The **Making Mission Possible** Series

Bioresources within a Net-Zero Emissions Economy:

Making a Sustainable Approach Possible

July 2021

Version 1.0

Energy Transitions Commission

Making a Sustainable Approach Possible

Bioresources within a Net-Zero Emissions Economy

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner who works with the ETC team, led by Faustine Delasalle. Our Commissioners are listed on the next page.

Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ. They bring together and build on past ETC publications, developed in close consultation with hundreds of experts from companies, industry initiatives, international organisations, non-governmental organisations and academia.

The report draws upon analyses carried out by ETC knowledge partners SYSTEMIQ and BloombergNEF, and elements of this report were developed in close collaboration with Material Economics. This report draws heavily on work developed by the Food and Land Use Coalition in partnership with IIASA and the World Resource Institute. We also reference analyses from the International Energy Agency and the International Renewable Energy Agency. We warmly thank our knowledge partners and contributors for their inputs.

This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century, but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2˚C, and that many of the key actions to achieve these goals are clear and can be pursued without delay.

Learn more at:
www.energy-transitions.org
www.linkedin.com/company/energy-transitionscommission
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Glossary

Abatement cost: The cost of reducing CO_2 emissions, usually expressed in US$ per tonne of CO_2.

Afforestation and reforestation: "The planting of new forests on land not currently under forest cover. The forests remove carbon from the atmosphere as they grow."[1]

Agricultural residues: "There are two types of agricultural crop residues: field residues are materials (including stalks and stubble (stems), leaves and seed pods) left on the ground after the crop has been harvested. Good management of field residues can increase efficiency of irrigation and help control erosion. Process residues are those materials (include husks, seeds, bagasse and roots) left after crop processing. They can be used as animal fodder, as soil improvers, and in manufacturing."[2] A large fraction of crop residues (i.e., 50-70%) should be left on the field to support soil health.

Agroforestry: "A multi-use form of land management where trees are grown in association with arable crops or pasture."[2]

Annual crops: "Crops whose life cycle, from seed to harvest, is complete in less than 12 months."[2]

BECCS: A technology that combines bioenergy with carbon capture and storage to produce energy and net negative greenhouse gas emissions (i.e., removal of carbon dioxide from the atmosphere). See 'BiCRS'.

BEV: Battery-electric vehicle.

BiCRS: Biomass carbon removal and storage. This term includes BECCS and other forms of carbon dioxide removal (e.g., biochar).[3]

Bio-based plastics: Plastics made from biomass feedstocks (i.e., composed of biogenic carbon). Bio-based plastics may or may not be chemically identical to plastics from fossil fuels and thus are not necessarily also biodegradable.

Biochar: "The thermal decomposition of biomass in the absence of oxygen forms a charcoal known as biochar. This can be added to soils to improve soil fertility and to act as a stable long-term store of carbon."[4]

Bioenergy: Renewable energy derived from biological sources in the form of solid biomass, biogas, or biofuels.

Biofuels: "Liquid fuels derived from biomass, used primarily for transport, including ethanol, biodiesel and other liquids."[5]

- ***Conventional biofuels*** "are derived from crops and waste using current conversion processes. Examples include bioethanol from sugar cane and biodiesel from cooking oil."[4]
- ***Advanced biofuels*** "incorporate a range of less developed methods. Many of these apply advanced conversion processes to the dedicated energy crops and the lignocellulosic parts of residues. Others use novel feedstocks such as algae."[4]

Biogas: "A mixture of methane and CO_2 produced by the bacterial decomposition (fermentation) of organic wastes and used as a fuel."[4]

Biogenic wastes: This refers to solid, liquid, or gaseous biomass that is left over from other activities or following the disposal of other products. These wastes can come from both municipal and agricultural sources. Sometimes referred to as 'residues'. Can be used for energy production.

Biomass or bio-feedstock: Organic matter, i.e., biogenic material, available on a renewable basis from living or recently living organisms. Includes feedstock derived from plants or animals, such as agricultural and energy crops, wood and forestry residues, organic waste from municipal and industrial sources (including manure), and algae.

'First generation' feedstocks are food crops such as such as oil seeds or cereals. They typically require agricultural land of reasonable quality and their cultivation for energy and materials uses could divert these crops away from food production.[4] Also called 'conventional' crops.

'Second generation' feedstocks are non-food, lignocellulosic biomass. "These include fast growing energy crops such as miscanthus or short rotation coppice (e.g., willow). Where land use is dedicated to production, more marginal land can be used."[4] Wastes and residues (e.g., straw, woodchips, waste oil, municipal solid waste, etc.) are also examples of second generation biomass.

Biomaterials: Products made of biomass, including wood products such as timber, or plastics made from biomass.

Bioresources: A term used to group all bioenergy and biomaterials.

Carbon capture and storage or use (CCS/U): We use the term 'carbon capture' to refer to the process of capturing CO_2 on the back of energy and industrial processes. Unless specified otherwise, we do not include direct air carbon capture (DACC) when using this term. The term 'carbon capture and storage' (CCS) refers to the combination of carbon capture with underground carbon storage; while 'carbon capture and use' (CCU) refers to the use of carbon in carbon-based products in which CO_2 is sequestered over the long term (e.g., in concrete, aggregates, carbon fibre). Carbon-based products that only delay emissions in the short term (e.g., synfuels) are excluded when using this terminology.

Carbon dioxide removals (CDR): sometimes shortened to 'carbon removals' refers to actions such as NCS or DACCS that can result in a net removal of CO_2 from the atmosphere.

Carbon emissions / CO_2 emissions: We use these terms interchangeably to describe anthropogenic emissions of carbon dioxide in the atmosphere.

Carbon offsets: Reductions in emissions of carbon dioxide (CO_2) or greenhouse gases made by a company, sector, or economy to compensate for emissions made elsewhere in the economy.

Carbon opportunity cost: The carbon footprint (and potential future sequestration) associated with land use had it not been converted to biomass production.

Carbon payback period: the time required for use of biomass to become beneficial for the climate (i.e., when net-zero emissions is reached) when considering the change in carbon stocks, relative to the counterfactual, as a result of biomass production.[4]

Carbon price: A government-imposed pricing mechanism, the two main types being either a tax on products and services based on their carbon intensity, or a quota system setting a cap on permissible emissions in the country or region and allowing companies to trade the right to emit carbon (i.e., as allowances). This should be distinguished from some companies' use of what are sometimes called 'internal' or 'shadow' carbon prices, which are not prices or levies, but individual project screening values.

Carbon sink: A reservoir for accumulating and storing atmospheric carbon.

Circular economy models: Economic models that ensure the recirculation of resources and materials in the economy, by recycling a larger share of materials, reducing waste in production, light-weighting products and structures, extending the lifetimes of products, and deploying new business models based around sharing of cars, buildings, and more.

1 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*

2 BP (2014), *Biomass in the Energy Industry – an introduction.*

3 Sandalow et al. (2021), Biomass carbon removal and storage (BiCRS) roadmap.

4 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*

5 BP (2014), *Biomass in the Energy Industry – an introduction.*

Climate-Smart Forestry: Strategies are aimed at (i) "increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services, (ii) enhancing the health and resilience through adaptive forest management, and (iii) using wood resources sustainably to substitute non-renewable, carbon intensive materials."[6]

Cultured meat: Meat derived from animal cells produced via *in vitro* cell culture (i.e., in a lab) rather than from the slaughter of animals.

Decarbonisation solutions: We use the term 'decarbonisation solutions' to describe technologies or business models that reduce anthropogenic carbon emissions by unit of product or service delivered though energy productivity improvement, fuel/ feedstock switch, process change or carbon capture. This does not necessarily entail a complete elimination of CO_2 use, since (i) fossil fuels might still be used combined with CCS/U, (ii) the use of biomass or synthetic fuels can result in the release of CO_2, which would have been previously sequestered from the atmosphere though biomass growth or direct air capture, and (iii) CO_2 might still be embedded in the materials (e.g., in plastics).

Direct air carbon capture (DACC): The extraction of carbon dioxide from atmospheric air. This is also commonly abbreviated as 'DAC'.

Direct air carbon capture and storage (DACCS): DACC combined with carbon storage.

Direct reduced iron (DRI): Iron (so called 'sponge iron') produced from iron ore utilising either natural gas or hydrogen. This DRI is then converted to steel in a second step called electric arc furnace (EAF). The DRI-EAF is an alternative primary steel production process enabling decarbonisation of the traditional coke-fired blast furnace/basic oxygen furnace (BF-BOF).

EBIT sectors: Energy, building, industry, and transport sectors.

Ecosystem services: Services from nature including nutrient cycling, flood and disease control, and recreational and cultural benefits.[7]

Electrolysis: A technique that uses electric current to drive an otherwise non-spontaneous chemical reaction. One form of electrolysis is the process that decomposes water into hydrogen and oxygen, taking place in an electrolyser and producing 'green hydrogen'. It can be zero-carbon if the electricity used is zero-carbon.

Embedded carbon emissions: Lifecycle carbon emissions from a product, including carbon emissions from the materials input production and manufacturing process.

Energy crops: In this report, we use energy crops to refer to 'second generation' crops that are unsuitable for consumption as food, such as miscanthus or short rotation coppice (e.g., willow or poplar).

Enhanced weathering: "Silicate rocks naturally fix carbon out of the air over geological timescales. This process can be speeded up by grinding up rocks (in order to vastly increase the exposed surface area) which can be dispersed over cropland."[8]

EU REDII: The EU Renewable Energy Directive sets renewable energy targets at EU level as well as specific targets for biofuels.[8]

Evapotranspiration: "The process of water loss from soil. This is a combination of evaporation from the soil surface and transpiration from the plants growing in it."[7]

FCEV: Fuel cell electric vehicle.

Feedstock: "Raw material, such as biomass, used for energy or material in a process."[7]

Final energy consumption: All energy supplied to the final consumer for all energy uses.

Forestry residues: "Small branches, tops, bark, and thinnings left over from commercial forestry operations and residues from wood processing industries (e.g., sawmills). Some residues need to be left for forest soil health. Residues do not include high-quality timber suitable for production of sawn wood."[8]

Gasification: Technological process that can convert any carbon-based raw material such as biomass into fuel gas, also known as synthesis gas (syngas for short).

'Green' (hydrogen, ammonia): refers to fuels produced using electricity from low-carbon sources (i.e., variable renewables such as wind and solar).

Greenhouse gases (GHGs): Gases that trap heat in the atmosphere. Global GHG emission contributions by gas – CO_2 (76%), methane (16%), nitrous oxide (6%) and fluorinated gases (2%).

Heavy Goods Vehicles (HGV) or Heavy Duty Vehicle (HDV): Both terms are used interchangeably and refer to trucks ranging from 3.5 tonnes to over 50 tonnes.

Hydrocarbons: An organic chemical compound composed exclusively of hydrogen and carbon atoms. Hydrocarbons are naturally occurring compounds and form the basis of crude oil, natural gas, coal, and other important energy sources.

Indirect land-use change: "Used to describe ancillary or unintended and indirect effects resulting from changing the use of land for one purpose to another. For example, if maize acreage in the US were used for fuel instead of animal feed and this created a market signal to plant more maize in Brazil using forest or pasture land, the impacts of the Brazilian conversion would constitute an indirect effect of the US action."[8]

Internal combustion engine (ICE): A traditional engine, powered by gasoline, diesel, biofuels, or natural gas. It is also possible to burn ammonia or hydrogen in an ICE.

Levelised cost of electricity (LCOE): A measure of the average net present cost of electricity generation for a generating plant over its lifetime. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity-generating plant divided by a discounted sum of the actual energy amounts delivered.

Lifecycle emissions: Emissions from the energy, material, and waste flows of a product and their impact on the environment.[7] Life cycle assessments (LCAs) should take into account the greenhouse gas impacts across land use change (if applicable), growth, harvesting, transportation, conversion, and use of bioresources.

Lignocellulosic: A term describing the characteristics of woody biomass (with plant cell walls consisting of cellulose intimately associated with lignin).[7]

Macroalgae: Commonly known as seaweed; includes species such as kelp. Macroalgae are very photosynthetically efficient and can be farmed in the ocean and used as food, other high-value uses, or as a source of energy.

Microalgae: Microscopic phytoplankton cultivated in pools on land. Microalgae are extremely efficient photosynthetic organisms and can be used to produce low lifecycle emissions food and animal feed as well as and other high-value products.

Natural carbon sinks: Natural reservoirs storing more CO_2 than they emit. Forests, plants, soils, and oceans are natural carbon sinks.

Natural Climate Solutions (NCS): Actions considered to be a subset of nature-based solutions (NBS) with a specific focus on addressing climate change. NCS has been defined as "conservation, restoration, and/ or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global

6 Verkerk et al. (2020), *Climate-Smart Forestry – the missing link.*

7 BP (2014), *Biomass in the Energy Industry – an introduction.*

8 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*

forests, wetlands, grasslands, agricultural lands, and oceans".[9] NCS can be coupled with technology to secure long-term or permanent storage of GHGs, examples include CCS, the use of technologies such as torrefaction to process biomass or monitoring to improve forest management techniques for increased density.

Nature-based Solutions (NBS): Activities that harness the power of nature to deliver services for adaptation, resilience, biodiversity, and human well-being, including reducing the accumulation of greenhouse gases (GHGs) in the atmosphere. Actions to protect, sustainably manage and restore natural or modified ecosystems which constitute natural carbon sinks, while simultaneously providing human, societal and biodiversity benefits.

Negative emissions (or 'net negative' emissions): is used for the case where the combination of all sector CO_2 emissions plus carbon removals results in an absolute negative (and thus a reduction in the stock of atmospheric CO_2).

Net-zero-carbon-emissions / Net-zero-carbon / Net-zero: We use these terms interchangeably to describe the situation in which the energy and industrial system as a whole or a specific economic sector releases no CO_2 emissions – either because it doesn't produce any or because it captures the CO_2 it produces to use or store. In this situation, the use of offsets from other sectors ('real net-zero') should be extremely limited and used only to compensate for residual emissions from imperfect levels of carbon capture, unavoidable end-of-life emissions, or remaining emissions from the agriculture sector.

Organic wastes: "Some key types of organic waste including wood waste, the organic fraction of municipal solid waste, livestock manures, sewage sludge, tallow and used cooking oil. These wastes should be minimised then reused/recycled before being used for energy production."[10]

Peat: "Partially carbonized vegetable substance formed by incomplete decomposition of plant material in water. Peat is an important store of carbon, which is released into the atmosphere when peat is burned (for fuel) or when peat soils are brought under cultivation."[11]

Peatlands: "Peatlands contain layers of partially decomposed organic material preserved in waterlogged environments. They contain a large fraction of the world's terrestrial carbon stock and when damaged or destroyed can become large sources of GHG emissions."[10]

Perennial crop: A crop from plants that do not need to be replanted each year. Examples include sugarcane, woody biomass and perennial grasses.[11] These "can lead to a net increase in the total soil carbon stocks when planted on marginal and degraded agricultural land or land currently used for annual crops. agricultural land may however create risks associated with indirect land-use change as these lands could otherwise be used for food production."[10]

Power-to-Liquid (PtL): Fuels and chemicals created from the combination of 'green' hydrogen (produced using renewable electricity) with CO_2 (e.g., from direct air carbon capture). See 'Synfuels'.

Primary energy consumption: Crude energy directly used at the source or supplied to users without transformation – that is, energy that has not been subjected to a conversion or transformation process.

Pyrolysis: the thermochemical decomposition of organic matter into gases, liquids, and a solid residual coproduct (including biochar or charcoal) in the absence of oxygen, which can then be used for its energy content.

Residues: Residues is used in this report to refer to biomass that is generated as a waste or co-product of an industry. Sources include forestry (e.g., bark, branches, and wood chips), agriculture (e.g., cereal straw and husks) and municipal and industrial waste (e.g., waste oils, manure from livestock production, and other organic wastes). See 'Agricultural residues' and 'Forestry residues'.

Rotation period: The time period from planting to harvest.

Short rotation coppice (SRC): "A management regime that promotes the growth of multiple stems by cutting trees back quite close to the ground every two to four years. SRC is often used to produce woody biomass."[11]

Short rotation forestry (SRF): "A management regime under which trees are planted and then felled when they have reached a size of typically 10–20cm diameter at breast height. Depending on tree species and climate, this can take between three and 20 years, and is therefore intermediate in timescale between SRC and conventional forestry."[11]

Soil carbon sequestration: "Increasing the amount of carbon stored in soils through improved agricultural practice."[10]

Soil organic matter: "The organic component of soil, which includes the living biomass of microorganisms, and fresh and partially decomposed residues. It also includes well-decomposed, highly stable organic material. Surface litter is generally not included as part of soil organic matter but can become part of it if physically incorporated into the soil. Soil organic matter is of vital importance for nutrient cycling, erosion protection and for its water-holding capacity."[11]

Stemwood: The wood of the stem of a tree which is used for high-value harvested wood products (i.e., materials rather than energy use).

