2*(8), 411–418. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/1540-9295%282004%29002%5B0411%3AGFASAO%5D2.0.CO%3B2

Von Cossel, M., Winkler, B., Mangold, A., Lask, J., Wagner, M., Lewandowski, I., Elbersen, B., van Eupen, M., Mantel, S., & Kiesel, A. (2020). Bridging the Gap Between Biofuels and Biodiversity Through Monetizing Environmental Services of Miscanthus Cultivation. *Earth's Future*, *8*(10). https://doi.org/10.1029/2020EF001478

Vysna, V., Maes, J., Petersen, J., La Notte, A., Vallecillo, S., Aizpurua, N., Ivits, E., & Teller, A. (2021). Accounting for ecosystems and their services in the European Union (INCA). In *Statistical report*. https://ec.europa.eu/eurostat/documents/7870049/12943935/KS-FT-20-002-EN-N.pdf/de44610d-79e5-010a-5675-14fc4d8527d9?t=1624528835061

Wang, L., Pedersen, P. B. M., & Svenning, J.-C. (2023). Rewilding abandoned farmland has greater sustainability benefits than afforestation. *Npj Biodiversity*, *2*(1), 5. https://doi.org/10.1038/s44185-022-00009-9

Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., & Högy, P. (2021). Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agronomy for Sustainable Development*, *41*(5), 59. https://doi.org/10.1007/s13593-021-00714-y

Wetlands International. (2023a). *EU countries face EU legal action over lack of sustainable water management plans*. https://europe.wetlands.org/eu-countries-face-eu-legal-action-over-lack-of-sustainable-water-management-plans/

Wetlands International. (2023b). EU countries miss extended deadline for biodiversity pledges. *Wetlands International News*.

Wiering, M., Boezeman, D., & Crabbé, A. (2020). The water framework directive and agricultural diuse pollution: Fighting a running battle? *Water (Switzerland)*, *12*(5), 1–12. https://doi.org/10.3390/w12051447

Wiesenthal, T., Mourelatou, A., Petersen, J.-E., & Taylor, P. (2006). *How much bioenergy can Europe produce without harming the environment?* https://www.eea.europa.eu/publications/eea_report_2006_7

Wilhelm, W. W., Johnson, J. M. F., Hatfield, J. L., Voorhees, W. B., & Linden, D. R. (2004). Crop and Soil Productivity Response to Corn Residue Removal. *Agronomy Journal*, 96(1), 1–17. https://doi.org/10.2134/agronj2004.1000a

Williams, M. A., & Feest, A. (2019). The Effect of Miscanthus Cultivation on the Biodiversity of Ground Beetles (Coleoptera: Carabidae), Spiders and Harvestmen (Arachnida: Araneae and Opiliones). *Agricultural Sciences*, *10*(07), 903–917. https://doi.org/10.4236/as.2019.107069

Wingenbach, M., Dünzen, K., Krieger, S., & Gibson, J. (2024). *Overview of Renewable Energy Spatial Planning and Designation of Acceleration Areas in Selected EU Member States*. https://caneurope.org/content/uploads/2024/05/RE-Spatial-Planning-Acceleration-in-EU-MS_13052024.pdf

Winqvist, C., Ahnström, J., & Bengtsson, J. (2012). Effects of organic farming on biodiversity and ecosystem services: taking landscape complexity into account. *Annals of the New York Academy of Sciences*, *1249*(1), 191–203. https://doi.org/10.1111/j.1749-6632.2011.06413.x

Wissner, N., & Graichen, V. (2024). *Policy Brief | Aviation in the EU climate policy*. https://www.oeko.de/fileadmin/oekodoc/2024-briefing-aviation-in-EU-policy.pdf

Wittekind, D., & Schuster, M. (2016). Propeller cavitation noise and background noise in the sea. *Ocean Engineering*, *120*, 116–121. https://doi.org/10.1016/j.oceaneng.2015.12.060

Wong, A. Y. H., Selin, N. E., Eastham, S. D., Mounaïm-Rousselle, C., Zhang, Y., & Allroggen, F. (2024). Climate and air quality impact of using ammonia as an alternative shipping fuel. *Environmental Research Letters*, *19*(8), 084002. https://doi.org/10.1088/1748-9326/ad5d07

WWF. (2021, July). *EU Forest Strategy hampered by shortsighted interests*. https://www.wwf.eu/?4040816/EU-Forest-Strategy-hampered-by-shortsighted-interests

Yatsiuk, Y., & Wesołowski, T. (2020). Diversity and abundance of large tree holes used by Tawny Owls *Strix aluco* in lowland temperate forests. *Bird Study*, *67*(3), 331–343. https://doi.org/10.1080/00063657.2020.1869179

Yugo, M., & Soler, A. (2019). A look into the role of e-fuels in the transport system in Europe (2030-2050). *Concawe Review*, *28*(1), 4–22. https://www.concawe.eu/wp-content/uploads/E-fuels-article.pdf

Zero Carbon Analytics. (2022). *The ecological impact of offshore wind farms*. https://zerocarbon-analytics.org/wp-content/uploads/2022/07/The-marine-environmental-impacts-of-offshore-windfarms.pdf

Annex A. Biodiversity policy (expanded)

A.1. Biodiversity Strategy for 2030

A.1.1. Biodiversity Strategy coverage

A key target of the EU Biodiversity Strategy is to protect 30% of the EU's land and sea by 2030. Whether or not these overall targets will be met at the EU level remains uncertain as protected area coverage for the land and sea varies between EU Member States. By the end of 2021, nine Member States, including Luxembourg, Bulgaria, Slovenia, Poland, Croatia, Cyprus, Germany, Slovakia and Greece, had already designated over 30% of their land area as protected (Figure 43). However, it is important to note that the statistics on protected areas are not always reliable, as some Member States include areas that do not meet IUCN protected area criteria (Tucker et al., 2023). In fact, Tucker et al. (2023) highlight discrepancies in reported figures by comparing estimates from national experts, which, in some cases, vary by several percentage points. According to EEA data, by the end of 2021, three EU Member States had also designated more than 30% of their sea areas as protected. These were Germany, Belgium and France (Figure 44). By the end of 2022, Member States were due to submit pledges concerning their contribution to meeting the 2030 targets on protected areas, however none made the deadline (Wetlands International, 2023b). Even with an extended deadline of 28 February 2023, just Luxembourg and Spain made pledges.

Figure 43. Terrestrial protected area coverage by country in the EU-27 by end of 2021

Source: Adapted from EEA (2023d)

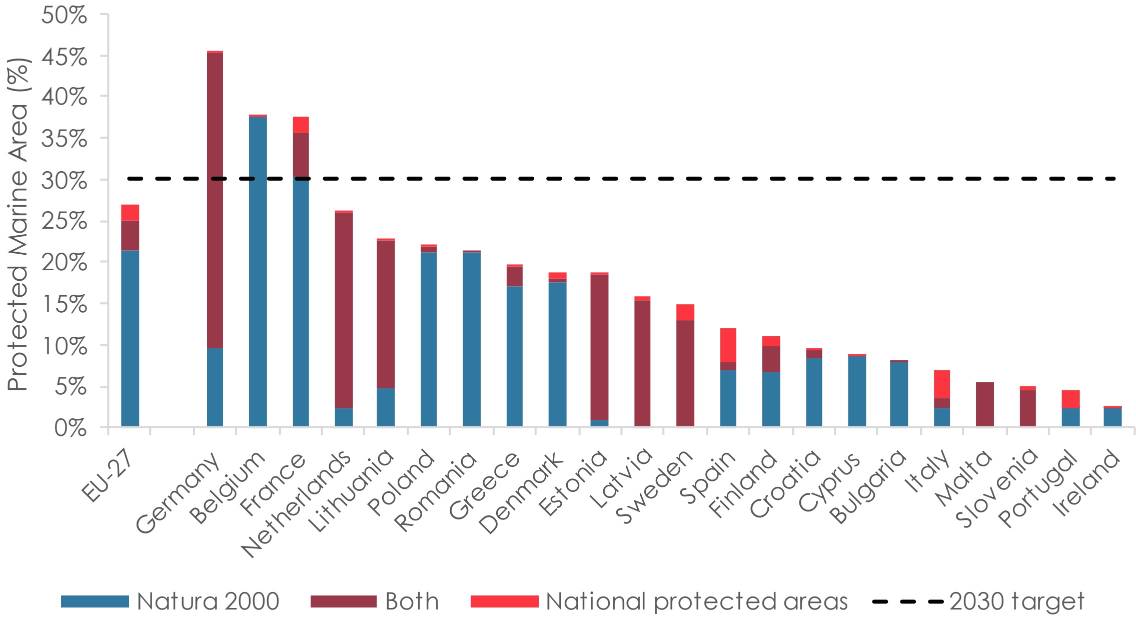


Figure 44. Marine protected area coverage in EU Member States, 2021

Source: Adapted from EEA (2023b)

It is encouraging to find that some Member States are ahead of the 2030 nature protection targets. However, it is important to recognise that the designation of an area as 'protected' does not automatically ensure the preservation of its biodiversity (Bowyer et al., 2020), and many protected areas are adversely impacted by human activities. For instance, the wetlands of Doñana National Park in Southern Spain, face significant threats due to excess groundwater abstraction for agriculture (Acreman et al., 2022) and water pollution (Paredes et al., 2021) despite being designated as part of the Natura 2000 network. Another study found that over 80% of EU marine protected areas had only minimal regulation of human activities, further highlighting the challenges that protected areas face (Aminian-Biquet et al., 2024).

A.1.2. Energy

Although there are no specific targets for energy, the Biodiversity Strategy calls for "win-win solutions for energy generation", recognising that "sustainably sourced renewable energy will be essential to fight climate change and biodiversity loss". It states that "the EU will prioritise solutions such as ocean energy, offshore wind, solar-panel farms that provide biodiversity-friendly soil cover, and sustainable bioenergy". The Strategy points towards the sustainability criteria of RED II and "promotes a shift to advanced (second-generation) biofuels based on residues and non-reusable and non-recyclable waste". It notes that "the use of whole trees and food and feed crops for energy production – whether produced in the EU or imported – should be minimised" and highlights the Commission's plans to assess the EU and global biomass supply and demand, especially the use of forest biomass, to inform the RED III, the ETS, and the LULUCF Regulation (Section 4.3.8 of the main text). The findings of the Commission's assessment on the use of forest biomass for energy were significant (Camia et al., 2021) and are be considered in more detail in Section 5.3.

A.1.3. Agriculture

The Biodiversity Strategy recognises the crucial role that agricultural practices can play in protecting biodiversity. It emphasises alignment with the EU's Farm to Fork Strategy (see Annex A.2.3) (European Commission, 2020a), which aims to create a sustainable food system in Europe, and the CAP, which promotes eco-schemes, precision agriculture, organic farming and agroforestry. According to the Biodiversity Strategy, efforts should include:

- reducing the risk and use of chemical pesticides, including more hazardous pesticides (by 50% by 2030);
- reducing nutrient losses from fertilisers by 50% and reducing the use of fertilisers by at least 20%;
- reducing the decline of pollinators through implementing the Pollinators Initiative (European Commission, 2018c);
- restoring 10% of agricultural land to high-diversity features such as buffer strips, hedgerows and ponds;
- increasing organic farming (to cover 25% of agricultural land).

Additionally, the Strategy recognises that reversing genetic diversity loss using different crop varieties is essential both for biodiversity and nutritional benefits.

A.1.4. Soils

Soil is a complex ecosystem which regulates ecosystem services such as fertility, nutrient cycling, and climate regulation through sequestering carbon (Nunes et al., 2020). Building on commitments related to the agriculture sector, the Biodiversity Strategy identifies that addressing soil health will be crucial, and that soil degradation from poor land management, deforestation, overgrazing, unsustainable farming practices, construction, and land sealing have all caused significant environmental and economic issues.

Additionally, the Strategy recognises that climate change is exacerbating soil erosion and the loss of soil organic carbon. As such, it identifies that it will be essential to restore contaminated and degraded soils by defining the conditions of healthy soils and improving the monitoring of soil quality. To address these issues, the EU Soil Strategy for 2030 was adopted in 2021, setting both medium- and long-term targets to 2030 and 2050 respectively (European Commission, 2021a). Anchored alongside the Biodiversity Strategy, the Soil Strategy has an overall vision to ensure that by 2050, all EU soil ecosystems will be in a healthy condition, and thus more resilient and better able to support climate change adaptation.

A.1.5. Forests

The Biodiversity Strategy for 2030 emphasises that forests are essential for biodiversity, climate and water regulation, carbon sequestration, soil stabilisation, and the provision of food, medicines, and materials including biomass. Although the EU has put forward forest policy strategies since 1998, these efforts have often been perceived as weak due to the EU's limited competency over forest policies and the influence of a powerful forestry lobby (FERN, 2021; WWF, 2021). Despite these challenges, the Biodiversity Strategy for 2030 recognises the pivotal role that sustainable forest management and biodiversity restoration plays in safeguarding forests. It aims to place all remaining primary and old-growth forests under strict protection and stresses the need to enhance the quantity, quality and resilience of EU forests, against threats like fire, drought, pests, diseases and other impacts exacerbated by climate change.

To advance these objectives, the Biodiversity Strategy commits to proposing a robust EU Forest Strategy (see Section 4.3.4 and Annex A.2.5). This Strategy seeks to overcome past limitations by promoting afforestation, reforestation and tree planting, with a specific goal of planting an additional 3 billion trees across the EU by 2030. In March 2023, the EU Commission released guidelines on biodiversity-friendly afforestation, reforestation and tree planting, which includes strategies for afforestation initiatives in agricultural land, reforestation in forested areas with a focus on restoration, and tree planting in urban, peri-urban, and agricultural environments (agroforestry) (European Commission, 2023h). Additionally, the Commission released guidelines for defining, mapping, monitoring and strictly protecting EU primary and old-growth forests (European Commission, 2023g), offering practical guidance to national policymakers to effectively identify and safeguard these crucial forest areas in line with the commitments of the Biodiversity Strategy.