Sustainable biomass / bio-feedstock / bioenergy: In this report, the term 'sustainable biomass' is used to describe biomass that is produced without triggering any destructive land use change (in particular deforestation), is grown and harvested in a way that is mindful of ecological considerations (such as biodiversity and soil health), and has a lifecycle carbon footprint that considers the opportunity cost of the land as well as the timing of carbon sequestration and carbon release specific to each form of bio-feedstock and use. For further detail see Section 1.1 of the report.

Synfuels (or syngases): Hydrocarbon liquid (or gas) fuels produced from hydrogen, carbon dioxide and electricity. They can be zero-carbon if the electricity input is zero-carbon and the CO_2 is from direct air carbon capture. Also known as 'synthetic fuels', 'power-to-fuels' (e.g., 'power-to-liquids') or 'electro-fuels'.

Technology Readiness Level (TRL): Describes the level of matureness a certain technology has reached from initial idea to large-scale, stable commercial operation. The IEA reference scale is used (1-11 from concept to maturity).

Total cost of ownership (TCO): Costs including the purchase price and the costs of operating an asset over its lifetime.

Traditional biomass: "Woody biomass and dung used as fuel for cooking and heating purposes, mostly in developing countries. These uses of biomass are inefficient and result in millions of premature deaths as a result of air pollution. Sourcing of this biomass is often linked to deforestation and other unsustainable harvesting practices. Due to these negative effects, use of traditional biomass is expected to be phased out over time."[10]

Woody biomass: Lignocellulosic biomass; a form of 'second generation' biomass.

Zero-carbon energy sources: Term used to refer to renewables (including solar, wind, hydro, geothermal energy), sustainable biomass, nuclear and fossil fuels if and when their use can be decarbonised through carbon capture.

9 Griscom et al. (2017), *Natural Climate Solutions.*

10 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*

11 BP (2014), *Biomass in the Energy Industry – an introduction.*

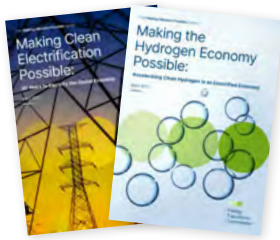
Major ETC reports and working papers

Global Reports

Better Energy, Greater Prosperity (2017) outlined four complementary decarbonisation strategies, positioning power decarbonisation and clean electrification as major complementary progress levers.

Mission Possible (2018) outlined pathways to reach net-zero emissions from the harder-to-abate sectors in heavy industry (cement, steel, plastics) and heavy-duty transport (trucking, shipping, aviation).

Making Mission Possible (2020) showed that a net-zero global economy is technically and economically possible by mid-century and will require a profound transformation of the global energy system.



Part of the Mission Possible Series – **Making Clean Electrification Possible** and **Making the Hydrogen Economy** (2021) set out a path to electrify the economy and highlighted a complementary role for clean hydrogen.

Sectoral and cross-sectoral focuses

Sectoral focuses provided detailed decarbonisation analyses on each on the six harder-to-abate sectors after the publication of the Mission Possible report (2019).

Our latest focus on building heating (2020) details decarbonisation pathways and costs for building heating, and implications for energy systems.

As a core partner of the Mission Possible Partnership, the ETC also completes analysis to support a range of sectoral decarbonisation initiatives:

In October 2020, the corporate members of the Clean Skies for Tomorrow initiative (CST) developed a **Joint Policy Proposal to Accelerate the Deployment of Sustainable Aviation Fuels in Europe.**

Produced for the Getting to Zero Coalition, **"The First Wave – A blueprint for commercial-scale zero-emission shipping pilots"** (2020) highlights five key actions that first movers can take to make tangible progress towards zero emission pilots over the next three to four years.

Steeling Demand: Mobilising buyers to bring net-zero steel to market before 2030 demonstrates that demand signals from steel buyers to steel manufacturers can help unlock investment and breakthrough technologies needed for net-zero primary steel.

Geographical focuses

China 2050: A Fully Developed Rich Zero-carbon Economy described the possible evolution of China's energy demand sector by sector, analysing energy sources, technologies and policy interventions required to reach net-zero carbon emissions by 2050.

China Zero Carbon Electricity Growth in the 2020s: A Vital Step Toward Carbon Neutrality (January 2021). Following the announcement of China's aim to achieve carbon neutrality before 2060 and peak emissions before 2030. This report examines what action is required by 2030 aligned with what is needed to fully decarbonise China's power sector by 2050.

A series of reports on the Indian power system and outlining decarbonisation roadmaps for Indian industry (2019-2020) described how India could rapidly expand electricity supply without building more coal-fired power stations, and how India can industrialise whilst decarbonising heavy industry sectors.

Setting Up Industry for Net-Zero (June 2021) explores the state of play in Australia and opportunities for transition to net-zero emissions in five supply chains – steel, aluminium, liquified natural gas, other metals and chemicals.

Introduction

A fundamental tension – Balancing bioresource supply and demand in a net-zero-emissions economy

Clean electrification should be at the heart of all strategies to achieve a net-zero-emission economy, with electricity applied to a far wider range of end applications than today and all electricity produced in a zero-carbon fashion. Electrification is the most efficient way to meet most energy needs. Thanks to rapidly falling costs of renewable electricity generation and the inherent efficiency gain associated with a switch to electricity, clean electrification can lower total energy system costs, while also delivering major local and global environmental benefits. As the ETC's latest report on the global power system describes, direct electricity use could and should grow from today's 20% of total final energy demand to reach close to 70% by 2050, with electricity generation to support direct electrification growing from 27,000 TWh to around 90,000 TWh [Exhibit 0.1].[1]

However, clean electrification cannot meet all decarbonisation needs since there are some sectors and use cases where direct electrification will likely remain impossible or uneconomic for many decades. Clean electricity will need to be complemented by other zero-carbon energy vectors – including hydrogen (used directly or in the form of derived fuels such as ammonia and synthetic fuels), fossil fuels combined with carbon capture and storage or use (CCS/U), and the use of sustainable biomass.

Box A

Primary vs final energy

Primary energy consumption is crude energy directly harvested from natural (including fossil) resources without transformation - it has not been subjected to an energy loss during a conversion or transformation process. Final energy consumption is all energy directly consumed by the final user. The difference between the two stems from efficiency losses in the conversion, transformation, or use processes (e.g., the process of converting biomass into a liquid biofuel). Final energy demand in the economy therefore entails substantially more primary energy input. Thus, the final energy from biomass presented in Exhibit 0.1 (c.18-25 EJ/year) represents a much larger primary biomass supply requirement (e.g., c.30-45 EJ/year if c.60% efficiency from primary biomass to final energy were achieved, an approximate average for modern bioenergy).[2]

In this context, demand for biomass is surging; in Europe biomass power generation has increased five-fold and use of biofuels in transport 25-fold since 2000.[3] Many bio-based decarbonisation routes have high technological readiness as biomass can be transformed into resources chemically similar or identical to the fossil-fuel resources they displace. The ability to 'drop-in' bioresources in existing equipment also minimises capital expenditure that might be required to adapt to other new zero-carbon technologies. Many climate mitigation pathways look to bioresources as the most straightforward, and apparently lowest cost, route to reduce emissions today [Exhibit 0.2] across sectors as diverse as power generation, mobility, industry, and the built environment.

In principle biomass production and use can be renewable, but not all forms of biomass production are sustainable or good from a carbon emissions point of view. And even where use of biomass does contribute to reducing net GHG emissions, biomass used for energy still emits pollutants at point of use, affecting local air quality.

- Bioresources production requires land for crop growth, and availability of land is limited by many competing uses, including for food to feed a growing global population, for ecosystem services (including preservation of biodiversity), and for alternative forms of climate mitigation (e.g., reforestation) [Exhibit 0.3]. On average, producing 50 EJ/year of biomass (similar to today's usage)[4] could require about 280 million hectares (Mha) of land (or 2.8 million km^2),[5] which

1 Energy Transitions Commission (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy.*
2 Total modern bioenergy has an approximate average efficiency of 58% (for power 32%, for heat 80%, for biofuels 60%). Chum et al. (2011), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.*
3 Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
4 Current supply is c.38 EJ/year for energy excluding woody biomass for materials (c.10 EJ/year produced + 4 EJ/year recycled) and traditional uses (c.25 EJ/year). IEA (2021), *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.* Materials estimates based on IIASA analysis of 2018 FAO data and GLOBIOM results.
5 Assumes an average energy crop (e.g., miscanthus, switchgrass, willow, and poplar) yield of ~180 GJ/ha/year (~13 tonnes dry biomass/ha) based off average productivity of 6.4 tC/ha/year from Smith et al. (2016) *Biophysical and economic limits to negative CO_2 emissions)*, carbon content of 50% by mass, and energy content of ~14 GJ/tonne.

is about 8% of all land currently devoted to agriculture and approximately 20% of global cropland.[6] Excess use of bioresources in the energy and industry system could therefore either compete with food production (pushing up food prices) or lead directly or indirectly to deforestation.[7]

- Further, biomass can only contribute to emissions reductions and climate mitigation targets if it is sustainably sourced, with low levels of carbon emissions across the full lifecycle of growth, collection, and transformation. This assessment must take into account emissions that arise from any land use change (direct or indirect), any carbon absorption that would occur if the land stayed in existing condition (opportunity cost).

- Biomass production practices should also take into account environmental considerations beyond greenhouse gases emissions, like soil health and biodiversity, as well as social considerations.

Current policy approaches often fail to take these factors into account and have produced perverse effects as a result. The EU Renewable Energy Directive (RED) biofuels mandate, for example, resulted in the expansion of harvested land for energy crop cultivation, which in some regions displaced food production and, combined with expansion of palm oil for food, resulted in major deforestation and associated release of emissions.[8] In addition, bioresource claims by sectors and companies, especially in the form of bioenergy, are often considered in silos, ignoring both other sectoral claims on bioresources and existing uses of biomass for materials (e.g., timber, pulp & paper) and for food.[9]

This report sets out a comprehensive analysis of how potential demands for biomass will compare with truly sustainable supply in a net-zero-emission economy. The inherent complexity of assessing biomass production and alternative land use means that no single figure for sustainable biomass supply can be defined.[10] We instead produce a range of estimates with:

- A 'prudent estimate' of 2050 biomass supply, given current trends and technologies, of about 40-60 EJ per annum, of which 10 EJ is best used as a material[11] (e.g., timber) leaving 30-50 EJ per annum available for use as an energy source or for other materials uses such as production of plastics feedstocks.

- A 'maximum potential scenario' which could reach 120 EJ per annum, given improvements in waste collection (+5 EJ), the development of macro algae technologies (+10 EJ), and the release of agricultural land from food production (+45 EJ) if (but only if) it were possible to dramatically reduce animal meat consumption.

By contrast, potential demands for biomass could amount to over 65 EJ/year even when considering only the four highest priority applications – wood materials, pulp and paper, plastics feedstock and aviation – and higher still if considering the broader spectrum of sectors which appear to be currently planning to use biomass as a key decarbonisation route.

This implies the need for policies which (i) enforce strong regulations to ensure that biomass is sustainably sourced, while pursuing opportunities to increase sustainable supply from waste, microalgae production, and through freeing up current agricultural land for other uses, (ii) create the conditions for prioritised use of bioresources (for example, by gradually phasing-out incentives for biofuel use in sectors, such as road transport, as more cost and carbon effective alternatives become available), (iii) support the key technologies that enable efficient, sustainable supply and use of bioresources, developing both biotechnologies and other technologies required to drive non-bio-based decarbonisation (e.g., ammonia for long distance shipping).

In some circumstances and with careful management, using biomass to produce energy can be low- or zero-emissions because the carbon released at the point of combustion was previously removed from the atmosphere during biomass growth. If combined with carbon capture and storage (CCS), it can become a 'carbon removal' technology. This report therefore also considers how the relative prioritisation of bioenergy use between sectors would change if we took into account the potential role of bioenergy with carbon capture and storage (BECCS) as a carbon removal technology.

6 c.3,270 Mha devoted to agriculture based on IIASA GLOBIOM and FOLU (2019), *Growing Better.*
7 Note, there are opportunities for dual uses of land where biomass production does not conflict other uses such as food production or ecosystem services, e.g., agroforestry.
8 Approximately 70% of the expansion for palm oil cultivation was on forest land, of which 18% was on high carbon stock peatland forest. Given the high risk of land-use change the European Commission is phasing out biodiesel from palm oil, unless proven to have low indirect land use change risks via certification (e.g., RSPO). European Commission (2019), IIASA (2015), USDA, FAOSTAT.
9 For example, the EU Renewable Energy Directive (RED) requires 10% of road transport fuels to be renewable by 2020. National Renewable Energy Action Plans include support for building heating and power from biomass, and national policies support timber in construction (e.g., all new French public buildings must contain at least 50% wood or other sustainable materials from 2022). Le Figaro (2020), *Du bois et de la paille dans davantage de bâtiments publics.*
10 Calvin et al. (2021), *Bioenergy for climate change mitigation: scale and sustainability.*
11 Composed of biomass for the timber and pulp & paper sectors. In addition, about 4 EJ of demand for biomass to be used to produce materials could be met from recycling of biomass rather than primary production (based on IIASA analysis of FAO data).

The report sets out in turn:

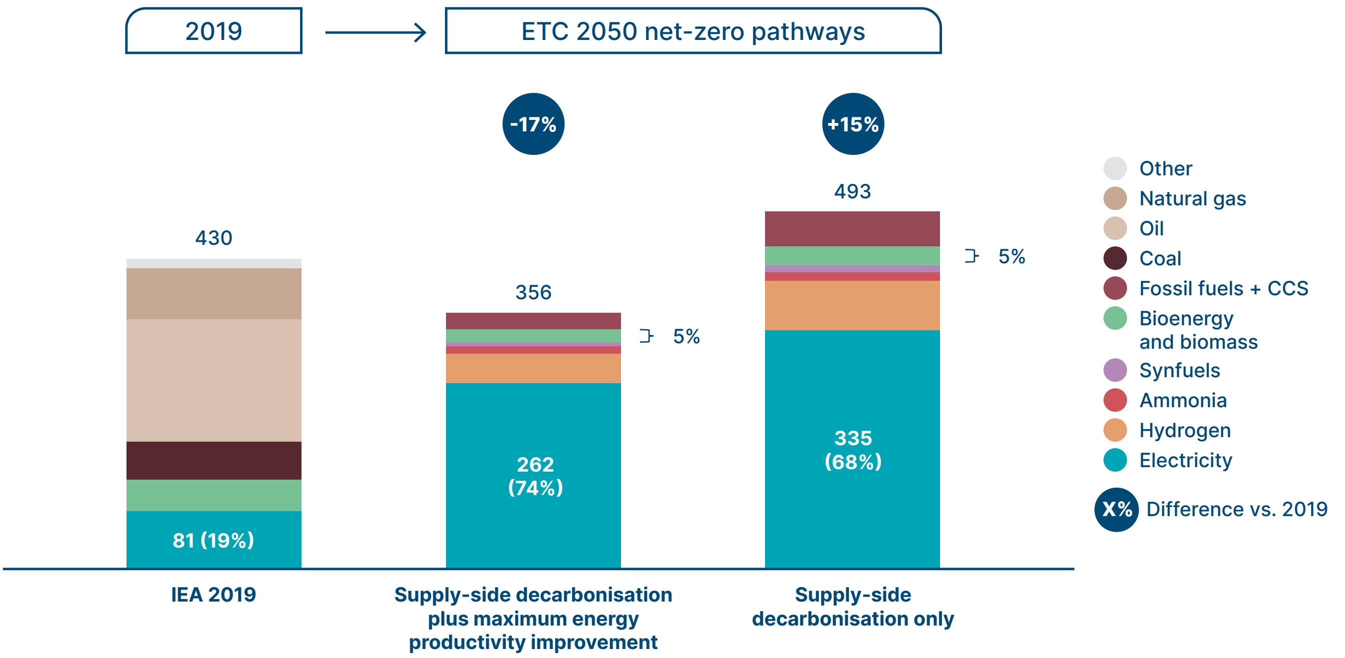
1. An assessment of total sustainable, low-emissions biomass supply available by mid-century.
2. Priority uses of bioresources within the energy and industrial sectors, given supply constraints.
3. The role of bio-based carbon dioxide removal and the implications for other sectors.
4. Critical industry and policy actions required during the 2020s to ensure the development of a sustainable approach to bioresources within a net-zero-emissions economy.

Exhibit 0.1

Final energy mix in a zero-carbon economy: clean electricity is the dominant form of energy, complemented by hydrogen and fossil fuels with CCS, with a constrained role for bioenergy

Final energy demand
EJ/year

Illustrative scenario



SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021); IEA (2020), *World Energy Outlook*.

Most climate mitigation pathways depend on significant biomass use in 2050 and beyond and do not account for materials uses

Total global biomass use (EJ primary energy)[1]: 2050 Bioenergy; 2050 Carbon removal via BECCS[2]; △ 2070; ○ 2100

Climate mitigation target	Shape of decarbonisation transition (illustrative, $GtCO_2$ emissions/year)	Scenario	Year net zero is reached	2050 Bioenergy	2050 Carbon removal via BECCS[2]
≤1.5°C	Immediate, fast decarbonisation	IPCC (P1)	2060	~40[3]	
		FOLU/IIASA ('Better futures')	2050	32	
		IEA Net-Zero Emissions	2050	~90	~13
		IPCC (P2)	2055	~65[3]	~10
		BP (Net Zero)	2050	~40	~15
		Shell (Sky 1.5)	2058	~83	~17
~1.5°C	Immediate, mid-pace decarbonisation	IRENA (1.5-S)	2050	~105	~47
		IPCC (P3)	2058	~100[3]	~10
		IEA-ETP (SDS)	2070	~112	~7
		UK CCC (High case)	-	84[4]	
		FOLU/IIASA (BECCS scenario[5])	-	~42	~64[6]
>1.5°C	Late decarbonisation	IPCC (P4)	2074	~100[3]	~160
		Shell (Waves)	2098	63	
		Shell (Islands)	>2100	70	

These estimates focus on energy and do not include the amount of biomass for materials uses.

In some studies there is discussion of materials, but this is generally limited.

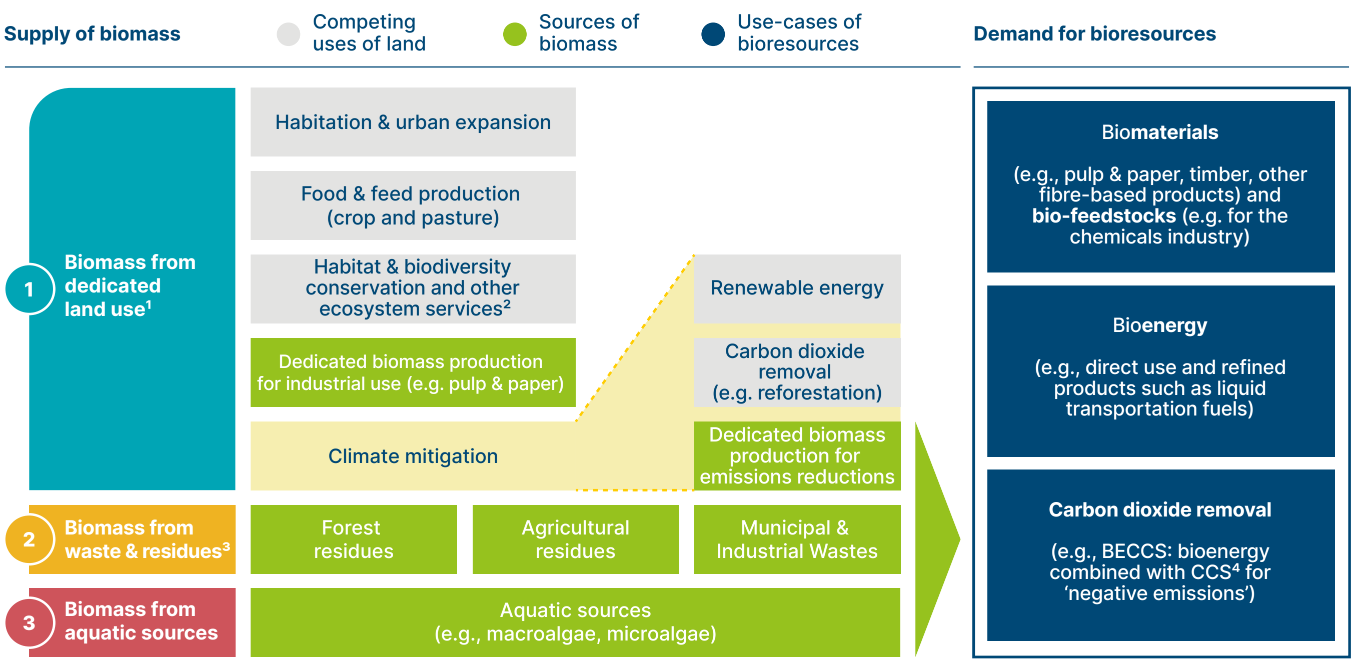
The UK Committee on Climate Change (CCC) notes that materials demand will outstrip supply.

[1] Modern bioenergy, excluding traditional biomass. [2] BECCS energy use determined under an assumption of ~10 EJ biomass per 1 $GtCO_2$ sequestered. [3] Calculated from IPCC reported percent increase relative to primary energy from biomass in 2010 (~50 EJ, Haberl et al. (2010)). [4] Excludes non-tradable biomass (i.e., feedstocks that are not suitable for long-distance trade due to low energy densities or other physical properties). BECCS estimates not included as estimated for the UK only. [5] Unpublished scenario from FOLU/IIASA (2019), *Growing Better*. [6] Amount of biomass used for BECCS not specified. Total increase in bioenergy compared to FOLU/IIASA 'Better futures' scenario without BECCS is 77 EJ, of which the difference in non-food crop bioenergy between scenarios is 51 EJ.

SOURCES: Energy Transmission Advisors (2020), Vivid Economics (2020), *An investor guide to negative emission technologies and the importance of land use*; FOLU/IIASA (2019), *Growing Better*: Better Futures, IPCC (2018), Shell (2021), BP (2020), ETC (upcoming 2021) Negative Emissions Consultation Paper, IEA-ETP (2020), IEA (2021) Net Zero by 2050; UK CCC (2018); IRENA (2021), *World Energy Transitions Outlook*.

Exhibit 0.2

Supply of sustainable, low lifecycle emissions biomass is constrained by competing uses of land



NOTES: [1] Parallel uses of land (e.g., double-cropping and forest/landscape management) can reduce competition between uses of land by combining biomass production with agriculture or ecosystem services;
[2] Includes ecosystem services such as nutrient cycling, soil quality maintenance, water regulation, erosion mitigation, water and air purification, recreation, etc.;
[3] Biomass from waste and residues are generated as a by-product of using land for other primary purposes listed in category 1 (e.g., agriculture, human habitation, managed forestry).
[4] BECCS: bioenergy with carbon capture & storage (CCS)

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission.

Exhibit 0.3

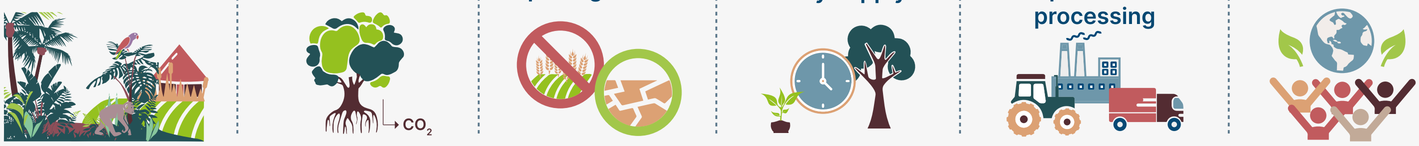
Energy Transitions Commission

BIORESOURCES WITHIN A NET-ZERO EMISSIONS ECONOMY

How much biomass can we use?

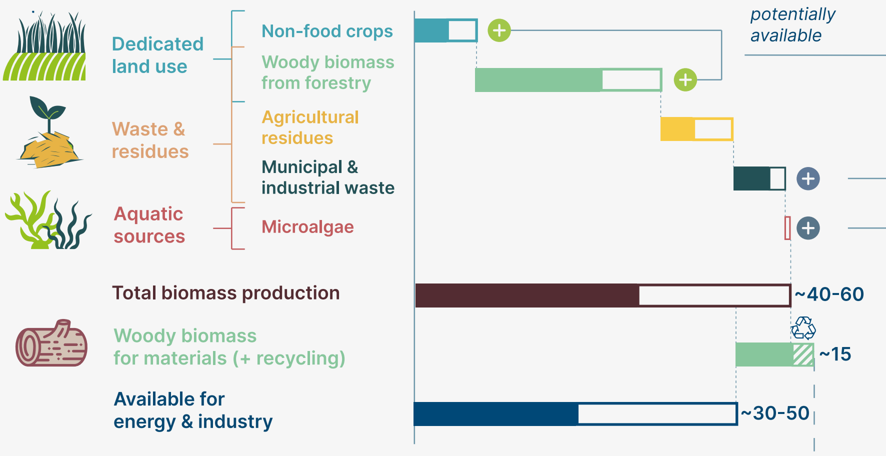
NOT ALL BIOMASS IS 'GOOD' BIOMASS; WHAT IS SUSTAINABLE BIOMASS?

- No competition with other critical uses of land
- No deforestation or peatland conversion
- Target degraded land, with little plant growth
- Respect growth periods which will delay supply
- Close-to-zero emissions collection, transportation and processing
- No environmental or social harm



WHAT WE CAN RELY ON: A CONSTRAINED SUSTAINABLE SUPPLY

Global sustainable biomass supply in 2050 – ***Prudent estimate***
EJ primary energy per year – *Illustrative scenario*



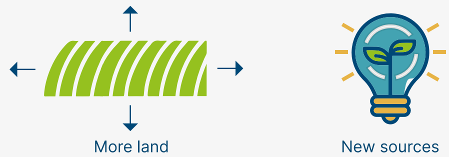
EXTRA BIORESOURCES IF RADICAL CHANGE HAPPENS

More available land
(Accelerated by biotechnologies)

- Dietary shift away from meat
- More productive plants (traditional crops, algae)
- Less food waste

New sources available

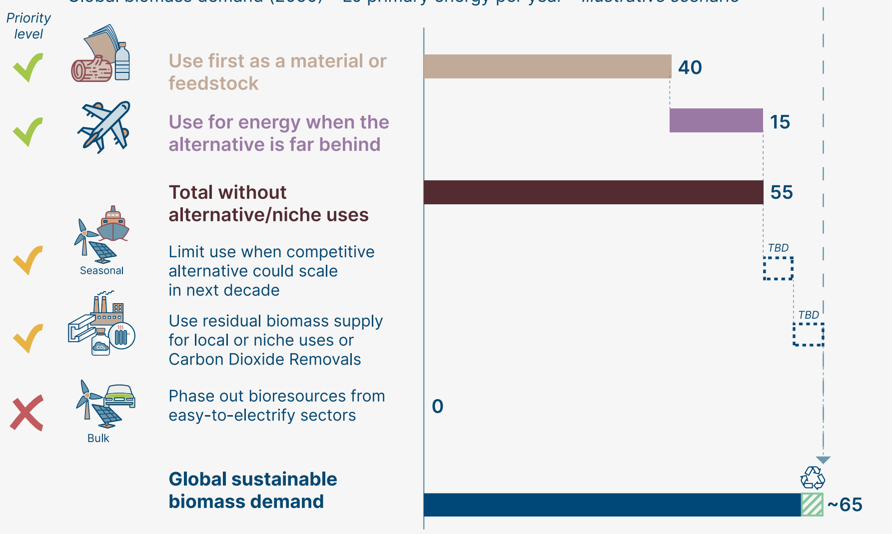
- Increase collection of organic waste
- Development of macroalgae (seaweed) for energy



Where should bioresources be used?

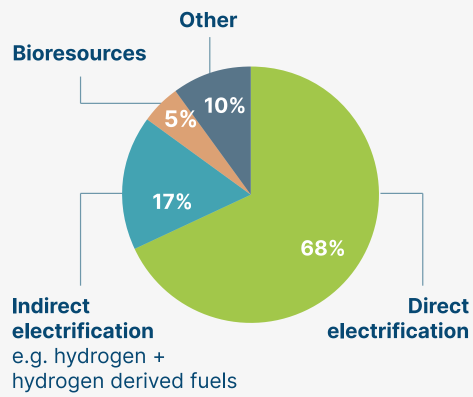
HOW TO PRIORITISE USES OF BIORESOURCES?

Global biomass demand (2050) – EJ primary energy per year – *Illustrative scenario*



CLEAN ELECTRICITY: THE CORE OF A NET-ZERO ECONOMY

Final energy demand in 2050
EJ primary energy per year – *Illustrative scenario*



Estimating sustainable biomass supply

Published estimates of biomass supply available for use in energy or material applications differ widely. The range reflects differences in the importance attached to sustainability criteria such as biodiversity, different estimates of lifecycle carbon emissions, and different assumptions about future trends in diet and agricultural productivity which affect the need for land for food production.

This chapter sets out our assessment of sustainable biomass supply and explains both our 'prudent estimate' of 40-60 EJ per annum, and our 'maximum potential estimate' of 120 EJ.[12] It covers in turn:

- Sustainability criteria, how they impact the range of supply estimates, and the ETC's two scenarios.
- Biomass from dedicated land use – and the related limitations and trade-offs.
- Waste and residues from forestry, agriculture, and municipal and industrial waste.
- Aquatic biomass.
- Biomass supply in the transition to 2050.
- Regional perspectives on biomass supply.

1.1 Sustainability criteria and how they impact the range of supply estimates

Published estimates of biomass supply available for use as an energy or material source vary widely: some suggest a potential of less than 10 EJ per annum while others indicate that upwards of 1,000 EJ of primary biomass could be available [Exhibit 1.1].[13] The huge range reflects different approaches to two key issues – the availability of land and the sustainability criteria that should be applied. The ETC believes that a prudent estimate of sustainable biomass supply, applying tight sustainability criteria, is towards the lower end of the range.

Estimates for total global biomass potential vary substantially

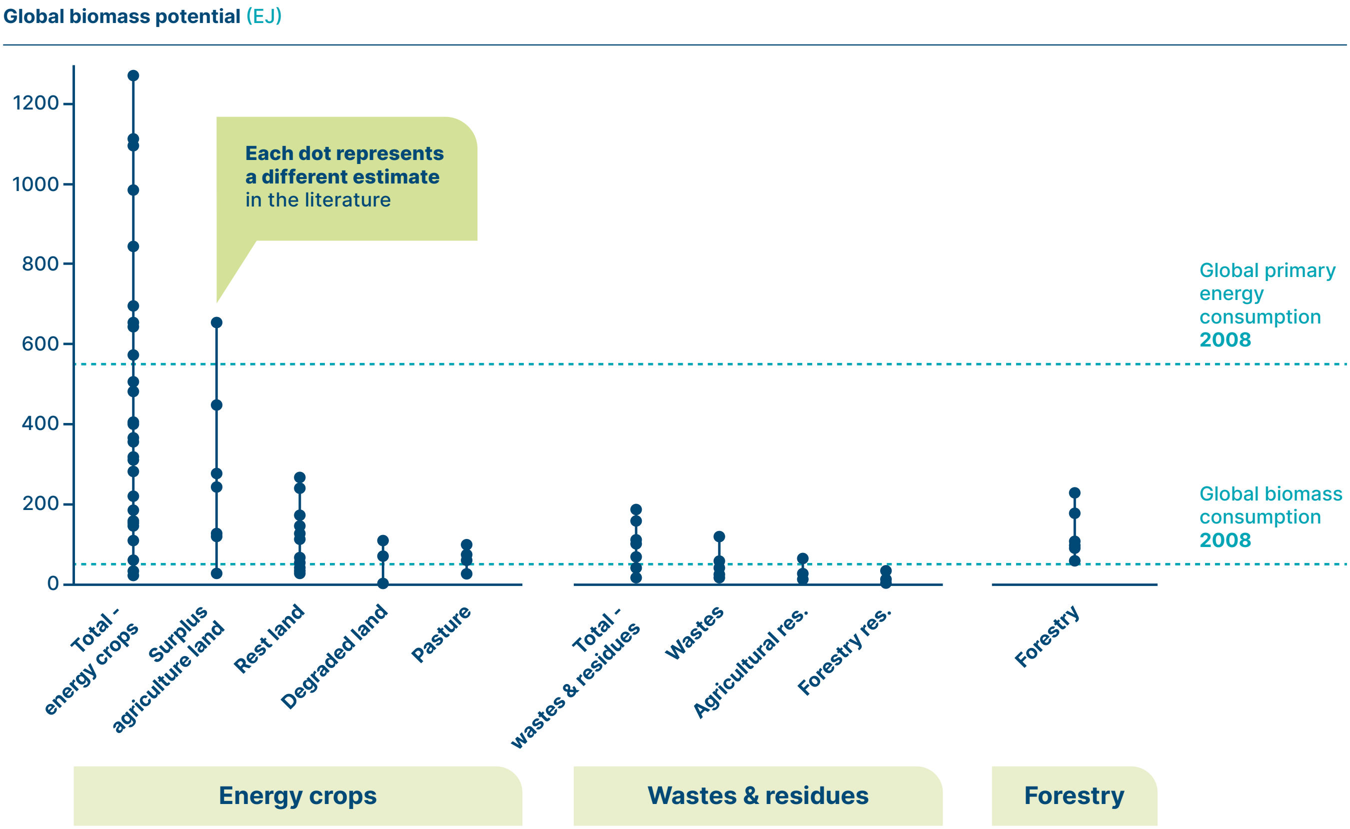


Exhibit 1.1

SOURCES: Figure reproduced with permission from UK Energy Research Centre (UKERC) (2011), *Energy from biomass: the size of the global resource* adapted from Slade et al. (2014), *Global bioenergy resources.*

12 With an additional ~4 EJ/year available for materials uses from recycled woody biomass.
13 Slade et al. (2014), *Global bioenergy resources.*

Types of biomass

There are three core categories of potential biomass supply:

- **Biomass grown on dedicated land:** Biomass grown on dedicated land includes both energy crops, such as miscanthus or short rotation coppice (e.g., willow or poplar), conventional crops (e.g., food crops such as oil seeds or cereals), and forestry (especially when producing woody biomass for materials, like for stem wood production).