A.1.6. Oceans, seas, coastal and inland waters

The Biodiversity Strategy recognises that restoring the health of marine and freshwater ecosystems is not only critical for biodiversity, but will also bring health, social and economic benefits to wider EU society. The strategy identifies that the full implementation of the Marine Strategy Framework Directive (MSFD) (Section 4.3.6 and Annex A.2.7) (European Union, 2008b), which aims to protect and preserve the marine environment across Europe, will be essential. The Strategy also identifies that an ecosystem-based approach to marine spatial planning can reduce the adverse impacts of human activities on sensitive species and seafloor habitats, and that spatial plans should cover all maritime sectors and activities.

For freshwater ecosystems, the EU's Biodiversity Strategy identifies that greater efforts are needed to implement the Water Framework Directive (WFD) (Section 4.3.5 and Annex A.2.6) (European Union, 2000), to restore rivers to free-flowing status and remove barriers for migrating fish. It recognises that barrier removal, as well as floodplain and wetland restoration, will be key to achieving the commitment of 25,000 km of free-flowing rivers by 2030. The Commission also commits to providing technical guidance and support to Member States, to ensure ecological flows and achieve good ecological status of all waters by 2027. Ecological status is influenced by water quality (e.g. levels of pollution of all types) as well as habitat degradation, and a waterbody with good ecological status shows low levels of distortion resulting from human activity.

A.1.7. Pollution

The Biodiversity Strategy recognises that pollution remains a major threat to biodiversity and significantly contributes to the ongoing extinction of species. Many types of pollution can drive biodiversity loss, including excess nutrients, chemical pesticides, pharmaceuticals, hazardous chemicals, wastewater, and plastics. As part of the EU's commitments in the Biodiversity Strategy, it adopted the Zero Pollution Action Plan for water, air and soil in 2021 which aims to reach zero pollution for 2050 (European Commission, 2021f). The Plan sets key 2030 targets to speed up pollution reduction, including targets to reduce:

- by more than 55%, the health impacts (premature deaths) of air pollution;
- by 30%, the share of people chronically disturbed by transport noise;
- by 25%, the EU ecosystems where air pollution threatens biodiversity;
- by 50%, nutrient losses, the use and risk of chemical pesticides, the use of the more hazardous ones;
- total waste generation; and
- by 50%, residual municipal waste.

A.1.8. Invasive Alien Species

The Biodiversity Strategy recognises that the rate of invasive species introductions has increased in Europe, and that this poses a risk to the EU's threatened species. To combat this, the EU has implemented the Invasive Alien Species Regulation (See Section 4.3.7 and A.2.8) (European Union, 2014b), which came into force in January 2015, aiming to manage established invasive species and reduce the risk to EU threatened species.

A.2. Other biodiversity-related policy

A.2.1. Soil Strategy for 2030 and proposed Soil Monitoring Directive

The proposed Soil Monitoring Directive may also provide the foundation for future soil-related policy initiatives through the EU Soil Observatory (a central hub for soil-related information, launched by the JRC), ensuring that soil health remains a priority within the EU's environmental and biodiversity strategies. The specific objectives of the proposed law include:

- Monitoring and assessment of soil health: implementing a harmonised program across the EU, utilising LUCAS[71] soil and biodiversity information, including various biological indicators, such as soil microbial biomass and diversity.
- Sustainable soil management, respecting the principles laid down in Annex III of the Directive (reproduced in Table 39).
- Addressing soil contamination: to help create a toxic-free environment by 2050, Member States must tackle unacceptable risks for human health and the environment caused by soil contamination. Soil contamination is defined as "the presence of a chemical or substance in the soil in a concentration that may be

71 Land Use and Coverage Area Frame Survey – a large-scale semi-regular survey aimed at collecting harmonised data on land use, land cover, and soil characteristics across EU Member States.

harmful to human health or the environment". Member states must take measures to identify, investigate and manage contaminated sites in accordance with provisions under Articles 12-16.

Table 39. Annex III of the EU's proposed Soil Monitoring Directive lays down principles for sustainable soil management

Sustainable soil management principles
(a) avoid leaving soil bare by establishing and maintaining vegetative soil cover, especially during environmentally sensitive periods;
(b) minimise physical soil disturbance;
(c) avoid inputs or release of substances into soil that may harm human health or the environment, or degrade soil health;
(d) ensure that machinery use is adapted to the strength of the soil, and that the number and frequency of operations on soils are limited so that they do not compromise soil health;
(e) when fertilization is applied, ensure adaptation to the needs of the plant and trees at the given location and in the given period, and to the condition of soil and prioritize circular solutions that enrich the organic content;
(f) in case of irrigation, maximise efficiency of irrigation systems and irrigation management and ensure that when recycled wastewater is used, the water quality meets the requirements set out in Annex I of Regulation (EU) 2020/741 on minimum requirements for water reuse, and when water from other sources is used, it does not degrade soil health;
(g) ensure soil protection by the creation and maintenance of adequate landscape features at the landscape level;
(h) use site-adapted species in the cultivation of crops, plants or trees where this can prevent soil degradation or contribute to improving soil health, also taking into consideration the adaptation to climate change;
(i) ensure optimised water levels in organic soils so that the structure and composition of such soils are not negatively affected;
(j) in the case of crop cultivation, ensure crop rotation and crop diversity, taking into consideration different crop families, root systems, water and nutrient needs, and integrated pest management;
(k) adapt livestock movement and grazing time, taking into consideration animal types and stocking density, so that soil health is not compromised and the soil's capacity to provide forage is not reduced;
(l) in case of known disproportionate loss of one or several functions that substantially reduce the soils capacity to provide ecosystem services, apply targeted measures to regenerate those soil functions.

Source: European Commission (2023i)

A.2.2. CAP

CAP 2023-2027 spans three regulations: the Horizontal Regulation (2021/2116), Strategic Plan Regulation (2021/2115), and Common Market Organisation Regulation (2021/2117), with direct payments to farmers allocated from the European agricultural guarantee fund (EAGF). The CAP 2023-27 includes various measures to improve the environment and reduce biodiversity loss in agricultural settings with funding towards its implementation. These policy tools include the following:

- Agri-Environment-Climate Measures (AECMs): initially termed Agri-Environmental

Schemes, were introduced as part of the 1992 reform, aimed to encourage farmers to adopt environmentally beneficial practices under the Rural Development Programmes.

- Greening Measures: introduced in the 2013 CAP reform, which require farmers to follow specific practices beneficial for the environment to receive full direct payments. Practices include crop diversification, maintaining permanent grassland, and creating Ecological Focus Areas (EFAs) such as fallow land, terraces, landscape features, buffer strips, and agroforestry areas. Greening payments constitute about 30% of a farmer's direct payments under Pillar I of the CAP. Although in recent years, significant derogations have been permitted (European Commission, 2024i); these may undermine the effectiveness of the payments as incentives for sustainable farming.
- Eco-Schemes: a newer addition to the CAP, under its 2023-2027 reform, these are designed to incentivise farmers to adopt practices contributing to environment and climate goals. These schemes cover a broad range of practices, such as organic farming, agroforestry, and maintaining high diversity landscape features such as hedgerows and ponds, which can support and enhance biodiversity and ecosystem services in agricultural landscapes.

The CAP Strategic Plan Regulation provides a legal framework for Member States to develop national strategies to support farmers and rural stakeholders across the EU (European Union, 2021). It lays down rules on the general and specific objectives of the CAP (under Article 6) and its related performance indicators (under Annex I), the types of interventions and requirements to meet those objectives, including rules and standards for good agricultural and environmental condition of land (GAEC) (Annex III) and the approach for Member States to provide their CAP Strategic Plans. The CAP Strategic Plans specify national and regional agricultural needs and priorities (European Commission, 2023a), with direct consideration for:

- Climate: including contributing to reducing greenhouse gas emissions (on 35% of the EU's agricultural land) and increasing carbon sequestration, protecting EU agricultural wetlands and peatlands to reduce carbon release, maintaining non-productive areas and landscape features (on at least 3% of arable land), storing carbon in soil and biomass.
- Natural resources: utilising crop rotation to protect soils and preserve soil potential, restoring soil fertility (on up to 47% of EU agricultural land), targeting water resilience and water retention capacity, reducing pollution from fertilisers and pesticides (by creating buffer strips along water courses of at least 3 metres), reducing the use and risk of pesticides, and doubling the area receiving CAP support for organic production to reach close to 10% in 2027.
- Biodiversity: creating space for nature on agricultural land and improving ecological connectivity, maintain and protect landscape features such as hedges, ditches, trees and fallow land on at least 4% of arable land, environmentally sensitive permanent grasslands remain covered by a ban on conversion or ploughing applicable in Natura 2000 zones.

A.2.3. Farm to Fork Strategy

Closely linked to the Biodiversity Strategy and the CAP, in May 2020, the European Commission published the Farm to Fork Strategy, focussing on fair and environmentally friendly food production, and is generally beyond the scope of this report (since the ReFuelEU Aviation and FuelEU Maritime exclude biofuels from food and feed crops from contributing towards the renewable fuel targets). We have considered it here only briefly for context, as it repeats several of the targets set out in the Biodiversity Strategy related to organic farming (25% of agricultural land by 2030) and reducing the use of chemical pesticides and nutrient losses – both targeting a 50% reduction by 2030. While these targets apply at the EU level; Member States define their own targets for organic agriculture for 2030 as part of the CAP strategic plans, ranging from 5% for Malta to 30% for Belgium (Wallonia region), Germany, Sweden, and Austria.

A.2.4. Pollinators Initiative

The Pollinators Initiative Annex provides a new action framework for addressing each priority, for example, the Commission and Member States should finalise the development and testing of a methodology for an EU pollinator monitoring scheme (EU-PoMS) and devise an integrated framework for monitoring pollinator decline by 2026 and develop indicators on the state of pollinator populations. Also, by 2026, the Commission will finalise development of conservation plans for pollinator species in agricultural and forest landscapes, as well as restoring pollinator habitats in agricultural landscapes. Additional action areas include mitigating the impacts of pesticide use on pollinators with an anticipated revision of the 2014 European Food Safety Authority (EFSA) Bee Guidance Document on the assessment of risks to bees from the use of pesticides to be completed by the end of 2024 (EFSA, 2013).

A.2.5. Forest Strategy for 2030 and proposed Forest Monitoring Law

Europe's forests play a crucial role in maintaining biodiversity, regulating the climate, and providing essential ecosystem services. Constituting the largest terrestrial ecosystem in the EU-27, forests cover 42.5% of EU land or around 160 million hectares (SoEF, 2020). However, forest extent varies between Member States, with two-thirds of forests occurring in just six Member States – Sweden, Finland, Spain, France, Germany and Poland.

The complexity of forests and their uses, particularly their supply of timber and other products, like those used for bioenergy means that integrated approaches are essential to avoid trade-offs between biodiversity, wood extraction and / or climate change mitigation. As Europe's forests absorb around 10% of the EU's annual greenhouse gas emissions in soils and biomass (EEA, 2023), they play a crucial role in sequestering and storing carbon, and the forest strategy seeks to maximise this potential, for example by including provisions within the 2023-2027 CAP to design forest related interventions.

Highly relevant to this report, the forest strategy states that wood-based bioenergy is the main source of renewable energy in the EU, supplying 60% of the share. Recognising the need to balance the socioeconomics and environmental sustainability of wood-based bioenergy, RED II included enhanced sustainability criteria for all types of biomass for energy. In addition, RED III provides further sustainability criteria for bioenergy (see Section 5.1) including consideration of the cascading use principle (prioritising highest value use first e.g. timber before fuel wood), minimising the use of 'industrial grade roundwood' for energy production, and eliminating financial support for energy production from saw logs, veneer logs, stumps and roots. Such practices can be detrimental to both soil health and biodiversity (Moffat et al., 2011).

The forest strategy also recognises that strategic forest monitoring, reporting and data collection is essential for forest resilience and committed to put forward a legislative proposal to enable coordinated action on EU forests. As such, the Commission put forward a legislative proposal for a Regulation on a Forest Monitoring Framework (European Commission, 2023j). It promotes the use of remote sensing technologies and geospatial data integrated with ground-based monitoring to provide a comprehensive monitoring approach, vital for improving understanding of the impacts of various land management practices, such as forestry residue harvesting. Detailed data can help to predict and mitigate negative impacts on soil health and biodiversity and support sustainable forest management which aligns with the EU's climate and biodiversity goals.

A.2.6. Water Framework Directive (WFD)

The WFD's main objectives include achieving 'good status' for all EU waters, managing water resources sustainably and protecting aquatic ecosystems. 'Good status' encompasses both good ecological and good chemical status, indicating that water bodies must maintain healthy populations of aquatic flora and fauna, and meet chemical standards for various pollutants. Specifically, 'good ecological status' includes factors such as biological quality elements (such as fish, invertebrates, and aquatic plants), hydro-morphological quality elements (such as river flow rate and habitat structure) and physico-chemical qualities (such as nutrient concentrations and pollution levels). The WFD includes in its Annex X, a list of priority substances for which Member States must monitor, and the standards for them are set in Annex I of the Environmental Quality Standards Directive (European Union, 2008a). These monitoring results are reported to the Commission and the EEA and evaluated to facilitate adaptive management.

The Directive also requires Member States to develop and implement River Basin Management Plans (RBMPs), following natural geographical and hydrological boundaries rather than administrative borders. This fosters collaboration between administrative bodies by integrating water management and biodiversity conservation within each river catchment. The RBMPs outline measures to protect and restore aquatic ecosystems, manage water resources sustainably, and ensure public participation and stakeholder engagement in water management decisions. For example, implementing sustainable water abstraction practices to maintain ecological flows and support aquatic life, or reduce nutrient and pesticide runoff from agricultural lands through buffer zones.

A.2.7. Marine Strategy Framework Directive (MSFD)

The MSFD includes specific descriptors for biodiversity, such as maintaining healthy fish populations, and the integrity of the sea floor. It also supports the establishment and management of Marine Protected Areas (MPAs) to conserve marine habitats and species, and promotes an integrated approach to maritime policy, ensuring that activities like fishing, shipping and renewable energy development are managed sustainably. Annex I of the MSFD outlines eleven qualitative descriptors to define good environmental status of EU marine waters. These are as follows:

1) Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.
2) Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems.
3) Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.
4) All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.
5) Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters.
6) Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded, and benthic ecosystems are not adversely affected.
7) Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems.
8) Concentrations of contaminants are at levels not giving rise to pollution effects.
9) Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards.
10) Properties and quantities of marine litter do not cause harm to the coastal and marine environment.
11) Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

A.2.8. Invasive Alien Species Regulation

The regulation establishes a framework for addressing the pathways of introduction and spread of invasive species and promotes coordinated efforts among Member States. It includes measures to be taken across the EU in relation to invasive alien species, with its list of ‘invasive alien species of Union concern’; having been through two (so far) Commission Implementing Regulations, in 2016 and 2022. The list includes species identified as posing a significant threat to biodiversity, ecosystems and their services, as well as human health and the economy. Species on this list are subject to restrictions on import, transport, sale, breeding, and release into the environment in the EU. The list is updated every six years on based on the latest scientific assessments.

The regulation also includes measures to prevent the intentional introduction of invasive species, including risk assessments and permits for activities which may involve such species. Member States are required to identify and manage pathways of unintentional introduction, such as through shipping, trade, and travel. Additionally, the regulation emphasises the importance of early detection and rapid response to new invasions. Member States must establish surveillance systems and contingency plans to detect and quickly eradicate invasive species before they become established, and when an invasive species of Union concern is detected, immediate action must be taken to prevent its establishment and spread.

For invasive species which are already widespread, the regulation mandates that management measures to minimise their impact on biodiversity and ecosystems must be taken. This includes habitat restoration, population control, and public awareness campaigns to educate stakeholders and the public on the risks associated with invasive species and the importance of prevention and management. Additionally, the regulation promotes cooperation and information exchange among Member States and between the EU and third countries, to encourage a coordinated response to the threat of invasive species across borders.

The EEA provides technical support and monitoring guidance for invasive alien species, and the EU Commission, in collaboration with Member States is responsible for the implementation and enforcement of the regulation. Member states must report on their progress and the measures taken, which are subject to review and evaluation by the Commission. While the regulation addresses the issue of invasive species in the EU, challenges remain in its implementation, such as ensuring adequate resources and coordination across different sectors and regions. Similarly, the effectiveness of the regulation depends on the commitment and capacity of Member States to enforce its provisions and take proactive measures against invasive species.

A.2.9. Land Use, Land Use Change and Forestry Regulation

The LULUCF Regulation determines the Union target of climate neutrality for 2035 in the land sector and sets a binding commitment for each Member State to ensure that accounted emissions from land use is entirely compensated for by an equivalent accounted removal of CO_2 from the atmosphere (i.e. the ‘no net debit’ rule). Although Member States already partly undertook this commitment individually under the Kyoto Protocol until 2020, the LULUCF Regulation establishes this commitment in EU law. Moreover, the scope is extended from only forests today to all land uses (including wetlands) by 2026. The regulation encourages land management practices that increase soil organic carbon stocks, for example restoration of forests and wetlands, and avoiding the conversion of grassland to cropland. Article 5 establishes general accounting rules for Member States to account for different land accounting categories (including forest, cropland, grassland, wetland or settlement etc.), and any changes in the carbon stock of the carbon pools within those land categories, i.e. what results in greenhouse gas emissions and removals.

A key element of the LULUCF regulation is the establishment of Forest Reference Levels (FRLs), using criteria and guidance provided in Annex IV of the regulation. The FRLs provide an estimate, expressed in tonnes of CO_2 equivalent per year, of the average annual net emissions or removals from managed forest land within the territory of each Member State, and provide a benchmark for assessing the performance of Member States in managing their forest lands sustainably and contributing to climate change mitigation. Member States FRLs have been established for the period 2021 to 2025, under Annex IV of the regulation.

Relative to the FRL 2000-2009 baseline, the total EU forest carbon sink has declined by 18% in the period 2021-2025 (Vizzarri et al., 2021). This has been largely attributed to (i) the impact of increased harvest rates, which have increased 16% since the 2000-09 reference period according to (Korosuo et al., 2021(Korosuo et al., 2021), driven by the evolution of the forest age class distribution (composition of forests age over time); and (ii) the effects of forest aging on reduced increment (older forests grow slower compared to young forests) (Grassi et al., 2021).

Annex B. Biodiversity impacts

B.1. Food and feed monocultures

Intensive cropland practices, particularly the use of monocultures, where a single crop is grown repeatedly across large areas, are often favoured by large-scale agriculture due to their economic efficiency and potential for high yields. However, these practices contribute significantly to biodiversity decline, as they reduce habitat diversity and complexity, disrupt ecosystems and often rely heavily on chemical inputs. The establishment of intensive often involves the conversion of natural and semi-natural habitats, leading to a simplification of ecological communities, loss of species diversity, and a reduction in ecosystem functions such as soil health, water retention, and natural pest control.

B.1.1. Temperate regions

In temperate regions, monocultures of oilseeds, cereals, and sugar beets tend to dominate the landscape. These monocultures, driven by the desire to improve agricultural efficiency and production, can have significant implications for biodiversity, soil health and water quality.

Agricultural intensification includes the conversion of complex natural or semi-natural systems into simplified managed ecosystems with intensified resource use (Tscharntke et al., 2005). These systems often involve the extensive use of chemical inputs, such as fertilisers, pesticides and herbicides, to maximise crop yields, with significant negative implications for soil health, water quality, and biodiversity (Donald et al., 2006; Geiger et al., 2010).

In Europe, studies have shown that intensive agricultural practices associated with monocultures are linked to the decline of farmland birds and invertebrate populations. Farmland birds – because they utilise a wide range of resources, materials and feeds – can serve as 'quality of life' indicators, providing insight into broader biodiversity trends (Donald et al., 2006). Studies in Europe show a clear correlation between intensive farming practices and the decline of these species (Donald et al., 2001).

The reliance on chemical inputs in monocultures has a range of adverse effects on the ecosystem and biodiversity, ranging from soil health implications and decline in water quality, to the loss of pollinators. The continued use of synthetic fertilisers can drive soil degradation, reducing the ability of soils to support diverse flora and faunal communities (Matson et al., 1997; Tilman et al., 2002). These chemical inputs can be particularly damaging for pollinators, which is particularly concerning given that almost €5 billion of the EU's annual agricultural output is dependent on pollinating insects (Vysna et al., 2021).

Meanwhile, soil biodiversity, plays a crucial role in nutrient cycling and as food for animals further up the food chain, is often diminished in monocultures (Tsiafouli et al., 2015). At the same time, nutrient enrichment from excess fertilisers can leach into water bodies, causing 'eutrophication', where high levels of nutrient runoff promote algal growth, depleting oxygen in water bodies and leading to the establishment of dead zones, where aquatic organisms cannot survive (Carpenter et al., 1998).

Generally, more diverse agricultural systems support higher levels of biodiversity (Tscharntke et al., 2021). A meta-analysis by Torralba et al. (2016) evaluates the impact of agroforestry on biodiversity and ecosystem services. The study, based on 53 publications and 365 comparisons, found that agroforestry generally provides some significant benefits over conventional agriculture and forestry, particularly in terms of enhanced erosion control, biodiversity, and soil fertility. However, no clear effect on provisioning services was established, and there was a trade-off in reduced biomass production. Silvopastoral and silvoarable systems show increased ecosystem service provision and biodiversity, especially compared to forestry land. The study suggests that Mediterranean tree plantations could help reduce soil erosion and increase soil fertility (Torralba et al., 2016).

While agroforestry has potential benefits, care needs to be taken when increasing its utilisation, as the balance between enhancing ecosystem services and avoiding unintended negative impacts must be carefully managed. For example, establishing agroforestry systems on semi-natural habitats could be very damaging for existing biodiversity. Thus, strategic integration into rural planning and policy measures should consider these complexities to support biodiversity and ecosystem services effectively. Some of the options for mitigating the impacts of conventional cropping and adopting improved agricultural practices for biodiversity, are examined more closely in Section 5.5 of the main text.

B.1.2. Tropical regions

Sometimes referred to as 'green deserts', tropical monocultures, for example of palm oil and soy, have been major drivers of land use change, deforestation and biodiversity loss. Malins (2019) notes that both palm oil and soybeans have been repeatedly identified as forest risk commodities and are identified by the European Commission as being associated with a higher indirect land use change risk than other biofuel crops. For example, the expansion of oil palm plantations in Southeast Asia, primarily in Indonesia and Malaysia, has led to significant deforestation. Figure 45 shows major results from research conducted by Gaveau et al. (2022), which utilised remote sensing technology and satellite imagery to estimate the impact of oil palm plantations in Indonesia, the world's largest palm oil producer. Over nineteen years, the area mapped under oil palm doubled, reaching 16.2 Mha in 2019 (64% industrial; 36% smallholder). Meanwhile forest area declined by 11% (9.8 Mha), a third of which (3.1 Mha) was ultimately converted into oil palm, mostly (2.9 Mha) being cleared and converted in the same year.

This has had major implications for a range of species. Oil palm plantations have reduced species richness compared with primary and secondary forests, and the composition of communities' changes significantly after forest conversion (Savilaakso et al., 2014). As indicated by Figure 45, the conversion of forests to palm oil plantations can have devastating impacts on large forest dependent animals, many of which are globally threatened, ranging from orangutans, Sumatran tigers and pygmy elephants in Southeast Asia, to gorillas and chimpanzees in West Africa, and Jaguars and Macaws in Latin America (Meijaard et al., 2020). Species of invertebrates, birds, reptiles, primates and other small mammals are also negatively affected (Foster et al., 2011).

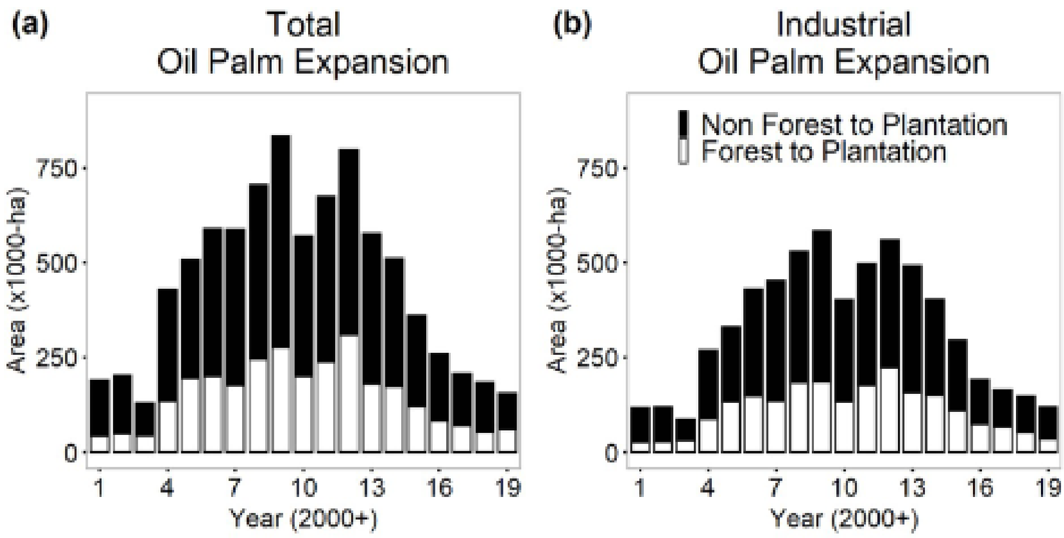


Figure 45. Time-series of Indonesia's expansion of industrial oil palm plantations, and the impact on old-growth 'primary forests' between 2000-2019

Source: Gaveau et al. (2022)

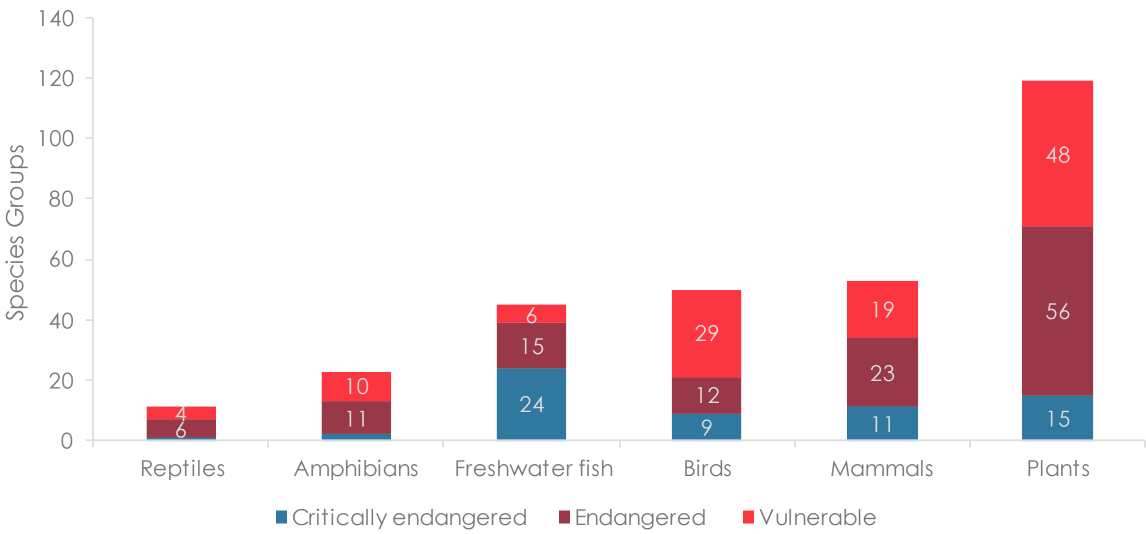


Figure 46. Species groups with more than eight threatened species with the terms 'palm oil' or 'oil palm' in the threats texts of the IUCN Red List of Threatened Species Assessments

Source: Based on Meijaard et al. (2020)

Soy cultivation has had similar implications for deforestation and biodiversity. This is especially the case in South America and specifically in the Brazilian Amazon and Cerrado regions, where the expansion of soy plantations has driven extensive deforestation, habitat fragmentation and associated threats to biodiversity (Lee et al., 2011). Between 2000 and 2019, the area cultivated with soybean in South America more than doubled from 26.4 Mha to 55.1 Mha (Song et al., 2021). Brazil's soy cropland represented a major proportion of this, booming from 13.7 Mha in 2000 to 40.9 Mha in 2022[72] (FAOstat, 2024). Richards et al. (2014) concluded that a third of Amazon deforestation in the period 2002 to 2013 was either directly or indirectly linked to soy expansion.