- **Biomass from waste and residues** of other sectors, in particular forestry (e.g., bark, branches and wood chips), agriculture (e.g., cereal straw and husks) and municipal and industrial waste (e.g., waste oils, manure from livestock production, and other organic wastes).

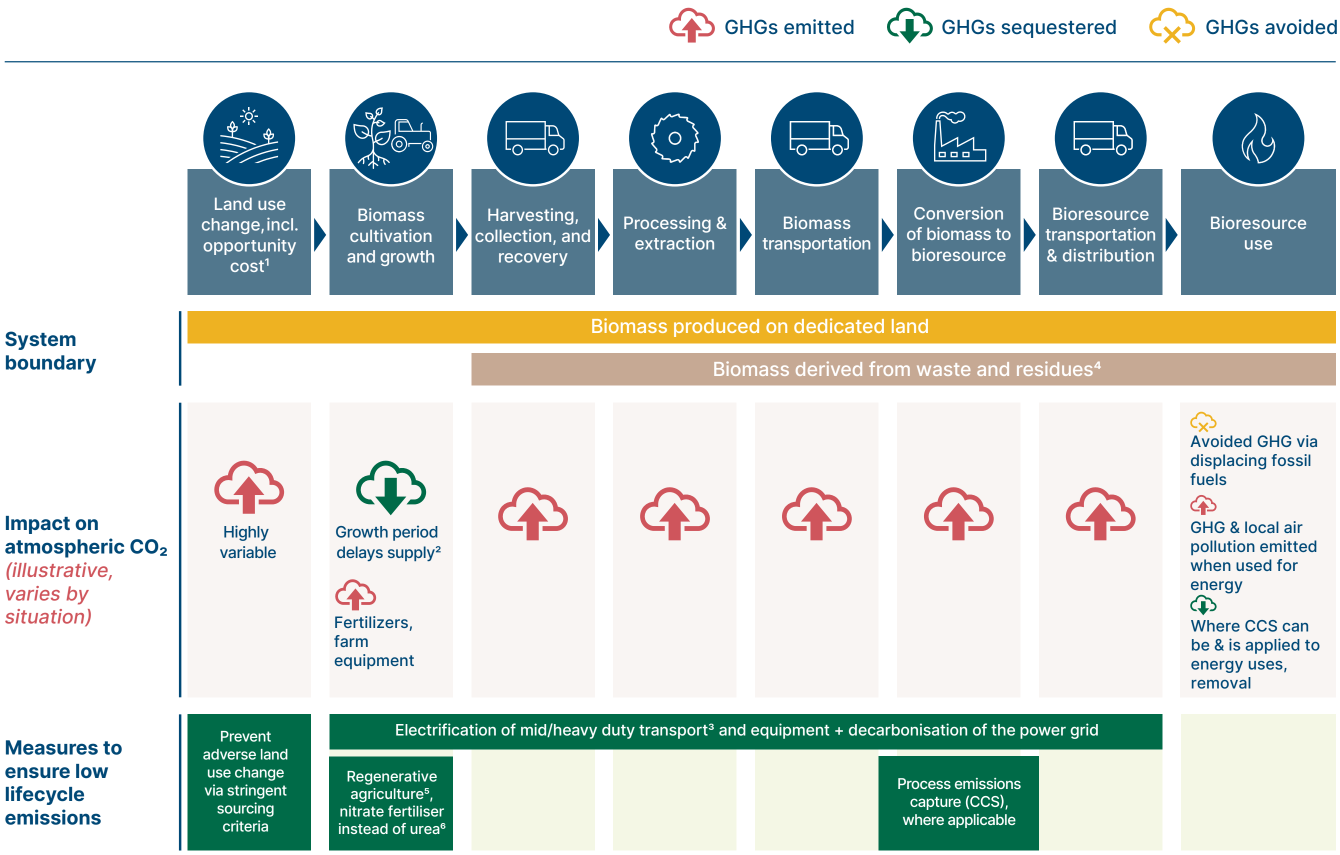
- **Biomass from aquatic sources**: such as macroalgae (seaweed) and microalgae.

In general, sustainability concerns are greatest in relation to the first category but must be carefully assessed for all three.

What is sustainable biomass?

'Sustainable biomass' supply represents material that is renewable, has a lifecycle carbon footprint equal or close to zero (including emissions related to indirect land use change), and for which the cultivation and harvesting practices used are mindful of ecological considerations, such as biodiversity and health of the land and soil, as well as social aspects.[14]

Biomass can only contribute to climate mitigation when produced with low lifecycle emissions across growth, harvesting, transportation, conversion, and use



NOTES: GHGs: greenhouse gases;[1] The 'opportunity cost' of carbon sequestration that would have occurred without intervention must be accounted for. [2] Growth period delays low lifecycle emissions biomass supply. In the case of managed forests, growth of biomass can take decades whereas the time lag is negligible for perennial crops.CO_2 is sequestered in carbon captured in biomass growth net of CO_2 released from decay of residues left on the land for soil health. [3] Additional role for clean hydrogen and zero-carbon fuels (e.g. ammonia) in some segments of mid/heavy duty transport. [4] Production emissions associated with waste and residues would be discounted as attributed to the primary product, but emissions from waste and residues collection still relevant. [5] Practices such as no-till farming, rotational grazing, mixed crop rotation, cover cropping, and the application of compost and manure. [6] Urea production requires CO_2 which typically stems from natural gas and is ultimately released upon application on the field. Nitrate production can be completely decarbonised via a switch of production technology to 'green' hydrogen.

SOURCE: Adapted from CORSIA (2019), Eligible Fuels - Life Cycle Assessment Methodology.

Exhibit 1.2

14 E.g., recognising existing livelihoods from use of land and development of economic alternatives where appropriate.

This implies three key **sustainability criteria**:[15]

- **Land availability and land use trade-offs:** Any biomass production should consider competing alternative uses of land – for human habitation, food production, habitat conservation, and climate mitigation. These alternatives define an opportunity cost to use of the land and a baseline for carbon emissions (whether source or sink) against which use of the land for bioenergy and biomaterials should be judged. Land available for additional biomass production is therefore restricted to a highly limited supply of marginal/degraded land or to crop- and pastureland that can be released from its current use.

- **Lifecycle carbon footprint:** In calculating the net impact biomass use has on atmospheric carbon, one must consider the balance of carbon dioxide absorption and emissions across its full lifecycle [Exhibit 1.2].
  - Where production of biomass would trigger a direct or indirect change in land use, the carbon stocks associated with the land before conversion and the opportunity cost of carbon that could be sequestered if biomass were not extracted, must be accounted for.[16] Such changes can result in substantial carbon emissions if land with significant carbon stocks (e.g., peatlands or other natural landscapes with high soil carbon) are converted for biomass production, or if biomass production displaces other activities (e.g., food production) on those lands. To achieve a net reduction in GHG emissions, the use of the land for bioenergy or biomaterials must result in lower GHG emissions overall than would have been emitted otherwise. Additionally, new biomass production cannot provide an immediate offset because plants must capture carbon through growth before they can be harvested for use.
  - Additionally, the carbon footprint related to production, collection, transportation, and processing of the biomass should be reduced to close to zero.

- **Other environmental and social considerations,** including in particular**:**
  - **Biodiversity and land conservation:** Areas of high biodiversity, such as natural forests, should be strictly avoided. High-intensity land management can impact biodiversity, therefore presenting a trade-off between biomass production and leaving land to nature. However, some land-use models can mitigate these trade-offs.[17]
  - **Ecosystem health:** When collecting biomass, in particular forestry and agricultural residues, one should only extract a portion of biomass residues from the land to maintain ecosystem/soil health.
  - **Social considerations** such as equity and cultural protection (e.g., indigenous people and land rights) are also important.

In addition to sustainability considerations, the available supply of biomass will also depend on technical and economic considerations regarding limits to collection and transport of some waste and residual sources of biomass.

Sources and models that apply tight sustainability standards

The huge range of estimates shown on Exhibit 1.1 reflects very different approaches to land availability and sustainability concerns. In our analysis, we have drawn primarily on seven studies which apply sustainability criteria broadly in line with those we have defined above. These are:

- Four global studies / scenarios:
  - The ACRE Satellite Model (proprietary, developed for industry) which reflects bottom-up geospatial mapping analysis and finds a very limited potential for sustainable biomass (<45 EJ per annum), primarily due to restrictive assumptions on land availability.[18]

15 See Chapter 4 for ways to take these criteria into account.

16 Searchinger et al. (2018), *Assessing the efficiency of changes in land use for mitigating climate change.*

17 For example, if degraded land is available for use, an agroforestry system could improve biodiversity through use of diverse species, provide a source of food for local communities, and generate waste materials that can be used for bioenergy. These benefits may outweigh the ability to sequester more carbon from planting a monoculture energy crop subsequently used for bioenergy and the carbon dioxide released captured and stored in long term geological storage (BECCS). See further discussion in Chapter 3.3.

18 Proprietary; used with permission.

- Two scenarios developed by the Food and Land Use Coalition (FOLU) with the International Institute for Applied Systems Analysis (IIASA) based on IIASA's Global Biosphere Management Model (GLOBIOM):[19]
  - One 'Better Futures' scenario that prioritises the release of land to be returned to nature (i.e., afforested or to other natural systems) and delivers a 1.5°C mitigation pathway without reliance on BECCS, and
  - One 'BECCS scenario' that assumes that 250 Mha of land released from food production could be devoted to bioenergy (with any additional freed up land returned to nature).
- The International Council on Clean Transportation (ICCT) assessment on global bioenergy potential in 2050, which reviews estimates in the literature and adds additional adjustments, finding a maximum sustainable bioenergy potential of 60-120 EJ per annum in 2050.[20]

- Three European studies:
  - European Commission study from IIASA (RECEBIO), an integrated assessment model using GLOBIOM/PRIMES[21] that targets an increased EU use of bioenergy for electricity and heat via modelling of woody biomass production and use.[22]
  - IIASA's study using GLOBIOM with a focus on indirect carbon & land impacts in the EU from biofuels.[23]
  - European Climate Foundation (ECF) funded EU study conducted by the ICCT using top-down analysis of public datasets to determine biomass availability for biofuels for transportation purposes.[24]

Box B

Determining a range of biomass supply upon which we can rely for climate mitigation

There are many studies of biomass supply that vary in their assumptions on sustainability. Even amongst those with strict sustainability criteria, such as the ones relied upon in this analysis, there is significant variation on some dimensions.

While they tend to be at the lower end of potentials overall, there are differences. For example:

- The FOLU BECCS scenario has a significant (>50 EJ/year) supply from energy crops on dedicated land as the model responds to increased demand.
- The ICCT study has an even greater reliance on energy crops, reflecting a maximum plausible limit rather than a prudent estimate.
- FOLU scenarios did not explicitly model agricultural residues or municipal and industrial waste, while these were included in ACRE and ICCT models.
- None of these studies considered aquatic biomass.

In this report, we have made a judgment on the range of sustainable, low lifecycle emissions biomass supply. This has been based on a comparison across studies and tested with a diverse group of stakeholders, but the reality is that there is significant inherent ambiguity in supply estimates. Chapter 4 addresses how to proceed in an environment of such uncertainty.

19 IIASA's Global Biosphere Management Model (GLOBIOM) underpins the analytics for the FOLU 2019 report *Growing Better – Ten Critical Transitions to Transforming Food and Land* Use. GLOBIOM is a global recursive dynamic bottom-up partial equilibrium model integrating the agricultural, bioenergy and forestry sectors.
20 Excludes biomass from forestry that is likely to be allocated to materials. Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*
21 PRIMES: Price-Induced Market Equilibrium System. The PRIMES model is an EU energy system model simulating energy consumption and supply.
22 IIASA (2016), *Study on impacts on resource efficiency of future EU demand for bioenergy (ReceBio). Final report.*
23 IIASA (2015), *The land use change impact of biofuels consumed in the EU: Quantification of area and greenhouse gas impacts.*
24 USDA (2016), *Waste and residue availability for advanced biofuel production in EU Member States.*

Prudent and maximum potential estimates

The availability of sustainable, low lifecycle emissions biomass is inherently uncertain, making it impossible to define one specific figure for sustainable supply.[25] We have therefore produced two supply scenarios:

- A prudent estimate, that is itself a range, of how much biomass can be used without major changes in land use, technology, and consumer behaviour and thus can safely rely upon for climate mitigation.
- A maximum potential case that might result from changes in technology and/or from major changes in consumer behaviour and feasible land use.

The 'prudent scenario' is shown on Exhibit 1.3 with:

- 5-10 EJ/year from non-food crops grown on dedicated land.
- 20-30 EJ/year derived from forestry, of which 10 EJ/year is likely to be allocated to materials uses (e.g., timber) with 10-20 EJ/year (entirely in the form of forestry residues, including low-quality fuel wood) subsequently available for energy use.
- 5-12 EJ/year from agricultural residues.
- 6-9 EJ/year from municipal and industrial wastes.
- 0-1 EJ/year from aquatic sources.

This results in about 40-60 EJ/year of primary biomass supply, of which about 10 EJ/year would be best used as a material,[26] leaving about 30-50 EJ/year available for use as an energy source. In addition, about 4 EJ/year of demand for biomass used as material could be met by recycling of woody biomass.[27]

Our maximum potential case [Exhibit 1.4] allows for three possible, but uncertain, future developments:

- Improved waste management and collection of organic waste, which could add c.5 EJ/year.
- Technological and commercial development of macroalgae production for energy, which might eventually increase supply by c.10 EJ/year.
- And – the largest, but most uncertain factor – increased availability of dedicated land, which might become possible if major consumer behaviour changes or synthetic meat and other biotechnologies significantly reduced the need for agricultural land and if the most appropriate use of that freed up land was for biomass production. This could increase supply by as much as c.45 EJ/year.

Sections 1.2, 1.3 and 1.4 below set out our detailed assessment of potential for each category of supply.

Exhibit 1.5 shows how this estimate compares with other published studies which have applied sustainability criteria of varying stringency. A key driver of different estimates is the assumption made about how much land can be dedicated to biomass crops without detriment to biodiversity.