72 At the same time, average Brazilian soybean yield went from around 2.4 t/ha to 3.2 t/ha.

Annex C. Modelling framework

C.1. Fuels and feedstocks

C.1.1. Feedstock types and fuel sub-types

As discussed in the main text, the scenario definitions distribute energy demand among the various fuel types. For fuels made from multiple feedstocks (cf. Table 17), the share of fuel made from each feedstock evolves in time, following the same trajectory for each scenario except in the case of lipid feedstocks. Here, we assume that the supply of residual lipid feedstocks is constrained at their current levels including both EU domestic production and imports (Eurostat, 2024g), except for the High Lipids scenario where the residual lipid supply is allowed to grow.

Recalling Table 17, in our nomenclature a given fuel type may be divided into sub-types. For instance, RFNBOs in aviation can be split into kerosene-like hydrocarbons and hydrogen used in novel engines, while RFNBOs in the maritime context cover MGO/HFO-like hydrocarbons, hydrogen, ammonia, methanol, or LNG. The assumed break-down of RFNBOs into these fuel sub-types implies assumptions about the development of novel engine technologies – e.g. will hydrogen-powered flight be a significant reality in 2050, or will we still be relying on liquid hydrocarbons? For all our scenarios, we adopt a standard split of fuel sub-types which evolves in time; an example is shown in Figure 47 for maritime RFNBOs.

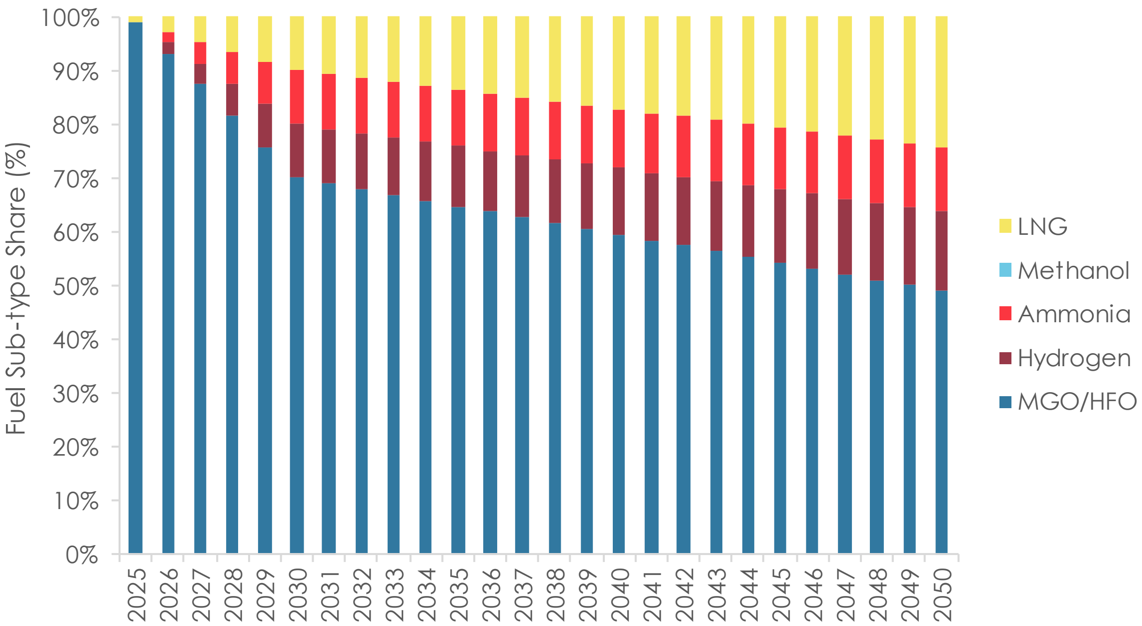


Figure 47. Assumed fuel sub-type split for RFNBOs in the maritime segment

The possible contribution of air lubrication and on-board CCS systems is neglected for this report (cf. DNV Maritime, 2023).

C.1.2. Fuel greenhouse gas intensities

We tabulate the assumed greenhouse gas intensities for aviation and maritime fuels in Table 40 and Table 41 respectively. For some fuels we assume a fixed value over time (e.g. aviation fuel made from agricultural and forestry residues follows the CORSIA defaults), while others are assumed to vary (e.g. grid electricity decarbonises over time in line with the evolving source mix).

Table 40. Greenhouse gas intensities for aviation fuels

Fuel Type	Feedstock	Unit	2025	2030	2035	2040	2045	2050
RFNBOs		gCO_2e/MJ	5.0	5.0	5.0	5.0	5.0	5.0
Lipids	UCO	gCO_2e/MJ	13.9	13.9	13.9	13.9	13.9	13.9
Lipids	Tallow	gCO_2e/MJ	22.5	22.5	22.5	22.5	22.5	22.5
Lipids	Annex IX Crop	gCO_2e/MJ	30.0	27.0	24.0	21.0	18.0	15.0
Biomass Crops	Cover Crop	gCO_2e/MJ	25.0	22.4	19.8	17.2	14.6	12.0
Biomass Crops	Annual Grass	gCO_2e/MJ	15.6	15.6	15.6	15.6	15.6	15.6
Biomass Crops	Perennial Grass	gCO_2e/MJ	10.4	10.4	10.4	10.4	10.4	10.4
Biomass Crops	SRF	gCO_2e/MJ	12.2	12.2	12.2	12.2	12.2	12.2
Residues	Agricultural	gCO_2e/MJ	7.7	7.7	7.7	7.7	7.7	7.7
Residues	Forestry	gCO_2e/MJ	8.3	8.3	8.3	8.3	8.3	8.3
Residues	Process	gCO_2e/MJ	10.0	10.0	10.0	10.0	10.0	10.0
Residues	True Waste	gCO_2e/MJ	5.0	5.0	5.0	5.0	5.0	5.0
Other Biofuels		gCO_2e/MJ	20.0	20.0	20.0	20.0	20.0	20.0
RCFs		gCO_2e/MJ	40.0	36.0	32.0	28.0	24.0	20.0
Electricity	Grid	gCO_2e/MJ	54.2	42.9	31.6	20.2	13.3	6.4
Electricity	Renewable	gCO_2e/MJ	2.3	2.4	2.5	2.6	2.7	2.8
Petroleum		gCO_2e/MJ	89.0	89.0	89.0	89.0	89.0	89.0

Note: These show the fuel lifecycle emissions per unit of energy of fuel supplied. This does not account for the efficiency of different engine types, which for the relevant fuels would reduce the emissions per unit of transport energy delivered.

Table 41. Greenhouse gas intensities for maritime fuels

Fuel Type	Feedstock	Unit	2025	2030	2035	2040	2045	2050
RFNBOs		gCO_2e/MJ	5.0	5.0	5.0	5.0	5.0	5.0
Lipids	UCO	gCO_2e/MJ	20.9	18.5	16.2	13.9	13.9	13.9
Lipids	Tallow	gCO_2e/MJ	32.9	29.4	26.0	22.5	22.5	22.5
Lipids	Annex IX Crop	gCO_2e/MJ	32.9	28.9	25.0	21.0	21.0	21.0
Biomass Crops	Cover Crop	gCO_2e/MJ	25.0	22.4	19.8	17.2	14.6	12.0
Biomass Crops	Annual Grass	gCO_2e/MJ	15.6	15.6	15.6	15.6	15.6	15.6
Biomass Crops	Perennial Grass	gCO_2e/MJ	10.4	10.4	10.4	10.4	10.4	10.4
Biomass Crops	SRF	gCO_2e/MJ	12.2	12.2	12.2	12.2	12.2	12.2
Residues	Agricultural	gCO_2e/MJ	7.7	7.7	7.7	7.7	7.7	7.7
Residues	Forestry	gCO_2e/MJ	8.3	8.3	8.3	8.3	8.3	8.3
Residues	Process	gCO_2e/MJ	10.0	10.0	10.0	10.0	10.0	10.0
Residues	True Waste	gCO_2e/MJ	5.0	5.0	5.0	5.0	5.0	5.0
Other Biofuels		gCO_2e/MJ	20.0	20.0	20.0	20.0	20.0	20.0
RCFs		gCO_2e/MJ	40.0	36.0	32.0	28.0	24.0	20.0
Electricity	Grid	gCO_2e/MJ	0.0	0.0	0.0	0.0	0.0	0.0
Electricity	Renewable	gCO_2e/MJ	0.0	0.0	0.0	0.0	0.0	0.0
Wind		gCO_2e/MJ	0.0	0.0	0.0	0.0	0.0	0.0
Natural Gas[73]		gCO_2e/MJ	84.8	84.8	84.8	84.8	84.8	84.8
Petroleum		gCO_2e/MJ	91.2	91.2	91.2	91.2	91.2	91.2

Note: See the note for Table 40. Recall that electricity supplied from on-shore power systems is automatically treated as zero-emission under FuelEU Maritime.

All fuel sub-types within a given feedstock category are allocated the same emissions intensity score. This means, for instance, that bio-hydrogen and Fischer-Tropsch hydrocarbons produced through gasification of perennial grasses are treated as having the same emissions per unit of fuel energy – even though their fuel production and refining stages may have different energy requirements.

73 For this report, we consider only fossil LNG.

C.1.3. Crop-based feedstock types

Table 42 repeats the fuel and feedstock types from Table 17 of the main text, and indicates which crops contribute to the crop-based feedstocks in the modelling. The list is not exhaustive of the crop types that have been or could be trialled for bioenergy purposes – for instance, there are many cover crop varieties that could be included. However, for the purposes of our modelling work we have selected crop types whose yields are reasonably well characterised in different regions of Europe and under different levels of land constraint.

Table 42. Modelled fuel types and feedstock types, which may in turn be divided into crop types

Fuel Type	Feedstock Type	Crop Type
RFNBOs	Renewable electricity	--
Lipids	UCO	--
	Category 1 & 2 fats	--
	Annex IX crops	Rapeseed, Ethiopian mustard, crambe, camelina, cardoon, safflower, castor
Biomass Crops	Cover crops	Biomass sorghum
	Annual grass	Biomass sorghum
	Perennial grass	Miscanthus, switchgrass, biomass cardoon, giant reed, reed canary grass
	SRF	Willow, poplar
Residues	Agricultural residues	--
	Forestry residues	--
	Process residues	--
	True wastes	--
Other Biofuels	Various	--
RCFs	Industrial gases, unrecyclable plastic & rubber	--
Electricity	Grid electricity	--
	Renewable electricity	--
Wind	Wind	--
Natural Gas	Petroleum	--
Petroleum	Petroleum	--

Note: '—' indicates that no crop types are distinguished for the given feedstock.

For the purposes of calculating yields and land area requirements, we account for the geographical distribution of each crop (split into Mediterranean, Atlantic, and continental/ boreal regions of Europe), and the emphasis on growing feedstock on marginal land in each region. Section 7.4.5 of the main text presents a brief investigation into the implications of increasing or decreasing the marginality of the land use.

C.1.4. Grid electricity mix

Grid electricity makes a modest contribution to energy demand in both transport segments over the period considered. We follow the European Commission's Joint Research Centre 'GECO 1.5C' scenario, interpolating linearly to the 2050 end-point (Tsiropoulos et al., 2020).

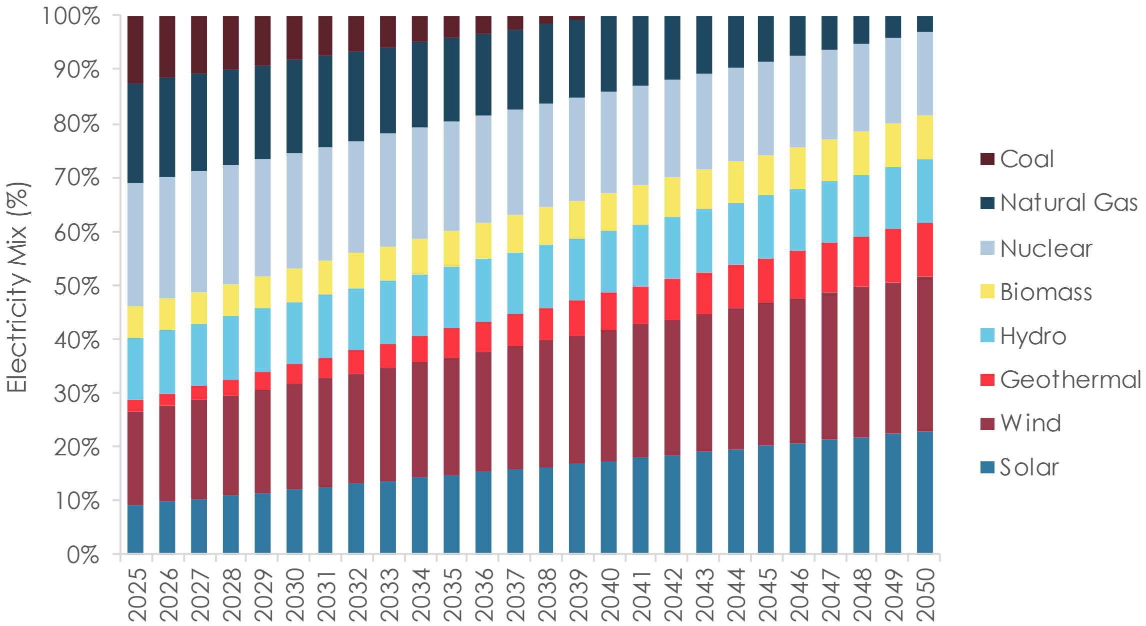


Figure 48. Assumed EU electricity mix for all scenarios

C.2. Energy demand

C.2.1. Engine efficiency

We introduced the various engine technologies in Section 3.1, and in Annex C.1.1 we discussed how we calculate the distribution of fuel sub-types that correspond to different engine types. The importance of recognising the fuel sub-types is that fuel efficiency varies by engine type, as illustrated for maritime engines by Figure 49.

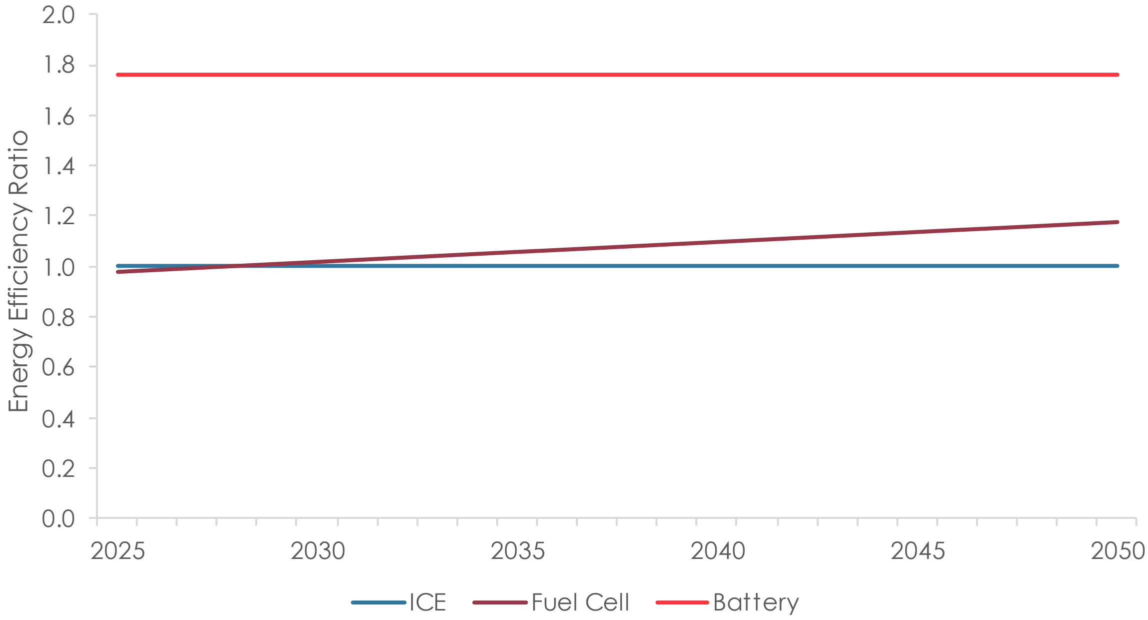


Figure 49. Assumed energy efficiency ratio for maritime engines

Note: ICE and battery efficiencies are fixed in time, while fuel cells' efficiencies improve linearly.
Source: Calculated from information contained in Hintze (2021)[74].

We calculate the effective EER for each fuel type by combining the information in Figure 49 with the distribution of fuel sub-types. This is shown in Figure 50, again for maritime fuels. The EER of lipids does not change in time as it is assumed that these are only used to make ICE-compatible hydrocarbons. The EER of natural-gas-based fuels (which for our purposes means fossil LNG) rises the fastest as we assume a relatively high penetration of LNG-compatible fuel cell engines in 2050.

74 Cf. van Biert et al. (2016), van Veldhuizen et al. (2023).

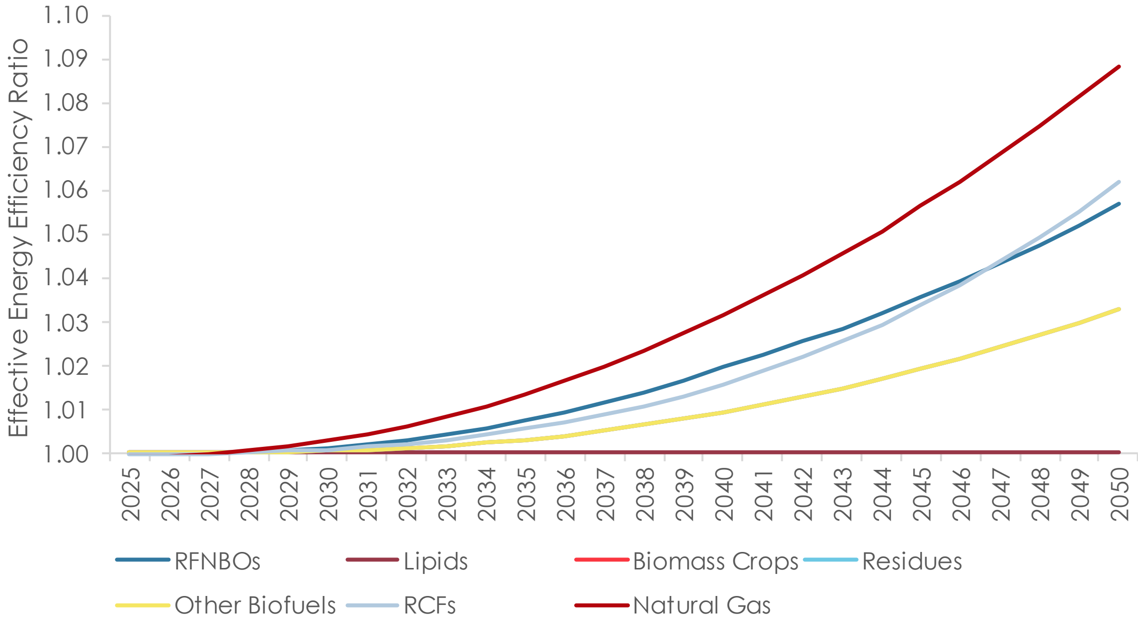


Figure 50. Effective energy efficiency ratio for maritime fuels

Note: The vertical axis has been set to start at 1. Electricity from batteries is omitted from this chart but are included in Figure 49.

C.2.2. Calculating total energy demand

Energy demand for aviation is drawn from the study supporting the ReFuelEU Aviation impact assessment (Giannelos et al., 2021) – we choose policy option 'A2'. Demand for maritime energy is estimated using historical data (Eurostat, 2024g) in tandem with projections from the FuelEU Maritime impact assessment (European Commission, 2021c)[75]. In the case of maritime transport, some energy will be delivered by wind propulsion (cf. Annex C.4.1), so the energy demand to be met by fuels is equal to the total demand minus the wind contribution.

For both aviation and maritime energy, we note that the same transport energy demand may be met with physical fuel because some engine types are more efficient than others. Thus, the overall energy demand must be adjusted for each scenario depending on the prevalence of the different fuel sub-types. For aviation, this makes little difference, as ICE-powered aircraft are expected to still be by far the dominant technology in 2050; but for ships the difference between the demand for transport energy on the one hand and the amount of fuel needed to meet that demand may differ more strongly.

C.3. Scenario design for FuelEU Maritime

In Section 7.2 we stated that scenario construction for the aviation sector was relatively

75 Of this, we note that ships with a mass below 5,000 tonnes are exempted from the regulation. This corresponds to about 10% of the energy demand at EU ports.

straightforward, and for the maritime sector less so. This is because FuelEU Maritime targets are stated as greenhouse gas emissions intensity targets, as opposed to the ReFuelEU Aviation renewable energy quotas.

C.3.1. Regulated emissions intensity

The FuelEU Maritime Regulation stipulates how emissions intensity is to be calculated for each ship or shipping operator. The formula (Equation (1) of Annex I) includes the lifecycle production and combustion emissions of each fuel used, electricity provided from shoreside charging points, the impact of methane slippage from LNG-powered engines[76], a reward factor for the use of wind-assisted propulsion, and a regulatory reward term for the use of RFNBOs.

Paraphrasing, the formula reads:

$$\text{GHG intensity} = (\text{Wind assistance reward factor}) \times \\ \times \left(\frac{\text{Fuel production emissions} + \text{Combustion emissions} + \text{Methane slip}}{\text{Physical energy supply} + \text{Regulatory reward term}} \right)$$

Shoreside electricity charging is rated as zero-emissions regardless of the electricity source, and the wind assistance reward factor (f_{wind}) is 1 by default but can be as low as 0.95 when a vessel's capacity for wind propulsion is greater than or equal to 15% of engine propulsion.

C.3.2. Scenario construction

Since emissions is intensity is the regulated quantity, it would make sense to follow the same strategy that we used for aviation and define scenarios in terms of the percentage contribution that each fuel makes to the overall target. This would guarantee adherence to the target. However, the equation in Annex C.3.1 is not readily invertible, which would make it difficult to unambiguously determine the volume of fuel used from this starting point. We therefore resort to again defining the scenario according to the share of total maritime energy contributed by each fuel. This is done in five-year steps, based on the FuelEU Maritime Impact Assessment's 'Policy Option 2' values for 2030 and 2050 (European Commission, 2021c, Table 2).

Finalising a maritime scenario in our model requires iteration. For a given year, we start with an initial proposed scenario and calculate the implied greenhouse gas intensity using the above equation. This may be higher or lower than the target, and so we adjust the scenario definition until tolerable agreement is reached.

Our scenario definitions must include values for the level of wind propulsion capacity in the overall fleet. A detailed bottom-up analysis would model the rate of introduction of different technologies on new ships, and the rate at which older ships without wind assistance leave the fleet; it would then be possible to calculate f_{wind} and the resulting greenhouse gas intensity for each ship. However, for our purposes it is sufficient to treat the entire fleet in one go.

76 Hydrogen slip for ships powered by ICEs and fuel cells is not acknowledged in the regulation.

Prototype vessels today have offered a wind-assisted contribution of 5-25% of total propulsion under favourable conditions (DNV Maritime, 2023). A scenario from the IMO (Faber et al., 2021) suggested that 5% of vessels in 2030 and 30% of vessels in 2050 could be fitted with some form of wind assistance technology. Following this, in our scenarios we use a calculated effective f_{wind} parameter which decreases from 1.00 in 2025 to just over 0.99 in 2050.

C.4. Calculating impacts

In this section, we briefly run through how impacts are calculated.

C.4.1. Greenhouse gas emissions and intensities

For aviation, the mass of greenhouse gas emitted by a given fuel is simply the product of the physical fuel energy consumed and the fuel's emissions intensity in each given year (emissions intensities are tabulated in Annex C.1.2). The total emissions are equal to the sum of emissions from all fuels. Since ReFuelEU Aviation targets work as renewable energy quotas, the result of this calculation has no regulatory implications.

For maritime transport the regulated quantity is the greenhouse gas intensity, the calculation of which is discussed in Annex C.3. Notwithstanding, we calculate maritime greenhouse gas emissions in the same way as aviation emissions: as the product of physical fuel consumed and the fuel's emissions intensity. This will give a different (more realistic) answer than if we were to multiply the regulatory 'GHG intensity' above by the fuel consumption.

For both aviation and maritime, certain non-CO_2 effects are neglected from the calculations as they are not recognised in the relevant regulations (cf. the discussion in Section 7.4.1). These include the formation of atmospheric contrails and nitrogen oxides from aeroplane exhausts, which on average have a powerful warming effect (Arrowsmith et al., 2020); and the emission of black carbon (warming) and sulphur oxides (cooling) from ship exhausts.

C.4.2. Feedstock demand

Demand for feedstocks is calculated from the consumption of each fuel-feedstock combination, and the yield factors shown in Table 43. These are assumed to be fixed in time. The yield values for aviation fuels are drawn from standard values used in the GREET and BioGrace models, while the yields on biomass input for maritime fuels are assumed to be 5% higher to reflect the fact that a less stringent fuel specification for ships may allow higher energy conversion efficiency in the refining process.

Table 43. Feedstock-to-fuel yield (PJ of fuel per Mt of feedstock) for aviation- and maritime-specification biofuels

Fuel Type	Feedstock	Unit	Aviation	Maritime
Lipids	UCO	PJ/Mt	36.4	38.2
Lipids	Tallow	PJ/Mt	36.4	38.2
Lipids	Annex IX Crop	PJ/Mt	34.6	36.3
Biomass Crops	Cover Crop	PJ/Mt	13.6	14.3
Biomass Crops	Annual Grass	PJ/Mt	13.6	14.3
Biomass Crops	Perennial Grass	PJ/Mt	13.6	14.3
Biomass Crops	SRF	PJ/Mt	12.3	12.9
Residues	Agricultural	PJ/Mt	13.6	14.3
Residues	Forestry	PJ/Mt	12.3	12.9
Residues	Process	PJ/Mt	10.0	10.5
Residues	True Waste	PJ/Mt	10.0	10.5
Other Biofuels		PJ/Mt	10.0	10.5

Note: These are gross yields – i.e. the fuel energy that can be produced per unit of feedstock. Net yield would subtract off the energy required to produce the feedstock, as in Bowman et al. (2021), but for our purposes this will be accounted for in the fuel production LCA.

C.4.3. Electricity and CO2 demand

We consider two types of electricity demand: direct supply (for running appliances and battery charging) and electrolysers[77]. The sum of these two gives us the total electricity demand in Figure 38. For the former, we assume the balance between grid and dedicated renewable electricity evolves in time, while for the latter, the Commission Delegated Regulation on RFNBOs dictates that the electricity come entirely from a limited set of renewable sources (European Commission, 2023). The electricity required to produce a given amount of RFNBO depends on the efficiency of electrolysers used. Rather than explicitly modelling the deployment rates of different electrolyser technologies and the incremental efficiency improvements, we follow Fischer et al. (2020) and assume a linear progression from 57% in 2025 to 71% in 2050.