- Our 'prudent estimate' is of the same order of magnitude as those produced by the ACRE model, by Greenpeace, by the UK Committee on Climate Change, and in the FOLU/IIASA 'Better Futures' scenario.[28]
- Our 'maximum potential estimate' is in line with the FOLU estimate (based on the IIASA model) of what might be available if large land area could be released from agriculture and devoted to bioenergy production (the FOLU 'BECCS scenario').[29] But it is significantly less than the higher end of the 130-400 EJ/year in 2070 estimated by a Ecofys and Shell study, published in 2015, which reflected optimistic assumptions about both agricultural land release and greater willingness to dedicate that land for biomass crops rather than to biodiversity and nature preservation.[30]

25 Calvin et al. (2021), *Bioenergy for climate change mitigation: scale and sustainability.*

26 Note: this report focuses on wood but the materials industry also relies on non-woody biomass including natural rubber, cotton and other non-wood derived fibres, bio-based and biodegradable plastics, straw as a construction material, etc.

27 Based on IIASA analysis of 2018 FAO data and GLOBIOM results.

28 FOLU 'prudent case' refers to the Better Futures scenario in FOLU (2019), *Growing Better: 10 critical transitions to transform food and land use,* where no land freed up from food production is dedicated to bioenergy crop production. UK Committee on Climate Change (2018), *Biomass in a low-carbon economy. IEA (2017), Energy Technology Perspectives (and sources within).*

29 IIASA GLOBIOM (latest GLOBIOM FOLU-scenario outputs shared Dec 2020).

30 Deng et al. (2015) Country-level assessment of long-term global bioenergy potential.

Global supply of sustainable biomass could be ~40-60 EJ/year, of which ~10 from forestry favouring material uses, leaving ~30-50 for energy and industry

Prudent estimate

Global sustainable biomass[1] supply (2050) – illustrative scenario
EJ/year (primary energy)

Illustrative

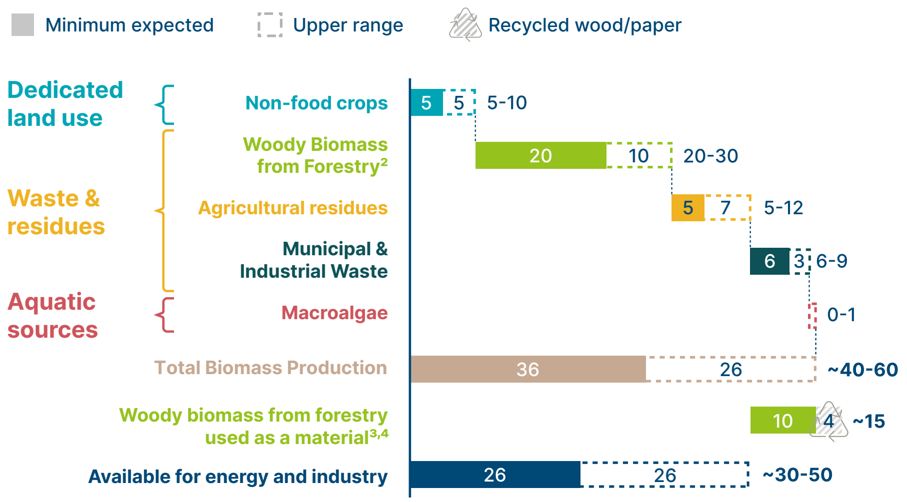


Exhibit 1.3

[1] The term 'sustainable biomass' is used to describe organic material that is renewable, has a life-cycle carbon footprint equal or close to zero (including considerations for the opportunity cost of land), and for which the cultivation and harvesting practices used are mindful of ecological considerations such as biodiversity and health of the land and soil.
[2] Includes high-quality stemwood from forestry suitable for the timber and pulp & paper sectors (~10 EJ/year today, FAO Industrial Roundwood production less by-products used for energy). This category also includes residues from forestry but excludes traditional fuelwood (~25 EJ/year today, assumed to reduce with modernisation) due to collection and sustainability assurance challenges.
[3] E.g., timber, pulp & paper. Based on current harvests from commercial forestry; may increase if forestry additional high-quality stemwood could be made available if freed up land were dedicated to forestry.
[4] Additional supply from recycled materials (~4 EJ/year today).

SOURCE: SYSTEMIQ analysis for ETC (2021).

If ambitious systems changes are achieved, maximum biomass potential by 2050 could be ~110 EJ/year for energy & industrial uses

Maximum potential

Maximum achievable only under extremely ambitious systems change scenarios; additional potential NOT to be relied upon.

Global sustainable biomass[1] supply (2050) – illustrative scenario
EJ/year (primary energy)

Illustrative

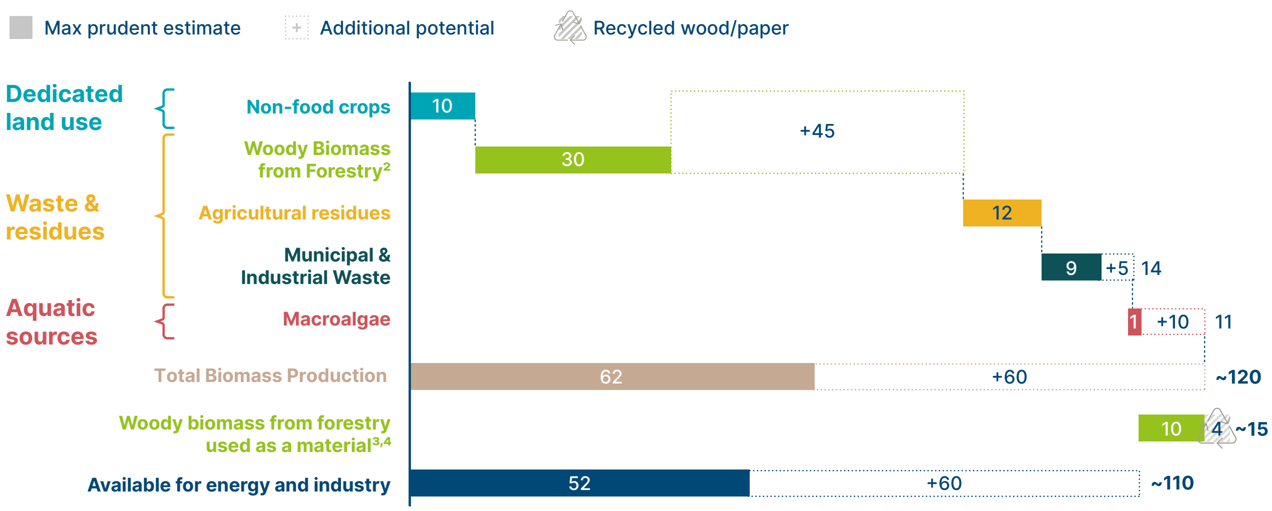


Exhibit 1.4

[1] The term 'sustainable biomass' is used to describe organic material that is renewable, has a life-cycle carbon footprint equal or close to zero (including considerations for the opportunity cost of land), and for which the cultivation and harvesting practices used are mindful of ecological considerations such as biodiversity and health of the land and soil.
[2] Includes high-quality stemwood from forestry suitable for the timber and pulp & paper sectors (~10 EJ/year today, FAO Industrial Roundwood production less by-products used for energy). This category also includes residues from forestry but excludes traditional fuelwood (~25 EJ/year today, assumed to reduce with modernisation) due to collection and sustainability assurance challenges.
[3] E.g., timber, pulp & paper. Based on current harvests from commercial forestry; may increase if forestry additional high-quality stemwood could be made available if freed up land were dedicated to forestry.
[4] Additional supply from recycled materials (~4 EJ/year today).

SOURCE: SYSTEMIQ analysis for ETC (2021).

Exhibit 1.6 sets out a detailed comparison between our scenarios and the estimates produced by the IEA in their recently issued *Net Zero by 2050 Roadmap*.[31] Overall the IEA's figures are close to our 'maximum potential scenario' and reflect many broadly similar assumptions, but with a few key differences:

- On agricultural residues and municipal and industrial wastes, the IEA's estimate of 43 EJ per annum is significantly higher than our 'maximum potential' estimate of 26 EJ/year. Five EJ/year of the difference is due to the IEA's inclusion of a portion of the biomass currently used for traditional firewood. In addition, they make more optimistic assumptions about agricultural residues, where some studies have suggested that up to 30 EJ/year might be available. Our maximum of 12 EJ/year draws on those studies which apply stricter sustainability criteria, particularly relating to the percentage of residues that must be left on the ground to maintain soil quality.[32] The IEA estimate also assumes significant investment to improve waste management, which is the key driver of the +5 EJ/year from municipal and industrial waste in our maximum potential estimate.

- IEA estimates of woody biomass residues available for energy use are the same at about 20 EJ per annum.

- The IEA does not consider aquatic sources of biomass such as macroalgae.

- On biomass supply from dedicated land, the IEA's estimate of 40 EJ/year lies much closer to our maximum potential of 55 EJ/year than to our prudent estimate of 5-10 EJ/year.

The most crucial swing factor in estimates of sustainable biomass supply is how much can be sourced from land dedicated to its production. We address this in the next section.

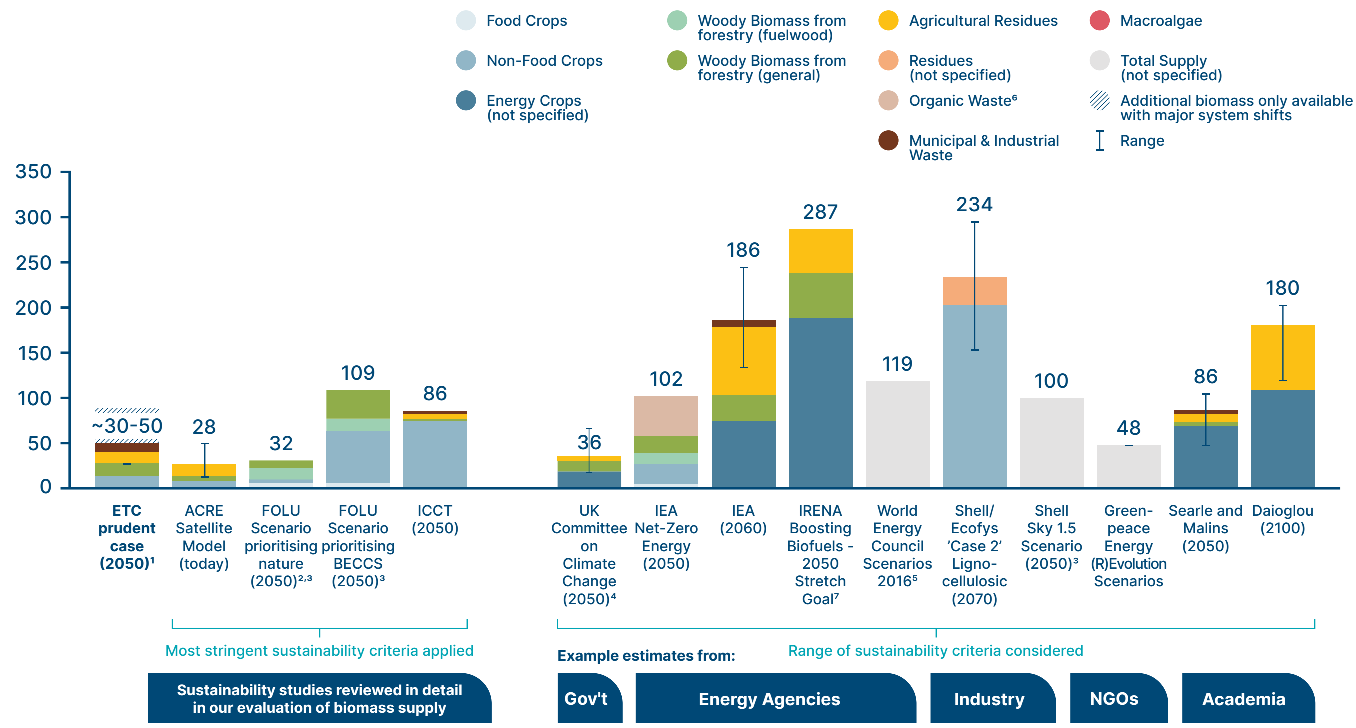
31 IEA (2021), *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.*

32 Hanssen et al. (2019), *Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models.*

Agricultural residue such as corn husks are an example of a sustainable biomass source.

ETC estimate is consistent with sustainability-focused estimates but lower than many others due to different assumptions around land use and sustainability trade-offs

Total global biomass supply (primary energy)
EJ/year



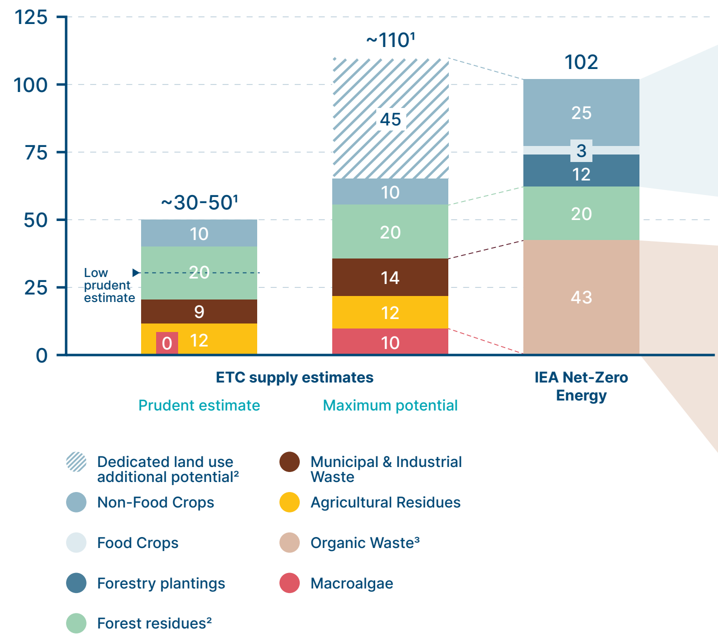
NOTES: [1] ETC estimate shows high end of prudent range, excludes ~10 EJ of woody biomass from forestry used as materials (based on current harvests from commercial forestry; may increase if forestry practices expand); dashed areas shows maximum potential from seaweed, waste and freeing up agricultural land (~60 EJ); excludes traditional fuelwood (~5-15 EJ) and biomass used in recycled materials (~4 EJ today).
[2] This scenario is effectively a 'no BECCS' scenario.
[3] Excludes traditional uses of biomass (fuelwood, charcoal and dung used in the residential sector, predominantly in developing countries).
[4] Mid scenario. Figures represent 'tradable' bioenergy feedstock suitable for international trade (e.g. forestry and energy crop feedstocks) while excluding 'non-tradable' feedstocks not suitable for long-distance trade due to low energy densities or other physical properties (e.g. biogenic waste).
[5] Unfinished Symphony Scenario.
[6] Organic waste streams include agricultural residues, food processing, and municipal and industrial organic waste streams.
[7] Recent 1.5°C Scenario from IRENA estimates primary bioenergy demand to be 153 EJ in 2050.

SOURCES: ACRE satellite model; FOLU/IIASA (2019), *Growing Better: Better Futures; ICCT – Searle et al. (2015) A reassessment of global bioenergy potential in 2050;* Deng et al. (2015), *Country-level assessment of long-term global bioenergy potential;* IEA (2017), *Technology roadmap: Delivering Sustainable Bioenergy;* IEA (2017), *Energy Technology Perspectives (and sources within);* UK Committee on Climate Change (2018), *Biomass in a low-carbon economy; Shell (2018), Sky 1.5 Scenario;* IEA (2021) *Net-Zero by 2050 - A Roadmap for the Global Energy Sector;* IRENA (2021), *World Energy Transitions Outlook.*

Exhibit 1.5

In the IEA net-zero pathway, 2050 biomass supply is weighted to waste, with dedicated biomass production closer to ETC supply if system changes freed up land for additional biomass production

2050 biomass supply for energy and industry
EJ primary biomas / year



Biomass supply from dedicated land, the IEA's estimate of 40 EJ/year lies closer to our maximum potential estimate (55 EJ/year, requiring freeing up of agricultural land and dedication to bioenergy) than to our prudent estimate of (5-10 EJ/year).

Agricultural residues and municipal and industrial waste, the IEA's estimate of 43 EJ is significantly higher than our "maximum potential" estimate of 26 EJ. IEA assumptions on organic waste (agricultural residues, food processing, and municipal and industrial biogenic waste streams) are more optimistic than our maximum potential for those combined sources (especially agricultural residues and biogenic waste collection).[4]

Exhibit 1.6

NOTES: [1] Excludes biomass from forestry for the timber and pulp & paper sectors (~10 EJ/year today + ~4 EJ/year recycled woody biomass, FAO Industrial Roundwood less by-products used for energy). Additional high-quality stemwood could be made available if freed-up land were dedicated to forestry.
[2] Significantly higher levels of biomass supply from dedicated land would only be possible if land is freed up from agricultural production through system shifts including major dietary changes, agricultural productivity improvements, and reductions in food loss and waste. These could be enabled by breakthrough biotechnologies.
[3] Organic waste streams include agricultural residues, food processing, and municipal and industrial organic waste streams.
[4] While studies of agricultural residue availability in 2050 suggest a range as high as 30 EJ/year or more from this source, those with stricter sustainability constraints (e.g., leaving 70% of agricultural residues on the land) estimate availability to be 12 EJ/year.