For battery charging, we assume the efficiency increases from 75% in 2025 to 90% in 2050. This range is informed by the performance of currently available lithium-ion batteries at the low end and the cycle efficiency of automotive batteries under ideal conditions at the high end (this can exceed 90%, Trentadue et al., 2018) and there is evidence that efficiency benefits from the use of larger mobile battery systems that would be relevant to maritime and aviation applications (Poupinha & Dornoff, 2024). Real-world performance will be impacted by fluctuating charge and discharge currents, system ageing, and ambient temperature variations (though these are controlled somewhat by the battery management system).

The production of PtL fuel requires a source of CO_2 – either from fossil point sources, biogenic

77 It is estimated that for PtL production relying on DAC as a CO_2 source, over 90% of the electricity is consumed by the electrolyser (Bennett & O'Connell, 2022). For PtL based on other CO_2 sources, and for green hydrogen and green ammonia production, this number will be even higher.

point sources, or DAC. This is calculated stoichiometrically based on the carbon content and the LHV of the fuel in question. The results are shown in Table 44.

Table 44. Carbon dioxide consumption for carbon-containing RFNBOs, in units of kgCO2/MJ

Fuel Sub-type	Kerosene	HFO/MGO	Methanol	LNG
$kgCO_2/MJ$	0.071	0.080	0.069	0.051

Note: For kerosene and MGO/HFO, we assume an average chain length of 8 and 30 respectively.

C.4.4. Land use

We take land use factors for electricity production from several sources (Gibon et al., 2022; Lovering et al., 2022; Ritchie, 2022; Schmidt et al., 2016) – see Table 45. From 2025 onward, we assume gradual efficiency improvements for solar, wind, and geothermal generation, leading to an increase in the energy production per unit area. Only the 2025 values are shown in the table.

Table 45. Annual electricity production per unit of land area (kWh/m2/year) for electricity sources in 2025

Source	$kWh/m^2/year$
Solar	79
Wind	2,500
Geothermal	2,474
Hydro	30
Biomass	0.6
Nuclear	3,333
Natural Gas	54
Coal	82

From Table 45, we see that biomass is the least area-efficient generation source by an order of magnitude, which bodes ill for crop-based biofuel feedstocks. Recalling from Table 42 that several crops may contribute to each feedstock type, we calculate the agricultural crop yield for a given feedstock type as a weighted average over the yields of contributing crops. For oil crops, we refer to yield in tonnes of vegetable oil per hectare per year, while for biomass crops, we refer to yield in tonnes of dry matter per hectare per year[78].

Crop yields naturally depend on where the crop is grown and on the quality of land, they are grown on (Searle & Malins, 2014). They may improve over time with the development of new varieties and cultivation techniques or degrade due to climate change. As has

78 Some Annex IX lipid crops and cellulosic cover crops will be produced as part of multi-year rotations, rather than annually. For a given plot of land where such crops are grown, the yield averaged over time will be lower than the yield measured at harvest time, because in some years the crop is not grown. Therefore, the land use we are talking about should be understood not as designating a fixed land area, but the location-agnostic area required per year.

been discussed at length in the main body of the report, one of the touted advantages of second-generation biofuel crops is their ability to grow reasonably well in adverse conditions; nevertheless, yield penalties must still be accounted for. We combine an assumed distribution of crop production for each crop (in terms of geographical distribution and the split between good-quality and marginal land) with the yield values reported in Panoutsou et al. (2022) to obtain the average yields shown in Table 46.

Table 46. Averaged agricultural yields of crop-based biofuel feedstocks over time

Fuel Type	Feedstock	Unit	2025	2030	2035	2040	2045	2050
Lipids	Annex IX crop	t/ha/year	0.9	1.1	1.3	1.5	1.7	1.9
Biomass Crops	Cover crop	t/ha/year	16.8	20.0	23.2	26.3	29.5	32.6
	Annual grass	t/ha/year	18.7	22.2	25.7	29.2	32.8	36.3
	Perennial grass	t/ha/year	17.8	21.1	24.4	27.8	31.1	34.5
	SRF	t/ha/year	10.9	12.7	14.6	16.4	18.2	20.0

Note: Lipid yield is in tonne of vegetable oil per hectare per year; biomass yield is in tonne of dry mass per hectare per year.

Land use for biogenic wastes and residues, for RCF feedstocks, for 'other biofuels', and for petroleum-based fuels is set to zero. While this may not be exactly true, the requirement for electricity and crop-based biofuel production is expected to make a far larger impact.

C.4.5. Agricultural inputs

We consider three major categories of agricultural inputs other than land: water, fertiliser, and pesticide. For each of these, the total impact for a given scenario is calculated as the product of feedstock demand and an input application rate in kg/ha (which may depend on the average modelled yield of the feedstock in question). We re-iterate that modelling results are sensitive to our assumptions about yield, regional distribution, land quality, and management practices; they should be treated as indicative only.

Water demand per unit of feedstock is split into blue and green components. Blue water is purposely abstracted from the environment (aquifers, lakes, rivers, etc.) to irrigate crops, while green water comes from precipitation. Over-use of either can compromise local biodiversity by reducing the availability of water to the surrounding ecosystems. For the novel crops considered in the modelling, we use global weighted average water demand for some representative analogue (Schmidt et al., 2016, Table 6) – for instance we use rapeseed values for intermediate oilseeds, and poplar values to cover all SRF. In the case of annuals, in general a primary crop grown in the main agricultural season will consume different amounts of water to a secondary crop grown in the off-season. The main season may be longer, and the higher value of the main crop may warrant greater irrigation levels; on the other hand, in places where the off-season is dry (like in the Mediterranean), more rather than less water may be needed to sustain the secondary crop. In the spirit of offering an indicative assessment of water consumption, we have simply used the values from the quoted source without modification.

Fertiliser application rates for a given crop depend on the prevailing environmental conditions as well as the type of rotation. Some cropping models will be more intensive, some less; since there is no stipulation in RED III, ReFuelEU Aviation, or FuelEU Maritime to limit fertiliser usage (aside from the possible greenhouse gas penalty when calculating the fuel LCA), it is likely that farmers will seek to simply optimise yield benefit against input costs. For the modelling, we adopt average fertiliser application rates (consisting of nitrogen, phosphorous, and potassium components) based on the EU Joint Research Centre values used by the 40B-SAF version of GREET (U.S. Department of Energy, 2024). Rates (in kg/ha) for our lipid Annex IX crops are based on values for camelina and carinata; for our perennial grasses, we use miscanthus and switchgrass; and for our SRF, we use willow and poplar. For perennial biomass crops, rates for nitrogen and potassium are comparable (60-80 kg/ha), and larger than those for phosphorous (roughly 10 kg/ha).

For lipid crops in the model, nitrogen application comes in at around 60 kgN/ha, and phosphorous and potassium are around 10 kg P_2O_5/ha and 1 kgK_2O/ha respectively. We compare this to other estimates in the literature. Iboyi et al. (2023) report urea application of 80 kgN/ha for winter carinata seed in Canada; so did Potter et al. (2023) when considering carinata in the USA and Denmark, and Grady & Nleya (2010) for camelina. Mohammed et al. (2017) found optimal seed and oil yields at 138 kgN/ha, 22 kgP_2O_5/ha, and 22 kgK_2O/ha in the USA; a report by EIP-AGRI (2021) quoted values of 37 kgN/ha, 30 kgP_2O_5/ha, and 40 kgK_2O/ha for camelina, and 80kgN/ha, 18 kgP_2O_5/ha, and 32 kgK_2O/ha for castor. For reference, fertiliser consumption for rapeseed is 71 kgN/ha, 16 kgP_2O_5/ha, and 21 kgK_2O/ha (U.S. Department of Energy, 2024); this is higher than what we have assumed for our Annex IX oilseeds, but adopting a slightly low value for our modelling is arguably consistent with the expectation that fertiliser usage would be lower for intermediate crops than for main crops.

Note that because the feedstock yield of biomass crops is considerably higher than the yield of oil from oilseeds – especially in adverse growing conditions – fertiliser consumption per unit of biofuel feedstock produced is commensurately higher. This also goes for pesticide application. We do not disaggregate pesticides into different types, and we follow Eurostat (2024d) and Gensch et al. (2024) for oil crop application rates, and Godard et al. (2013) for biomass crops. Similar comments concerning input requirements for secondary versus primary crops apply here too.

C.5. Scenario descriptions

Our scenarios were introduced in Section 7.2. Here we provide a little more detail about the assumptions for each scenario.

C.5.1. Aviation scenarios

Scenarios for aviation are defined by the contribution made by alternative fuels to the overall target (recall that in this study we assume that the ReFuelEU Aviation target is hit perfectly). This is shown in Table 47.

Table 47. Scenario definitions for the aviation segment (quinquennial points only)

Scenario	Fuel Type	2025	2030	2035	2040	2045	2050
High RFNBO	RFNBOs	0%	2%	8%	15%	23%	53%
	Lipids	65%	63%	58%	50%	42%	12%
	Biomass Crops	10%	10%	10%	10%	10%	10%
	Residues	15%	15%	15%	15%	15%	15%
	Other Biofuels	5%	5%	5%	5%	5%	5%
	RCFs	5%	5%	5%	5%	5%	5%
	Electricity	0%	0%	0%	0%	1%	1%
High Lipid	RFNBOs	0%	1%	5%	10%	15%	35%
	Lipids	65%	64%	60%	55%	49%	29%
	Biomass Crops	10%	10%	10%	10%	10%	10%
	Residues	15%	15%	15%	15%	15%	15%
	Other Biofuels	5%	5%	5%	5%	5%	5%
	RCFs	5%	5%	5%	5%	5%	5%
	Electricity	0%	0%	0%	0%	1%	1%
High Biomass	RFNBOs	0%	1%	5%	10%	15%	35%
	Lipids	55%	54%	50%	45%	39%	19%
	Biomass Crops	20%	20%	20%	20%	20%	20%
	Residues	15%	15%	15%	15%	15%	15%
	Other Biofuels	5%	5%	5%	5%	5%	5%
	RCFs	5%	5%	5%	5%	5%	5%
	Electricity	0%	0%	0%	0%	1%	1%
High Residue	RFNBOs	0%	1%	5%	10%	15%	35%
	Lipids	50%	49%	45%	40%	34%	14%
	Biomass Crops	10%	10%	10%	10%	10%	10%
	Residues	30%	30%	30%	30%	30%	30%
	Other Biofuels	5%	5%	5%	5%	5%	5%
	RCFs	5%	5%	5%	5%	5%	5%
	Electricity	0%	0%	0%	0%	1%	1%

Note: These values represent the contribution that each fuel makes to the total alternative fuel share, and do not include fossil jet fuel. The sum of fuels values for each scenario-year is 100%.

C.5.2. Maritime scenarios

Scenarios for maritime are defined slightly differently to those for aviation. First, we must decide how much wind power will be built into vessels. In Annex C.3.2, it was decided that this would be selected to give an overall f_{wind} value just above 0.99 in 2050, and that this would be the same for all scenarios. We estimate that the contribution of wind propulsion would reduce the fuel energy demand by about 2%. Naturally, a more aggressive deployment of wind-assistance technology would decrease fuel demand further, while simultaneously lowering the fuel-related emissions target through a lower f_{wind} parameter (cf. the equation in Annex C.3.1); but it is unlikely to shift the needle by much more than two percentage points beyond what we have already assumed for our scenarios.

In the second stage of scenario construction, we establish the assumed contribution of all fuels, not just alternative fuels, to the mix. This is because the share of conventional fossil maritime fuel in each year is not fixed by the FuelEU Maritime target. Table 48 shows our adopted scenario definitions.

Table 48. Scenario definitions for the maritime segment (quinquennial points only)

Scenario	Fuel Type	2025	2030	2035	2040	2045	2050
High RFNBO	RFNBOs	0%	1%	6%	11%	20%	29%
	Lipids	0%	7%	12%	17%	22%	27%
	Biomass Crops	0%	0%	4%	7%	10%	14%
	Residues	0%	0%	3%	6%	9%	12%
	Other Biofuels	0%	0%	1%	2%	2%	3%
	RCFs	0%	1%	2%	2%	3%	3%
	Electricity	0%	2%	2%	2%	2%	2%
	Wind	0%	0%	0%	0%	0%	0%
	Natural Gas	3%	9%	15%	21%	13%	5%
	Petroleum	97%	79%	56%	32%	19%	6%
High Lipid	RFNBOs	0%	0%	0%	0%	2%	4%
	Lipids	0%	8%	25%	41%	56%	70%
	Biomass Crops	0%	0%	0%	0%	2%	4%
	Residues	0%	0%	0%	0%	2%	3%
	Other Biofuels	0%	0%	1%	2%	2%	3%
	RCFs	0%	1%	2%	2%	3%	3%
	Electricity	0%	2%	2%	2%	2%	2%
	Wind	0%	0%	0%	0%	0%	0%
	Natural Gas	3%	9%	15%	21%	13%	5%
	Petroleum	97%	79%	56%	32%	19%	6%

Scenario	Fuel Type	2025	2030	2035	2040	2045	2050
High Biomass	RFNBOs	0%	1%	3%	5%	10%	14%
	Lipids	0%	7%	10%	15%	19%	24%
	Biomass Crops	0%	0%	8%	16%	24%	32%
	Residues	0%	0%	3%	5%	8%	11%
	Other Biofuels	0%	0%	1%	2%	2%	3%
	RCFs	0%	1%	2%	2%	3%	3%
	Electricity	0%	2%	2%	2%	2%	2%
	Wind	0%	0%	0%	0%	0%	0%
	Natural Gas	3%	9%	15%	21%	13%	5%
	Petroleum	97%	79%	56%	32%	19%	6%
High Residue	RFNBOs	0%	1%	3%	6%	10%	15%
	Lipids	0%	7%	11%	15%	20%	25%
	Biomass Crops	0%	0%	3%	6%	10%	13%
	Residues	0%	0%	7%	14%	21%	28%
	Other Biofuels	0%	0%	1%	2%	2%	3%
	RCFs	0%	1%	2%	2%	3%	3%
	Electricity	0%	2%	2%	2%	2%	2%
	Wind	0%	0%	0%	0%	0%	0%
	Natural Gas	3%	9%	15%	21%	13%	5%
	Petroleum	97%	79%	56%	32%	19%	6%

Note: These values represent the contribution that each fuel makes to the total fuel share, including conventional fossil maritime fuels (MGO/HFO). The sum of fuels values for each scenario-year is 100%.