SOURCES: ETC (2021); IEA (2021) Net-Zero by 2050 - A Roadmap for the Global Energy Sector.

1.2 Biomass from dedicated land use: Limitations to sustainable supply

Our prudent scenario suggests that only c.5-10 EJ/year of biomass supply for use as an energy source can be sustainably sourced from dedicated land use. Additional supply of as much as c.30-45 EJ/year might be available, but only if major changes in consumer behaviour and/or technology significantly reduced the land required for animal meat production.

The competing uses of land

The Earth's land surface area is 149 million km^2 which is 14,900 million hectares or Mha. But, of this, 1,900 Mha is covered in ice or lakes (of which the majority is Antarctica and Greenland).[33] Of the other 13,000 Mha, 21% is urban, barren, and non-arable land, leaving nearly 10,200 Mha of arable and natural land. The use of this remaining arable and natural land is currently split as follows [Exhibit 1.8]:[34]

- 32% (c.3,270 Mha) for agriculture, including crop- and pastureland.
- 37% (c.3,680 Mha) for forests, (natural and managed).
- 31% (c.3,230 Mha) for natural ecosystems other than forests.

Today, cropland is concentrated in the temperate regions; most land is unavailable for cultivation

Global land cover[1]

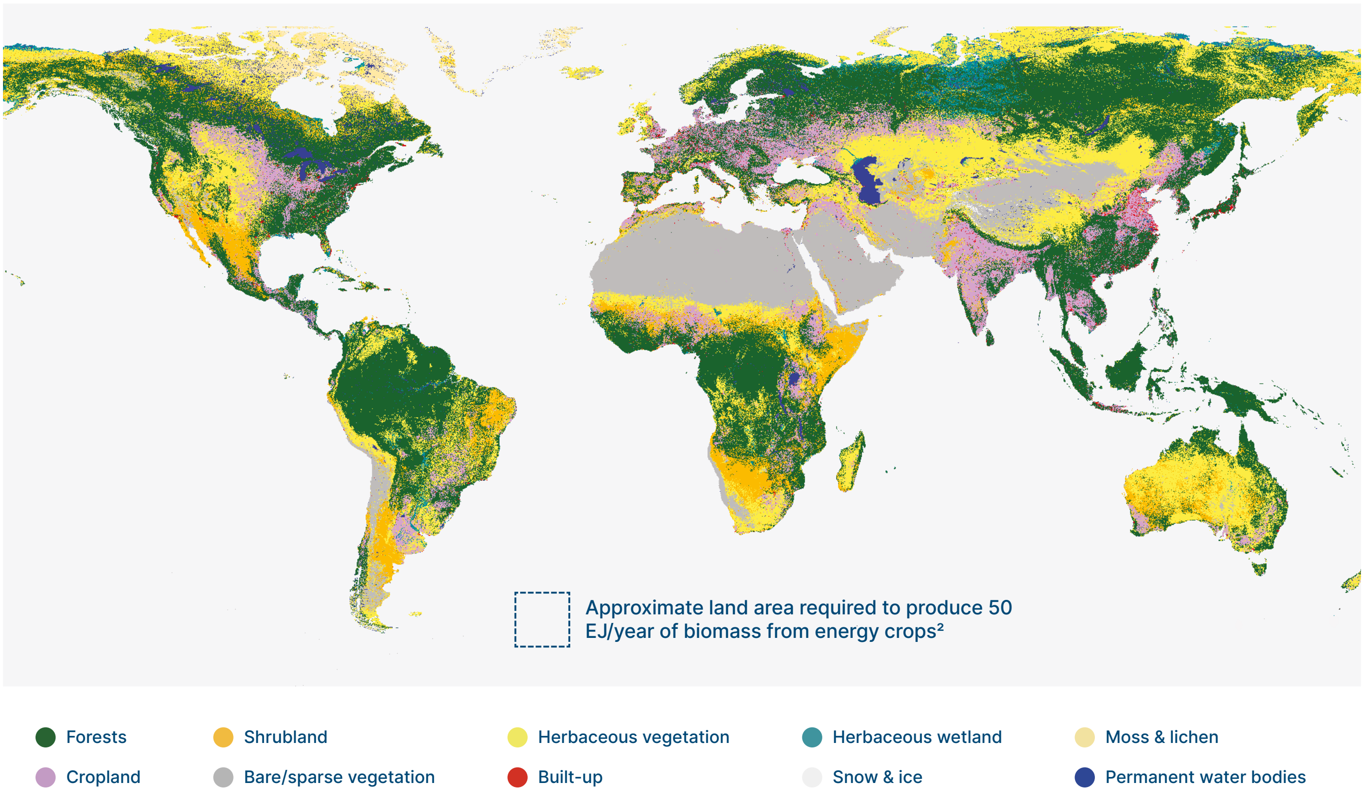


Exhibit 1.7

NOTES: [1] Map represents the main land cover type in each pixel, however, note many pixels contain different land use types (e.g., land use in Indonesia is a mix of both of forest and cultivated land. [2] Approximately 1,670 km x 1,670 km. Assumes 0.18 EJ of energy crop biomass can be produced per million hectares each year. Average of annual energy crop carbon sequestration (~6.4 tonnes of carbon (23 tCO_2) per hectare per year based on Smith et al. (2016) Biophysical and economic limits to negative CO_2 emissions) assuming biomass is ~50% carbon by mass with an approximate energy content of ~14 GJ per tonne. Note: relative size of square to geographical areas is distorted by Mercator map projection.

SOURCES: Buchhorn, M. et al. (2020). Copernicus Global Land Service: Land Cover 100m: Collection 3: epoch 2019: Globe (Version V3.0.1) [Data set]. Zenodo. DOI: 10.5281/zenodo.3939050. © Copernicus Service Information 2021.

33 Ritchie et al. (2013), *Land Use - OurWorldInData.org.*
34 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*

Under current trends, the need for agricultural land is expected to grow. A further 400 Mha or 4 million square kilometres[35] of natural ecosystems (equivalent to the size of Mexico) could be converted to crop- and pastureland to feed a growing population of a little over 9 billion people by mid-century.[36] This will likely come at the expense of forests and other natural lands, with major implications for biodiversity.

Biomass production is a land-intensive way to produce energy. This reflects the inherent inefficiency of photosynthesis, which typically converts less than 1% of solar energy into usable energy in plants, compared with solar PV which can convert more than 15% of solar energy into electricity.[37] The precise amount of land required for biomass production varies by plant type and environmental conditions, but on average about 0.18 EJ of energy crop biomass can be produced per million hectares each year;[38] to produce 50 EJ would therefore require about 280 Mha[39] or about 8% of agricultural land.[40] In addition, there may be important regional shifts in the location of arable land as agriculture adapts to a changing climate.

Exhibit 1.7 shows this area as a notional square in the context of the Earth's total area and seen against total global land area, this could seem manageable. But any expansion of biomass production from dedicated land would come at the expense of agricultural land, forests, or other natural ecosystems [Exhibit 1.8].[41] It is therefore essential to establish clear criteria for the types of land which can be used for biomass production. Applying these criteria implies that only a very limited amount of sustainable biomass can be sourced from dedicated land, unless major changes in consumer behaviour and/or technology substantially reduce the amount of land needed for food production.

Under current trends, need for crop & pasture land will continue to grow at the expense of nature

Total Global Surface Land Use (million hectares)[1]

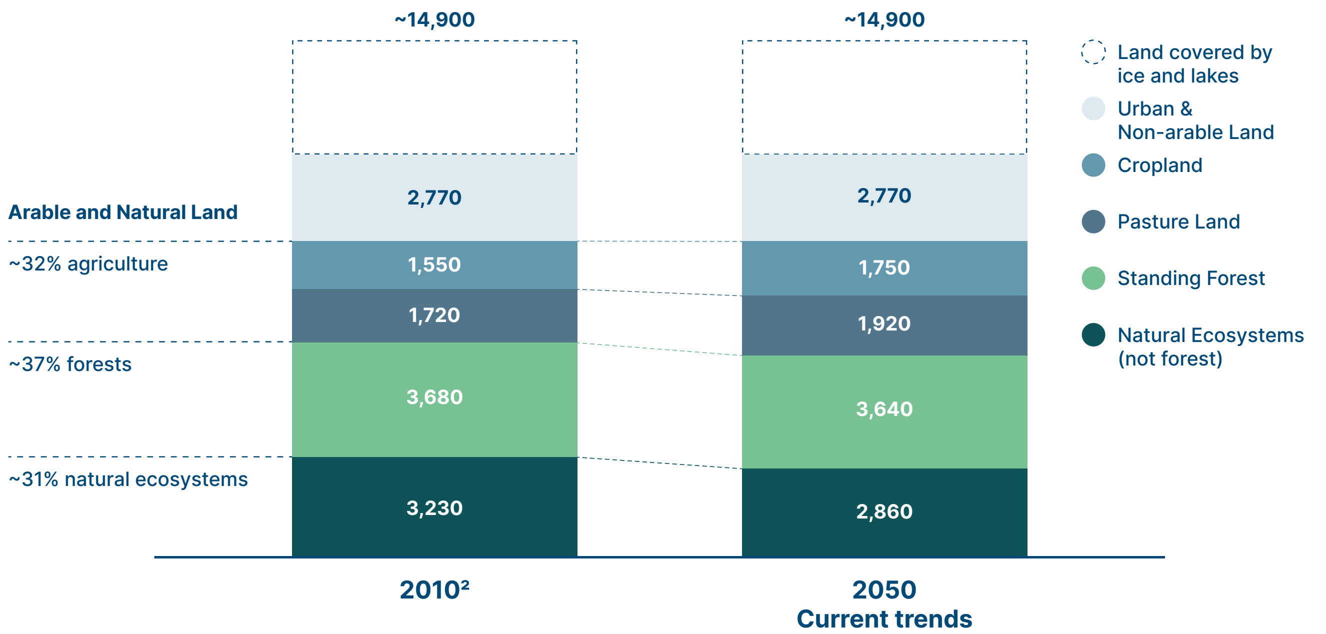


Exhibit 1.8

NOTES: [1] Global surface area excludes oceans. Land covered by lakes and ice (e.g., Antarctica) not available. Minor difference in totals and percentages due to rounding.
[2] Baseline data forecast from 2000.

SOURCES: ETC analysis interpreted from IIASA GLOBIOM / FOLU Growing Better 2019 Report; Ritchie et al. (2013), Land Use - OurWorldInData.org.

35 I.e., an area 2,000 km x 2,000 km.
36 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*
37 Blankenship, et al. (2011) *Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement*. Note: Energy efficiency of photosynthesis is defined as energy content of biomass that can be harvested divided by solar irradiance over the area with a theoretical maximum efficiency of c.12%. Photosynthesis in crop plants is ≤1% overall but during the growing season, C3 and C4 plants can reach as high as 3.5% and 4.3% efficiency, respectively.
38 Equivalent to 180 GJ/ha/year. Energy crops include miscanthus, switchgrass, willow and poplar short rotation coppice, eucalyptus, and annual crops such as sorghum. Average of annual energy crop carbon fixation (c.6.4 tonnes of carbon (23 tCO_2) per hectare per year based on Smith et al. (2016) *Biophysical and economic limits to negative CO_2 emissions*) assuming biomass is c.50% carbon by mass with an approximate energy content of c.14 GJ per tonne.
39 Roughly 1,670 km x 1,670 km, equivalent to half the size of the Amazon rainforest.
40 Assumes c.3,270 Mha devoted to agriculture based on IIASA GLOBIOM and FOLU (2019), *Growing Better.*
41 Some land use models can mitigate these trade-offs, e.g., agroforestry where tree plantings are integrated with agricultural production.

Carbon trade-offs and other considerations related to land use change

The Earth's carbon is cycled between carbon reservoirs through biological and geochemical processes. Rocks and sediments in the lithosphere contain the greatest store of carbon, but significant amounts are also held in the oceans (c.40,000 gigatonnes of carbon), the atmosphere (c.800 Gt), and terrestrial ecosystems in the forms of plants (c.550 Gt), soils (c.2,000 Gt), animals, and microorganisms.[42] Focusing on fluxes between the atmosphere and land, carbon is fixed from the atmosphere by photosynthesis, some of which is transferred to the soil (e.g., through decay of leaf litter and dead roots) and some carbon is returned to the atmosphere through respiration and decomposition of organic matter.

Over time, carbon sequestration by plants can lead to a build-up of significant carbon stocks on the land. As biomass grows, atmospheric carbon is captured and held in phytomass (living plant biomass) above and below ground (e.g., in stem and roots). Below-ground carbon makes up approximately one-third of total phytomass; the rate at which carbon is sequestered above and below ground depends on the climate and type of plant.[43] Tropical forests hold the greatest amount of phytomass carbon of any land type. Carbon sequestration above and below ground and fluxes into the soil can accumulate over time, creating large carbon stocks. Soil carbon density varies geographically – moist boreal, cool temperate, and tropical soils contain the greatest soil carbon with peat being the most important soil storage form in terms of carbon [Exhibit 1.9]. Together, these stocks are significant; the total carbon stored in soils, resulting from eons of biomass growth and carbon deposition, exceeds the amount stored in the atmosphere and in biomass.[44]

42 IPCC (2013), *AR5 Climate Change - Chapter 6: Carbon and Other Biogeochemical Cycles.*

43 Dragan et al. (2012), *Analysis of the possibilities for carbon credits generating in private forests*; Scharlemann et al. (2014), *Global soil carbon: understanding and managing the largest terrestrial carbon pool*; Mathew et al. (2017) *What crop type for atmospheric carbon sequestration: Results from a global data analysis.*

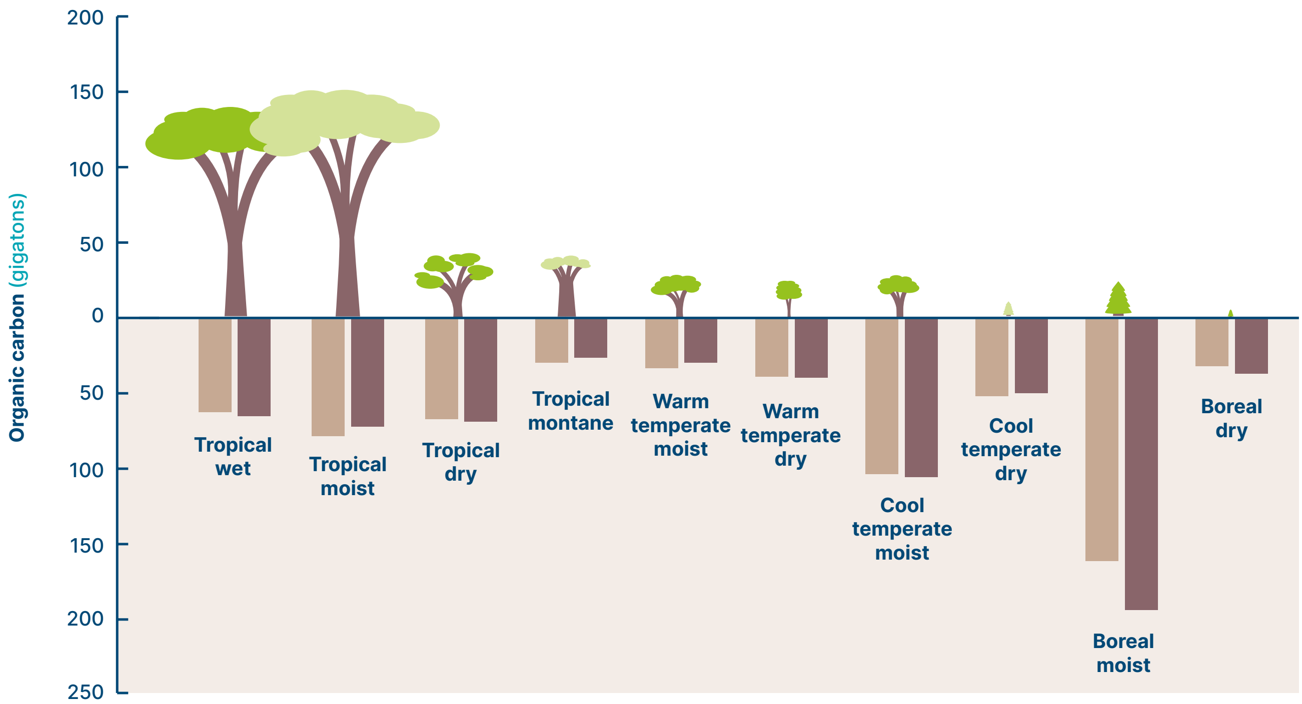
44 Scharlemann et al. (2014), *Global soil carbon: understanding and managing the largest terrestrial carbon pool.*

Tropical forest in southern Brazil.

The amount of carbon stored by ecosystems can be significant and varies geographically

Organic carbon (gigatons carbon)

Above- and below-ground plant biomass   Topsoil   Subsoil



Soil carbon density (tonnes carbon / hectare)

<5 20 75 100 150 200 300 >400 Mg C Ha^{-1}

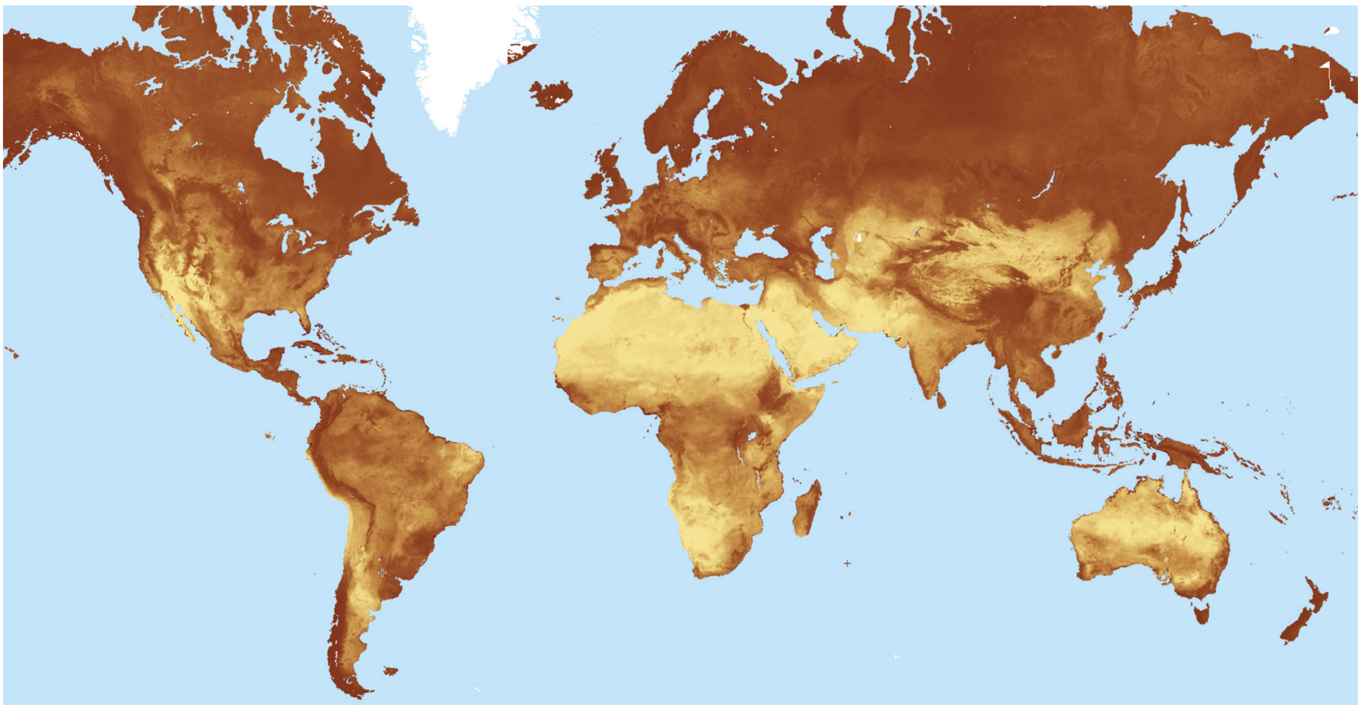


Exhibit 1.9

SOURCES: Top: Adapted with permission from Figure 2 in Janowiak et al. (2017), Considering Forest and Grassland Carbon in Land Management from United States Department of Agriculture, Forest Service. Figure designed by Kailey Marcinkowski based on data from Scharlemann J.P.W. et al. (2014), Global soil carbon: understanding and managing the largest terrestrial carbon pool. **Bottom:** World Resources Institute, ISRIC, Sanderman et al. "Soil Carbon Density." Accessed through Global Forest Watch on 3rd July 2021. www.globalforestwatch.org.

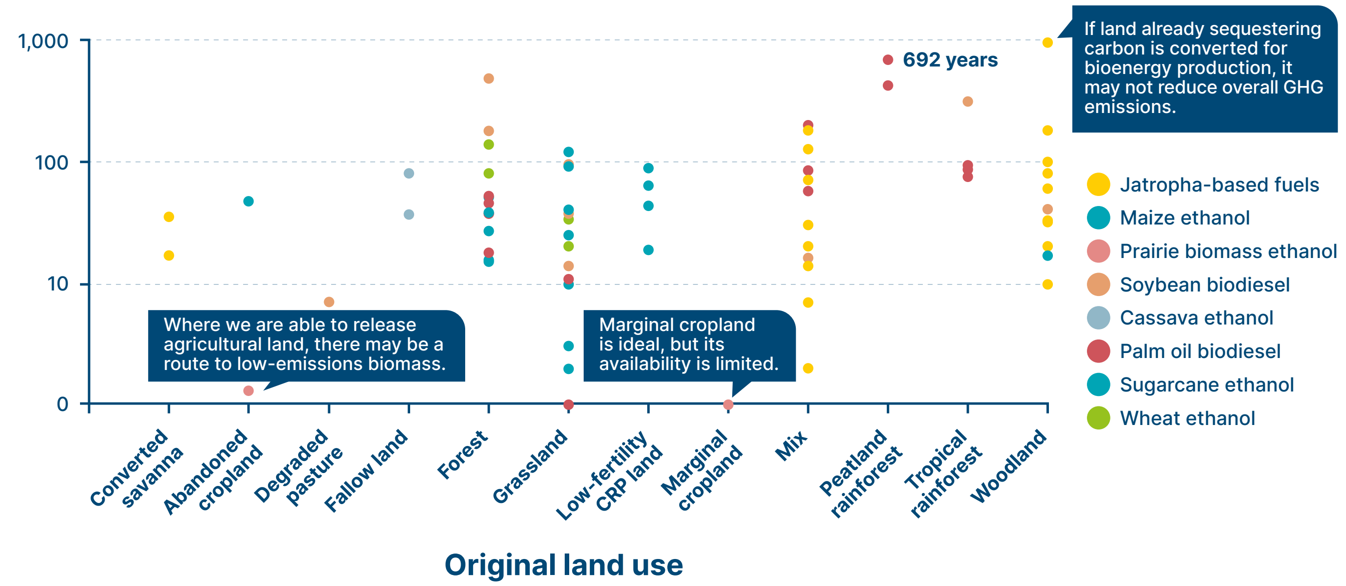
Any proposals for biomass production that require land-use change must therefore consider the impact on both existing carbon stocks and existing sequestration flows:

- Land-use change can often produce a large-scale release of existing carbon stocks: for example, an estimated 20 to 50% of soil organic carbon is lost when converting native vegetation to cropland.[45] Such one-off stock releases often dwarf the benefit of future carbon sequestration from biomass production. Transformation of high carbon stock land into plantations for biofuel production, for example, can lead to carbon payback periods of more than 300 years [Exhibit 1.10].

- In addition, future sequestration via biomass production must be compared with the sequestration which was in any case occurring. For biomass to have a low emissions footprint, it must represent additional net carbon sequestration which will not be achieved on lands that already sequester significant carbon flows.

Conversion of land with high carbon stocks leads to long carbon payback periods

Carbon debt payback period[1] (years), *biofuels example*



NOTE: GHG: greenhouse gas.
[1] Carbon debt payback periods reported were compiled by Gasparatos et al. (2017) from a range of sources in the literature.
SOURCE: Adapted from Table 1 of Gasparatos et al. (2017), *Renewable energy and biodiversity: implications for transition to a green economy.*

Exhibit 1.10

These carbon considerations inform the following principles:

- No biomass production in areas already sequestering significant carbon above and below ground in growing biomass (e.g., tropical forests). Conversion of natural forests for biomass production is counterproductive. As such, where forestry is discussed in this report, it refers only to managed forests for industrial timber.

- No biomass production on land with rich soil carbon stocks (e.g., peatlands or intact forests).

- In general, biomass production should not trigger land-use changes that will release significant carbon to the atmosphere (e.g., conversion of intact landscapes).

In addition to perturbations to carbon stocks, bio-geophysical impacts of land use change should be considered. In particular the effect of albedo modifications (i.e., the extent to which energy is reflected back from the earth's surface) can be as important as carbon balance effects.[46, 47] Where more reflective land cover is replaced with dark foliage, for example, more heat will be retained. For this reason, reforestation in the tropical belt is typically preferable to the boreal regions, and growing biomass on what was previously scrub, semi-desert, or desert land may in some circumstances not be good

45 Scharlemann et al. (2014) *Global soil carbon: understanding and managing the largest terrestrial carbon pool.*
46 Surface albedo, evapo-transpiration, emissions of biogenic volatile organic compounds, and surface roughness can affect the climate locally and globally. Cowie et al. (2020), *Applying a science- based systems perspective to dispel misconceptions about climate effects of forest bioenergy.*
47 Creutzig et al. (2015), *Bioenergy and climate change mitigation: an assessment.*

for the climate.[48] Conversely however, the far greater biodiversity richness of tropical forests is an additional reason to strongly oppose any conversion of tropical forest to bioenergy production.

Overall, these principles imply that any new biomass production should come either from existing agricultural land or land which has previously used for agriculture but has been abandoned. But use of existing agricultural land competes with food production, and while marginal and abandoned lands in general have low carbon opportunity costs, detailed analysis has suggested that the realistic potential is limited. Using such land for bioenergy crop production could in principle provide employment and income opportunities for local people, but land that initially appeared to be marginal, abandoned, or otherwise available in geospatial studies has often been found, in reality, to be already in use. In some cases, initial estimates of marginal or abandoned land have been reduced by 60 to 90% following investigation [Exhibit 1.11].[49] Complexity around land rights and ownership further complicates the issue of marginal land.

Detailed investigation of land estimated to be available for biomass production reveals many areas are already in use

Validation points sampled from a land availability map

No human impact | Medium human impact | High human impact | Very high human impact

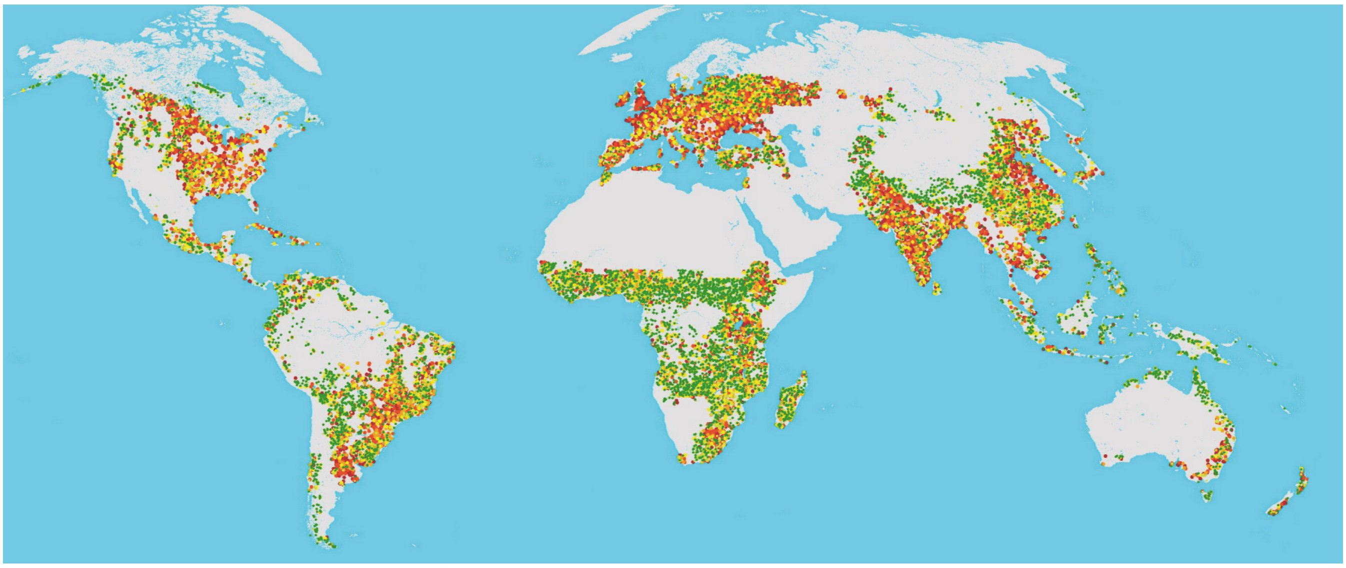


Exhibit 1.11

SOURCE: Reprinted (adapted) with permission from Fritz S, See L, van der Velde M, et al. Downgrading recent estimates of land available for biofuel production. Environ Sci Technol. 2013;47(3):1688-1694. doi:10.1021/es303141h. Copyright © 2013, American Chemical Society.

Prudent estimate of biomass supply from dedicated land

Reflecting these considerations our prudent scenario for the amount of biomass which can be extracted from dedicated land as a source of energy is 5-10 EJ per annum. This reflects the following assumptions:

- To avoid competition with food production, we allow for no 'first-generation'[50] bioenergy crops which could also be used for food.[51] Most recent studies of sustainable biomass supply similarly assume a very limited role for food crop biomass (e.g., 0 to 5 EJ/year).[52] Studies which do suggest much higher figures (e.g., up to 75 EJ/year) typically apply far less stringent biodiversity criteria and/or are driven by an assumed level of demand which must be met by some form of supply.[53] There may, however, be circumstances where food-based feedstocks are less problematic (e.g., where land is abundant on a regional basis or where sustainable production is already in place).

48 Fuss et al. (2018), *Negative emissions—Part 2 - Costs, potentials and side effects.*
49 Fritz et al. (2013). *Downgrading recent estimates of land available for biofuel production.*
50 I.e., sourced from food crops.
51 Sourcing biomass from sustainably managed forests and perennial energy crops has also been found to cause less harm to global biodiversity than use of food crops. Di Fulvio et al. (2019) *Spatially explicit LCA analysis of biodiversity losses due to different bioenergy policies in the European Union;* Calvin et al. (2021) *Bioenergy for climate change mitigation: scale and sustainability.*
52 Globally, approximately 4 EJ of energy are derived from food crops annually today. ACRE satellite model *(proprietary)*; IIASA GLOBIOM (latest GLOBIOM FOLU-scenario model outputs shared Dec 2020).
53 IIASA GLOBIOM (latest GLOBIOM FOLU-scenario outputs shared Dec 2020); ICCT: Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

- We assume that managed forests exist primarily to provide materials (e.g., timber or pulp and paper inputs), and produce c.10 EJ/year of biomass used in these material applications.[54] The 10-20 EJ/year of residues from forestry (considered further below) thus arise as by-product rather than from land dedicated specifically to biomass production.

- The 5-10 EJ/year derived from land specifically dedicated to biomass energy production therefore takes the form of non-food, lignocellulosic crops such as miscanthus or short rotation coppice.[55]

Can we free up land for carbon mitigation?

Significantly higher levels of biomass supply from dedicated land would only be possible if land is freed up from agricultural production. Four factors might make that possible, presented in order of potential impact:[56]

- **Dietary shift** at a global scale could have a major impact but depend on inherently unpredictable consumer behaviour.[57] The production of food from animals is extremely resource inefficient. Livestock farming uses three-fifths of the world's agricultural land but produces less than one-fifth of global food calories.[58] Dietary shifts away from livestock products could therefore improve land use efficiency in the food system. Modelling by the UK's Committee on Climate Change (UK CCC) shows that a 35% reduction in consumption of meat and 20% reduction in dairy consumption by 2050 (substituted by plant-based products) could release nearly 4.5 million hectares of UK land by 2050, around one sixth of the total land area [Exhibit 1.12].[59] Modelling by IIASA/FOLU shows that if global diets converged to a pattern compatible with good human health and within planetary boundaries, European consumption of meat and dairy would have to fall by 65% per capita.[60]

- **Productivity improvements:** Better agronomic practices could increase crop yields without requiring additional fertiliser and pesticides. Increasing stocking rates for livestock could also increase productivity per hectare through techniques such as rotational grazing. IIASA/FOLU modelling suggests that a combination of measures could deliver a 56% increase on average global yields by 2050 (versus 2010), compared with a likely 44% increase on historic trends. Additionally, marine aquaculture could nearly double by 2050 and require 50% less fishmeal relative to 2020.[61] Opportunities to increase land productivity through microalgae are discussed in Section 1.4.