C.6. Further modelling results

In this section we show any additional modelling results that were not included in the main text. These are intended to further contextualise our modelling decisions.

Figure 51 shows an example of how demand for hydrogen used in the refining of alternative fuels evolves in time. For comparison, in 2022 the EU consumed around 8.2 Mt of fossil hydrogen, of which 57% was in the refining sector (European Hydrogen Observatory, 2023). In Figure 51 we see a demand of up to 2 MtH_2 in 2050, and in contrast with today's hydrogen supply, this would presumably have to be sourced from further electrolysis or bio-gasification, requiring yet more renewable electricity and biomass feedstock.

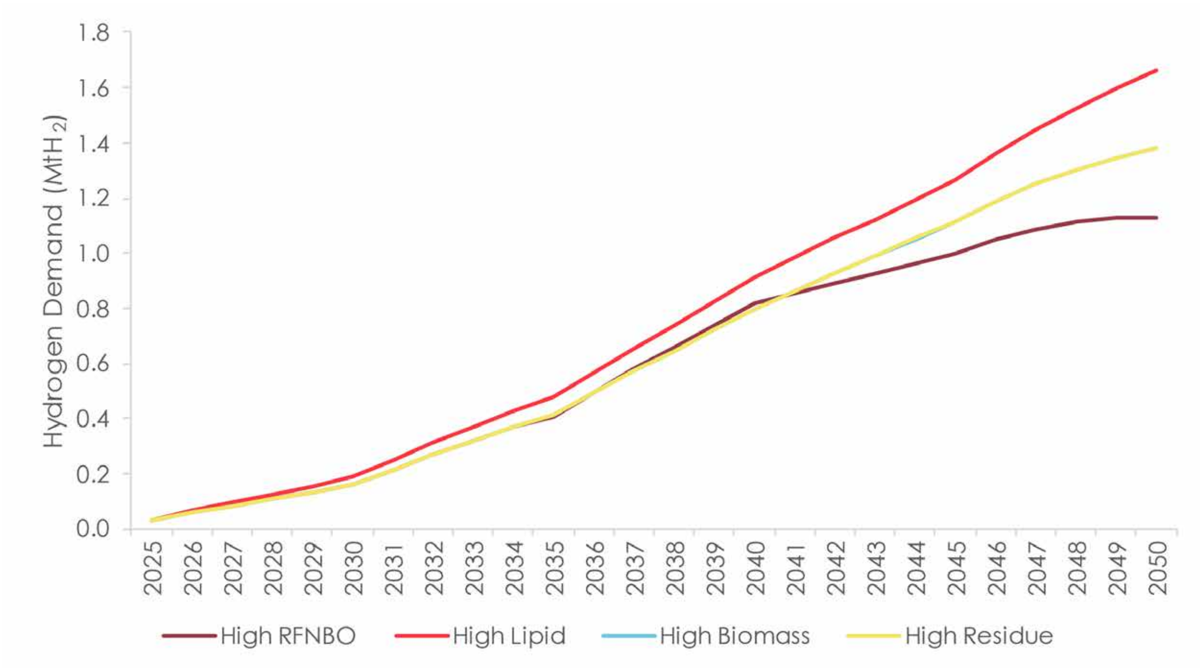


Figure 51. Annual consumption of hydrogen for biofuel and RCF production

Figure 52 shows the CO_2 needed to satisfy EU PtL demand for aviation and shipping under our four scenarios. Unsurprisingly, the High RFNBO scenario has the highest CO_2 consumption, reaching nearly 80 $MtCO_2$/year in 2050. For comparison, it has been estimated that the global availability of biogenic point-source CO_2 for RFNBO production is in the range 320-370 $MtCO_2$/year (MMMCZCS, 2024). For DAC, the IEA's Net Zero Emissions scenario sees about 350 $MtCO_2$ for CCU in 2050 – mostly for PtL fuel (Baylin-Stern et al., 2022). Together, we are looking at around 700 $MtCO_2$ that could conceivably be used for global PtL production in 2050.

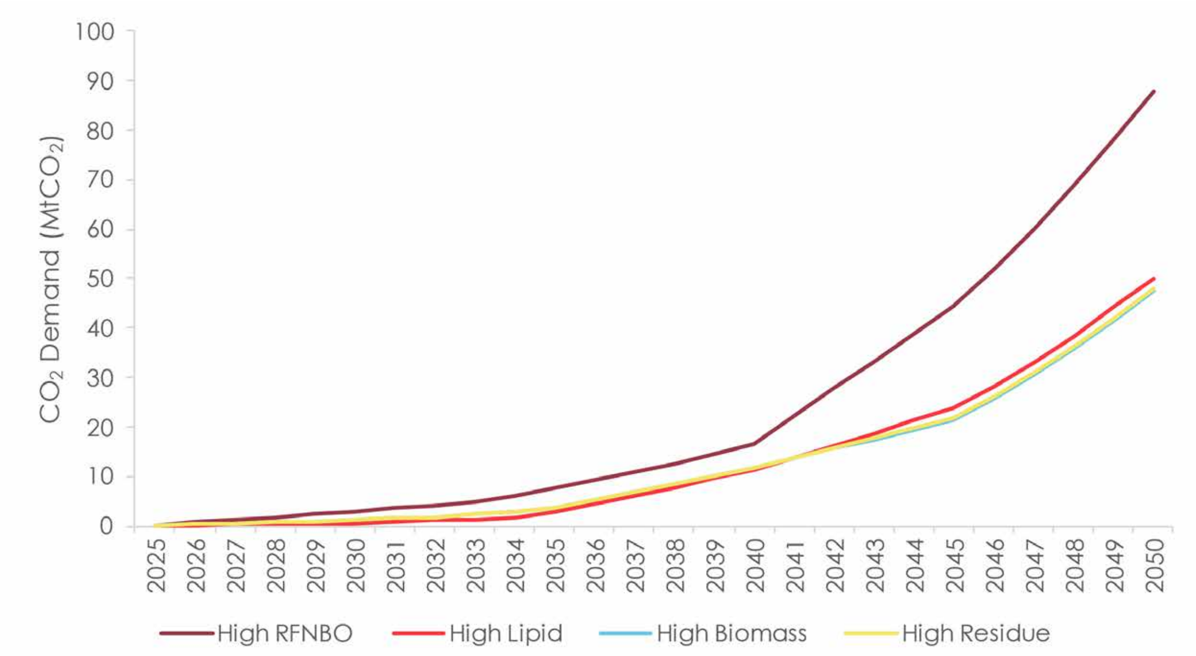


Figure 52. Annual consumption of carbon dioxide for PtL production

As discussed in Section 6.1 and Section 7.4.3, electricity generation also has a land footprint. Figure 53 shows the land needed in 2050 to generate electricity for direct supply, for battery charging, and for running electrolysers to make RFNBOs. RFNBO electricity is assumed to come solely from solar, wind, and geothermal sources, while electricity for direct supply and battery charging is a mix of grid and renewables[79]. It is striking that, though biomass supplies less than 1% of electricity used in aviation and maritime in 2050, it is responsible for a considerable fraction of the electricity's land use.

79 In contrast to RFNBOs, renewable electricity used for this purpose is assumed to include hydroelectric and biomass in addition to solar, wind, and geothermal.

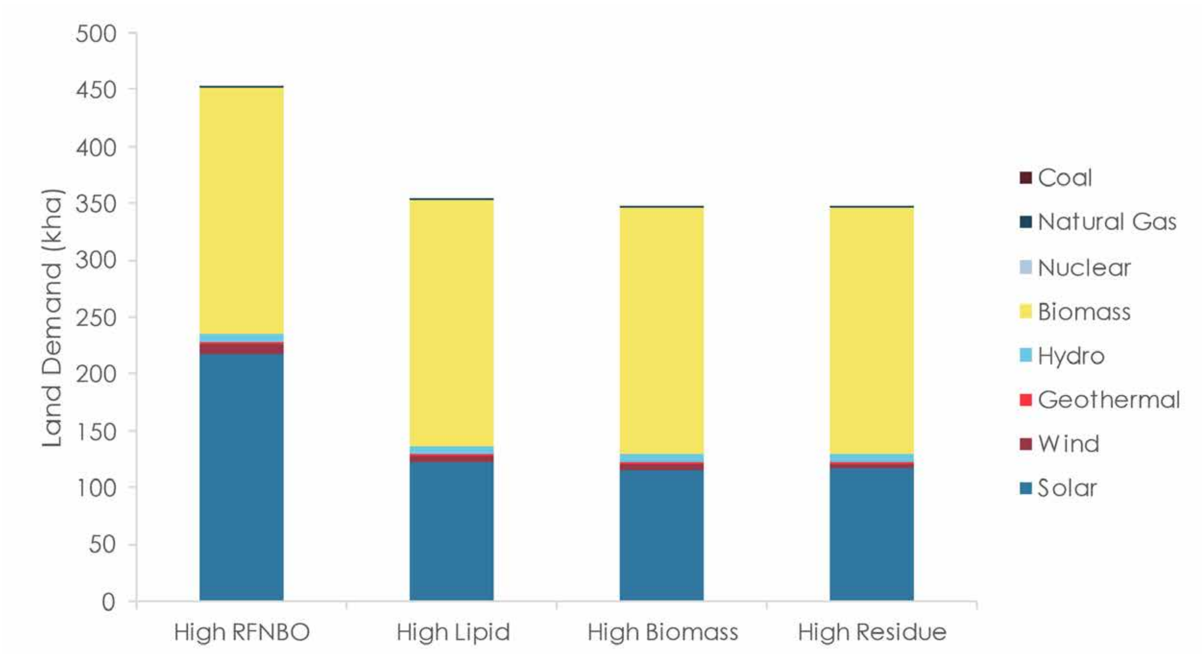


Figure 53. Land footprint of the electricity generation installations needed to supply aviation and maritime transport in 2050

Note: Includes electricity required for direct supply / battery charging, and to run electrolysers for RFNBO production.

Consumption of electricity for direct supply and battery charging is constant between scenarios, but electricity demand for RFNBOs changes. One corollary is that consumption of electricity (and hence demand for land) from solar, wind, and geothermal is the only thing that changes. Recalling the land efficiency values from Table 45, it is no surprise that though biomass-based electricity makes a relatively small contribution to the aviation and maritime energy mixes, its contribution to the land footprint is considerable.

Finally, we consider the use of agricultural inputs for growing biofuel feedstocks. Water consumption – both blue and green – owing to cultivation of biofuel feedstock was considered in Section 7.4.4 of the main text. Here, Figure 54 shows the total fertiliser demand in 2050 under the four scenarios (summing over N, P, and K components), and Figure 55 shows total pesticide demand (summing over herbicides, fungicides, and insecticides). See Annex C.4.5 for a discussion of average application rates.

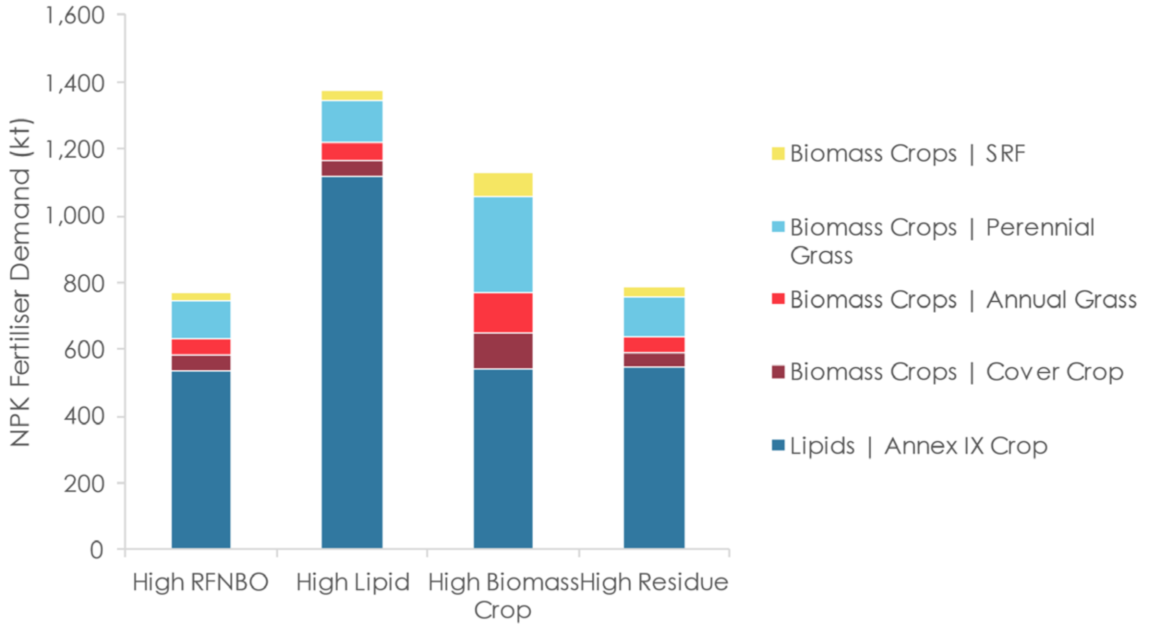


Figure 54. Estimated consumption of fertiliser in 2050 under the four scenarios

Note: These values are a sum of the mass of nitrogen, phosphorous, and potassium fertilisers.

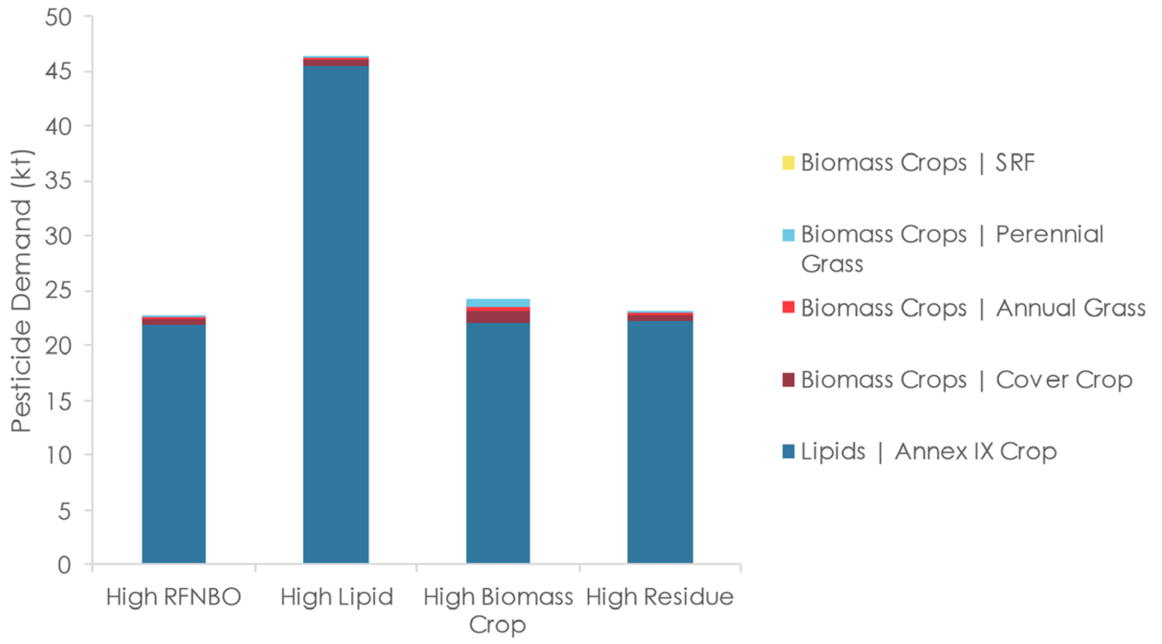


Figure 55. Estimated consumption of pesticide in 2050 under the four scenarios

Note: These values are a sum of the mass of herbicides, fungicides, and insecticides.

Annex D. Ranking biodiversity risk

Section 8 considers the results of the modelling scenarios and their likely implications for biodiversity in the EU. For each scenario, rankings of Low, Moderate, High and Very High are applied based on the compliance model results and the expected impacts to biodiversity. These assessments are part qualitative and part quantitative based on the scale and nature of the demand or impact of each metric. All risk categories which were assessed for their biodiversity impacts are given in Table 22, and the rankings for the biodiversity assessment for 'additional land demand' and 'land use intensification' are given as examples of the ranking system and presented in the main body of text (Section 8). All remaining categories and their associate impact ranks are presented in the tables in this section.

Several of the risk categories have numeric values assigned to their ranks (additional land demand, land use intensification, water demand, fertiliser and pesticide consumption). Here we provide some additional context for the ranks assigned to these values.

As our review of the literature could not obtain any estimates of total water consumption for agricultural in the EU, our threshold values for water demand (Table 52) consider the total estimated water abstraction for agriculture in the EU, which was around 204,112 million tonnes (Mt) in 2019 (European Environment Agency, 2022). Accordingly, we set our highest biodiversity risk threshold for water demand at approximately 200,000 Mt, reflecting a scenario where bioenergy feedstock production places a pressure on water resources equivalent to the total agricultural water abstraction in the EU. As water abstraction for irrigation is a significant driver of water stress in the EU, particularly in regions prone to drought or where water resources are already over-exploited. While rainwater (green water) contributes substantially to meeting agricultural demands, using water abstraction as an indicator is reasonable because it directly reflects the pressures placed on finite freshwater supplies, which are critical to both ecosystems and human needs. Any substantial increase in water abstraction for bioenergy crops could exacerbate water scarcity and degrade aquatic ecosystems, which are already under significant strain.

For fertiliser consumption (Table 53) our threshold values consider the total estimated consumption of mineral fertilisers (containing nitrogen and phosphorous) in the EU in 2022, which was around 10 million tonnes (Eurostat, 2024f). Accordingly, we set out highest biodiversity risk threshold for fertiliser consumption at over 10% of total estimated consumption, i.e. >1 million tonnes. This threshold follows a precautionary approach, as nitrogen and phosphorous from fertilisers are already major causes of water pollution in Europe. This has already prompted policymakers to target significant reductions in their application within the EU's Biodiversity Strategy for 2030 (which targets a 20% reduction in fertiliser use by 2030). In this sense, any additional nutrient inputs for bioenergy crops are going to increase pressure on land and waterways.

The same can be said for pesticide consumption (Table 54). While our literature review did not find any estimates of annual pesticide consumption for the EU, it is reasonable to take estimates of EU pesticide sales as an agri-environmental indicator of overall pesticide consumption, which was approximately 322,000 tonnes in 2022 (Eurostat, 2024a). To represent the highest risk to biodiversity, we set the 'Very High' risk threshold at over 10% of estimated annual sales i.e. exceeding 35,000 tonnes. Again, this is precautionary but given that the Biodiversity Strategy for 2030 aims to reduce the use and risk of chemical pesticides by 50%

by 2030, an increase in pesticide use for energy cropping is likely to create significant tension with this policy target.

Table 49. Ranking biodiversity risk based on pollution risk due to bioenergy and renewable energy developments

Rank	Description	Example
Low	Negligible pollution risk, or effective management practices in place.	• Use of integrated pest management systems • Use of organic fertilisers with minimal runoff • Implementation of buffer strips to catch run-off • Controlled application of pesticides
Moderate	Some pollution risk, with potential for localised pollution incidents, manageable with proper practices.	• Moderate use of chemical inputs in bioenergy crop production • Occasional pesticide and fertiliser runoff • Partially managed waste disposal
High	Significant pollution risk, with frequent pollution incidents affecting soil and water quality, requires careful management to mitigate.	• Frequent chemical runoff into waterways • High levels of fertiliser use causing eutrophication of local waterways • Pesticide contamination affecting non-target species • Agricultural waste leading to soil and water pollution
Very High	Severe pollution risk, with persistent, long-term and widespread, with potentially irreversible impacts.	• Persistent pesticide pollution impacting ecosystems • Toxic chemical buildup in soil and water bodies • Severe eutrophication from nutrient runoff • Large-scale agricultural pollution affecting multiple ecosystems

Table 50. Ranking biodiversity risk based on invasive species risk due to bioenergy

Rank	Description	Example
Low	Negligible little to no risk of invasive species, due to use of native or non-invasive species, or non-biological productive systems.	• Cultivation of native species with no invasive potential • Use of well-managed crop systems • Regular monitoring for invasive species • Implementation of strict biosecurity measures
Moderate	Some risk of invasive species, with potential for certain species to spread outside intended areas, manageable with proper practices.	• Use of non-native species with low invasive risk • Periodic monitoring and control efforts • Mixed native and non-native crop systems • Occasional escape of non-native species into wild areas • Expansion of energy crops through propagules
High	Significant risk of invasive species, with frequent incidents of species spreading and impacting local ecosystems, requires careful management to mitigate impacts.	• Use of non-native species with moderate invasive potential • Limited management of invasive species • High potential for non-native species to spread • Escape of invasive species into adjacent habitats
Very High	Severe risk of invasive species, with major ecological impacts due to invasive species outcompeting native flora and fauna, with potentially irreversible impacts.	• Widespread planting of highly invasive species • Lack of invasive species management • Rapid spread of invasive species displacing natives • Invasive species causing significant ecological disruption

Table 51. Ranking biodiversity risk based on soil health due to bioenergy and renewable energy developments

Rank	Description	Example
Low	Minimal soil disturbance or degradation, with little to no impact on soil health.	• Use of perennial grasses with deep root systems to stabilise soils • establishment of perennial grasses / SRF as part of phytoremediation process • conversation tillage practices minimise soil disturbance • use of cover crops to maintain soil organic matter • crop rotation practices to reduce soil erosion
Moderate	Some soil disturbance and degradation, with the potential for increased soil erosion and nutrient runoff, manageable with proper practices.	• Rotational intermediate cropping system which produces biomass for bioenergy but may lead to intensification and soil disruption • Occasional tillage disrupts soil structure • Moderate use of chemical fertilisers impact soil biota • Intermittent monoculture reducing soil biodiversity • Removal of crop residues reduces soil organic matter
High	Significant soil disturbance and degradation, with high risk of erosion and nutrient depletion, requires careful management to mitigate impacts.	• Frequent tillage leading to soil compaction • Continuous monoculture depleting soil nutrients • High levels of chemical inputs causing soil acidification
Very High	Severe and extensive soil disturbance, leading to long term soil degradation and loss of soil fertility, with potentially irreversible impacts.	• Intensive and continuous monoculture deplete nutrients, driving long-term degradation • Intensification on marginal lands increases soil erosion • Use of heavy machinery drives soil compaction • Extensive chemical usage causes significant decline of soil microbiota

Table 52. Ranking biodiversity risk based on water demand due to bioenergy

Rank	Values (Mt)	Description	Example
Low	<10,000	Minimal water demand, mostly with reliance on rain-fed systems.	• Residues harvested from rain-fed forestry or agricultural systems • Drought-resistant crops minimise water requirements • Water-efficient crop varieties • Efficient drip irrigation systems
Moderate	10,001-100,000	Noticeable water demand, with some reliance on irrigation, potentially impacting local water resources, manageable with proper practices.	• Crops with moderate water requirements • Mixed rainfed and irrigated agriculture • Irrigated bioenergy crops in areas with moderate water availability • Supplemental irrigation required during dry periods • Use of traditional irrigation methods with moderate efficiency
High	100,001-200,000	Significant water demand, potentially with impact on local and regional water resources, requires careful management to mitigate impacts.	• High water-demand crops in water-scarce areas • Crops requiring frequent irrigation • Inefficient flood irrigation practices • Extensive irrigation of bioenergy crops needed in semi-arid regions • Energy crops established in area of intensive agriculture all competing for water resources
Very High	>200,001	Extremely high-water demand, with severe impacts on local and regional water resources, practices are likely to be unsustainable.	• Water-intensive crops require extensive irrigation • Irrigation in regions with significant water scarcity • Area of intensive agriculture creates competition for water resources and high dependency on groundwater extraction • Large-scale bioenergy plantation requires constant irrigation, impacting downstream water availability • Over-irrigation leading to depletion of water resources

Table 53. Ranking biodiversity risk based on fertiliser consumption due to bioenergy

Rank	Values (t)	Description	Example
Low	<100000	Minimal fertiliser use, no significant effect on biodiversity or soil health.	• Low-input bioenergy crops selected • Organic farming practices utilised
Moderate	100,001-300,000	Noticeable increase in fertiliser use, manageable with proper practices.	• Intermediate oilseed crops • Integrated nutrient management practices
High	300,001 – 1,000,000	Significant fertiliser use, requiring careful management to mitigate impacts.	• Intensive bioenergy cropping • High input monocultures
Very High	>1,000,001	Extremely high fertiliser use, with profound implications for biodiversity and soil health.	• Large-scale monocultures with high fertiliser dependence

Table 54. Ranking biodiversity risk based on pesticide consumption due to bioenergy

Rank	Values (t)	Description	Example
Low	< 5,000	Minimal pesticide use, unlikely to affect non-target species or ecosystems significantly.	• Low input bioenergy crops selected • Organic farming practices adopting natural pest control methods • Integrated pest management, combines biological, cultural and mechanical controls to minimise pesticide use. • Harvesting residues presumably requires no additional nutrient inputs
Moderate	5,001-20,000	Moderate pesticide use, with manageable risks to biodiversity using integrated pest management (IPM) practices.	• Intermediate oilseed crops managed with IPM • Targeted pesticide applications incorporating precision agriculture • Intercropping with pest-repellent plants reduces overall pesticide needs

Rank	Values (t)	Description	Example
High	20,001-35,000	High pesticide use, requiring strict management practices to mitigate significant impacts on non-target species and ecosystems.	• Large-scale monocultures require regular pesticide applications to control pest outbreaks • Intensively managed bioenergy cropping requires high pesticide application to maintain yields
Very High	>35,001	Extensive pesticide use, likely to cause substantial harm to non-target species, disrupt ecosystems, and conflict with EU biodiversity targets.	• Extensive bioenergy monocultures require heavy and frequent pesticide to prevent crop losses • Areas within intensive bioenergy crop production where integrated pest management strategies are not feasible

Table 55. Ranking biodiversity risk based on indirect land use change (ILUC) due to bioenergy

Rank	Description	Example
Low	Minimal, little to no ILUC impacts.	• Utilisation of existing agriculture or forested land (harvesting residues) selected over changing land use. • Crops produced through phytoremediation on contaminated land rather than established on marginal lands
Moderate	Noticeable, some ILUC impacts.	• Moderate displacement of food and / or feed crops or natural habitats, may trigger some conversion of natural habitats
High	Significant ILUC, requires careful management to mitigate impacts.	• Significant displacement of food and / or feed crops, leads to conversion of natural habitats elsewhere
Very High	Severe indirect land use impacts, with potentially irreversible consequences.	• Large-scale displacement of food or feed crops, drives extensive conversion of natural habitats elsewhere