- **Reductions in food loss and waste,** which are significant across the value chain from production to end use. In the UK CCC's Balanced Pathway to Net Zero, food waste in the supply chain is reduced by 60% by mid-century.[62] IIASA/FOLU modelling includes a 25% reduction of food loss compared to current trends by 2050.[63]

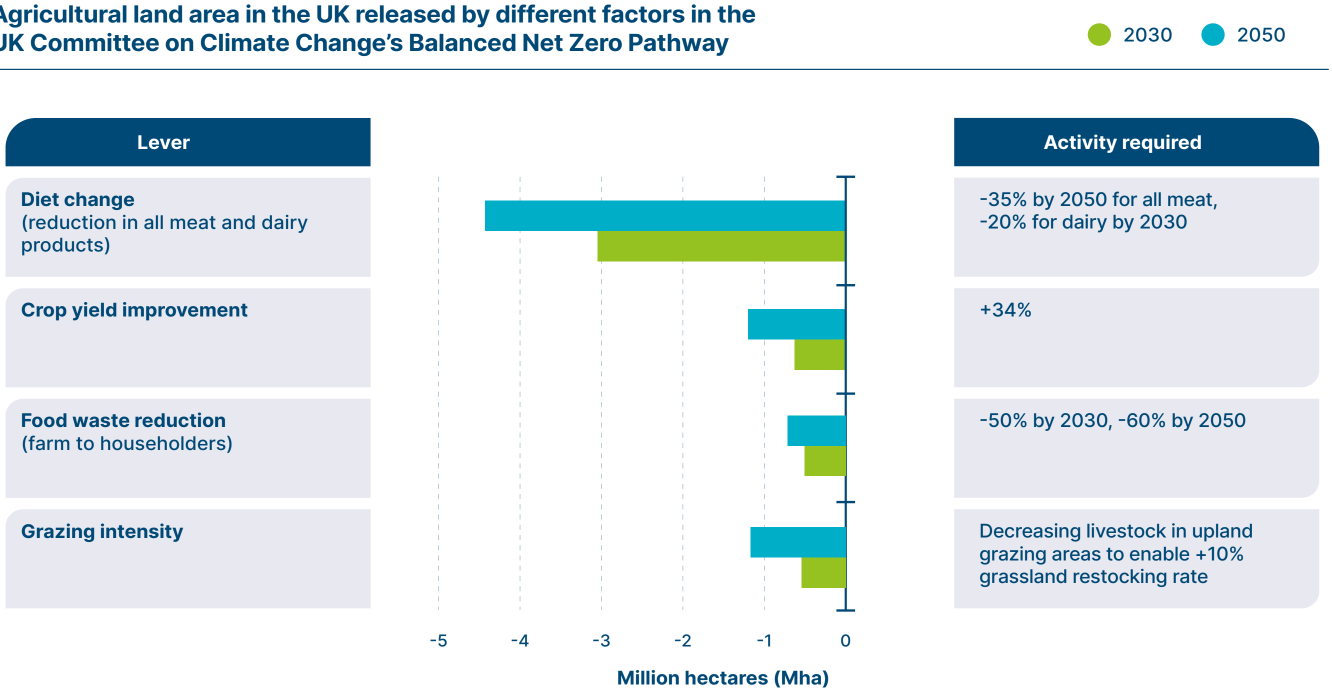
- **Breakthrough biotechnologies:** Genetic engineering breakthroughs such as CRISPR technologies and gene drives have dramatically improved the speed and accuracy of DNA modification, allowing us to engineer plant and animal species that are safe to consume while being more resource efficient. In particular, precision fermentation techniques could make possible synthetic milks and cultured meats whose production requires one tenth as much cropland as the animal alternatives they replace. Ambitious estimates suggest that land needs for cattle pasture, rangeland, and feed cropland could halve by as early as 2040. Even if the technologies take longer to become commercial, a significant impact is likely at some stage.[64]

Combining ambitious assumptions along each of the first three dimensions (which might be enabled by breakthrough biotechnologies), the IIASA/FOLU modelling suggests that, compared with the current trends, pastureland could reduce by 67% and cropland (much of which is used to provide livestock feed) by 25%. This could free up a maximum of 1,310 Mha of land of which 1,050 Mha (c.10 million km^2) could be suitable for managed forests and/or energy crops [Exhibit 1.13].[65, 66]

54 This figure could increase if forestry practices are expanded. The estimate of c.10 EJ/year is based on FAO industrial roundwood figures (after removing by-products used for energy). An additional c.4 EJ/year of recycled woody biomass is estimated to be available for materials uses. Woody biomass allocations are based on categorisation by IIASA.
55 Based on IIASA GLOBIOM FOLU-scenario modelling, this is likely to occupy approximately 30-55 Mha in 2050.
56 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*
57 Figure 7.7 of UK Committee on Climate Change (UK CCC) (2020), *The Sixth Carbon Budget - Methodology Report.*
58 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*
59 Figure 7.7 of UK Committee on Climate Change (UK CCC) (2020), *The Sixth Carbon Budget - Methodology Report.*
60 The Lancet (2019), *Food in the Anthropocene: The EAT Lancet Commission on Healthy Diets from Sustainable Food Systems.*
61 Based on analysis of cost potentials of aquaculture by UCSB; emLab UCSB (2019), *Estimating the Ocean's True Potential for Feeding the Planet*
62 UK CCC (2020), *The Sixth Carbon Budget.*
63 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*
64 RethinkX (2019). *Rethinking Food and Agriculture 2020-2030.*
65 Note: only a fraction of that land, if available, might be used as such.
66 Note: The 'available land' category of Exhibit 1.13 was not discretely identified in GLOBIOM. Where land is made available, GLOBIOM reallocates it to forestry or natural landscapes depending on the demand for biomass and sequestration needed to achieve climate targets. The 'available land' category presented represents an ETC evaluation of potential scenarios for how land could theoretically be re-allocated.

Diet change has the biggest potential to increase land availability

Agricultural land area in the UK released by different factors in the UK Committee on Climate Change's Balanced Net Zero Pathway



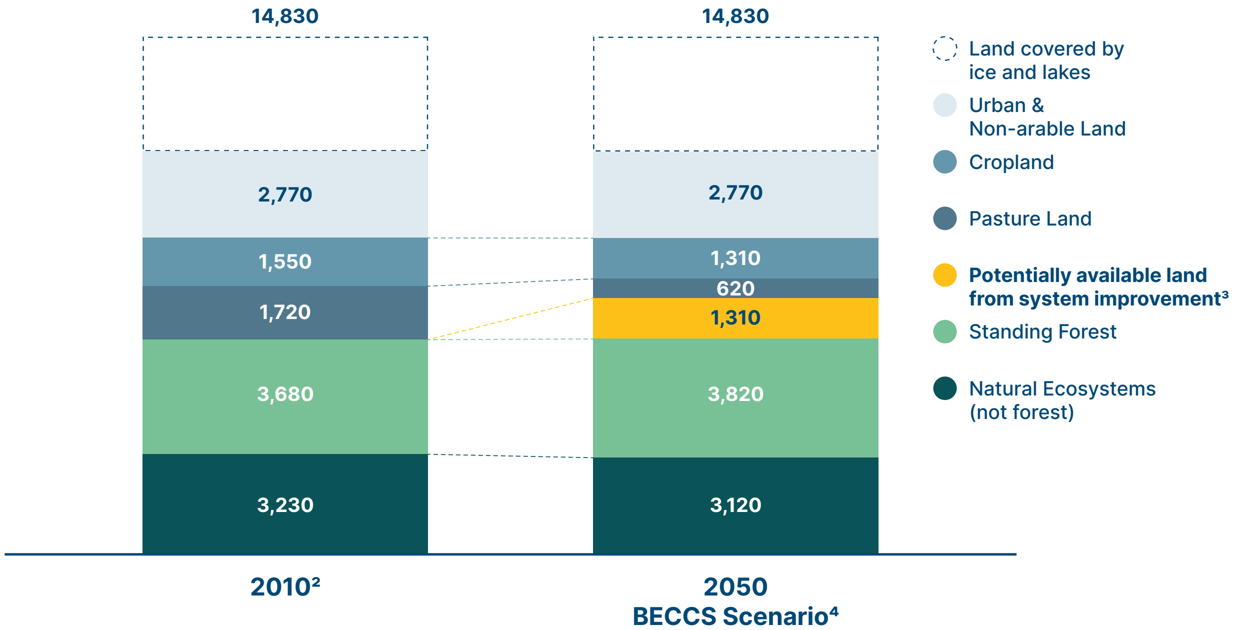
NOTE: A negative number indicates land is released.

SOURCE: Figure 7.7 of UK Committee on Climate Change (UK CCC) (2020), The Sixth Carbon Budget - Methodology Report.

Exhibit 1.12

Dietary shifts, agricultural improvements, and food waste reduction might free up >1B hectares globally

Total Global Surface Land Use (million hectares)[1]



NOTES: [1] Global surface area excludes oceans. Land covered by lakes and ice (e.g., Antarctica) also unavailable.
[2] Baseline data forecast from 2000.
[3] Of which a maximum of 1,050 Mha is likely to be suitable for managed forests and/or energy crops, though only a fraction of this potential might be used as such.
[4] Unpublished scenario from FOLU/IIASA (2019), *Growing Better*.

SOURCE: Adapted from IIASA GLOBIOM / FOLU (2019), *Growing Better: 10 critical transitions to transform food and land use.*

Exhibit 1.13

If such significant land did become available, the crucial question would be how best to use it and whether a significant proportion should be devoted to bioenergy production.[67] **Three scenarios** help illustrate the range of possibilities and their relative merits [Exhibit 1.14].

- **Return all released agricultural land to nature**. This would maximise the biodiversity benefit and would result in significant carbon sequestration but would not provide a source of either biomass for use either as a material or energy source.[68]

- **Additional managed forestry**. Dedicating 800 Mha of released land to managed forests (with the other 200 Mha returned to nature) could generate about 45-50 EJ/year of additional biomass of which about 18 EJ/year might be best used for materials with about 30 EJ/year of woody biomass residues available for energy use.[69] However, as it takes time for trees to reach maturity, this supply upside may not be available until mid-century. The trees would sequester atmospheric carbon during their growth, after which a stable carbon stock could be maintained through rotation forestry [Box C]. Compared to leaving land for nature, forestry has negative effects on biodiversity [Exhibit 1.15] but steps can be taken to mitigate the harm [Box D].

- **Additional energy crop plantations**. In this scenario we assume that 250 Mha would be dedicated to energy crop plantations, with the other 750 Mha returned to nature. This could yield as much biomass by energy content (about 45 EJ/year)[70] as 800 Mha devoted to forestry, with all of that biomass used for energy production, rather than as materials. If combined with CCS it could also, as Chapter 3 will discuss, have the greatest carbon sequestration impact, sequestering significant biomass each year and with harvests every year or every few years. But within the area used for biomass production this could have the most detrimental impact on biodiversity, which is substantially reduced in mono-crop energy plantation landscapes.[71,72]

67 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*

68 The relative biodiversity benefits will be greater in locations in close proximity to existing biodiversity hotspots. Our prudent supply estimate does not rely on additional land availability.

69 Assumes woody biomass energy density of 0.0072 EJ/m^3 and total forestry yield of c.8-9 m^3/ha/year of which c.5 m^3/ha/year are residues based on Lauri et al. (2014) and ETC analysis.

70 In addition to reasonable estimate of c.5-10 EJ/year in 2050 from energy crops. Assumes 250 Mha of land producing 180 GJ of biomass per hectare per year from energy crops sequestering c.6.4 tonnes of carbon (23 tCO_2) per hectare per year based on Smith et al. (2016) *Biophysical and economic limits to negative CO_2 emissions.*

71 Biggs et al. (2005). *A biodiversity intactness index.*

72 Thus, intensive energy crop plantations are best suited where land is in an area less relevant for nature (e.g., isolated or far from natural landscapes). Alternatively, less intensive options include the integration of energy crops into agriculture landscapes to ameliorate ecosystem impacts. Depending on the state of land at the point of conversion, cultivation could provide some benefits to biodiversity, e.g., the cultivation of energy-crops to formerly degraded land provides vegetation; however, benefits to biodiversity will be smaller than other alternatives considered (e.g., returning land to nature or managed forestry).

One key trade-off to be considered, if land were available, would therefore be whether:

- **To focus bioenergy production on intensive cultivation of energy crops** (or fast-growing timber plantations) which, because they have high land (yield) efficiencies, would enable significant bioenergy production, accepting the negative impact on biodiversity and ecosystems on the land used for cultivation. However, efficient, intensive cultivation of low-quality land can enable other land within a system to be left to return to nature, potentially providing biodiversity benefits at the overall system level.

- **To focus on managed forestry**, which is less land efficient, producing a more limited harvest for materials and residues for energy and with longer growth periods before harvest. However, managed forests can support greater biodiversity than intensive energy crop plantations (while still far less so than natural forests) and tend to be more multifunctional.[73]

- **To afforest available land with the intention of leaving it to nature but recognising the option of harvesting this biomass in the future** should lack of progress on decarbonisation require it (e.g., for additional supply of biomass). As supply of low lifecycle emissions biomass would be delayed by decades regardless, to allow trees to mature, so this option has the advantage of postponing critical biodiversity trade-offs while sequestering carbon in the meanwhile.

Chapter 3 looks in detail at the relative carbon sequestration achieved by the different options over time. But for the purposes of our 'maximum potential scenario', we assume that up to about 45 EJ/year of additional biomass supply for use as an energy source could be available, if, but only if, significant land was released from agriculture (e.g., as a result of a significant fall in animal meat production).

If more land is made available due to dietary and other shifts, it can either be returned to nature or used to produce biomass at the expense of biodiversity

Alternative illustrative scenarios for how to use ~1 billion ha of land no longer required for crop and pasture due to dietary and other shifts:

	Return to nature	More managed forestry	More energy crops
	~1,000 Mha to nature	~200 Mha to nature + ~800 Mha to managed forests	~750 Mha to nature + ~250 Mha to energy crop plantations
Outcome:			
EJ of useful energy	No change to current supply estimates	Additional woody biomass supply from 2050[1] of ~30 EJ/year forestry residues + ~18 EJ/year materials[2]	Additional biomass supply from dedicated land of ~45[3] EJ/year
Biodiversity	Large amount of land returned to nature, with high biodiversity return	Less biodiversity on managed land	Minimal biodiversity on managed land, but large area returned to nature
Carbon sequestration	High levels of carbon sequestration in growth period; eventually plateaus	High levels of carbon sequestration in growth period; eventually plateaus	Ability to plant fast-growing (high sequestration) crops and replace year-on-year
		Use of biomass will also affect carbon in atmosphere (e.g., BECCS will sequester carbon while use for energy without carbon storage will be ~net zero emissions)	

Exhibit 1.14

NOTES: [1] Depending on length of time required for newly planted trees to reach maturity. Assumes woody biomass energy density of 0.0072 EJ/m^3 and total forestry yield of ~8-9 m^3/ha/year of which ~5 m^3/ha/year are residues.
[2] In addition to the 2050 reasonable estimate of ~10-20 EJ/year residues + 14 EJ/year materials from forestry (~10 EJ/year stemwood production + ~4 EJ/year recycled woody biomass).
[3] In addition to reasonable estimate of ~5-10 EJ/year in 2050 from energy crops. Assumes 250 M ha of land producing 180 GJ of biomass per hectare per year from energy crops sequestering ~6.4 tonnes of carbon (23 tCO_2) per hectare per year.

SOURCES: ETC analysis interpreted from IIASA GLOBIOM / FOLU (2019), *Growing Better*; Smith, P. et al. (2016) *Biophysical and economic limits to negative CO_2 emissions.*

73 Calvin et al. (2021), *Bioenergy for climate change mitigation: scale and sustainability.*

Intensive land management for biomass production has a negative impact on biodiversity

Change in Biodiversity Indicator Index from 2010 (%)

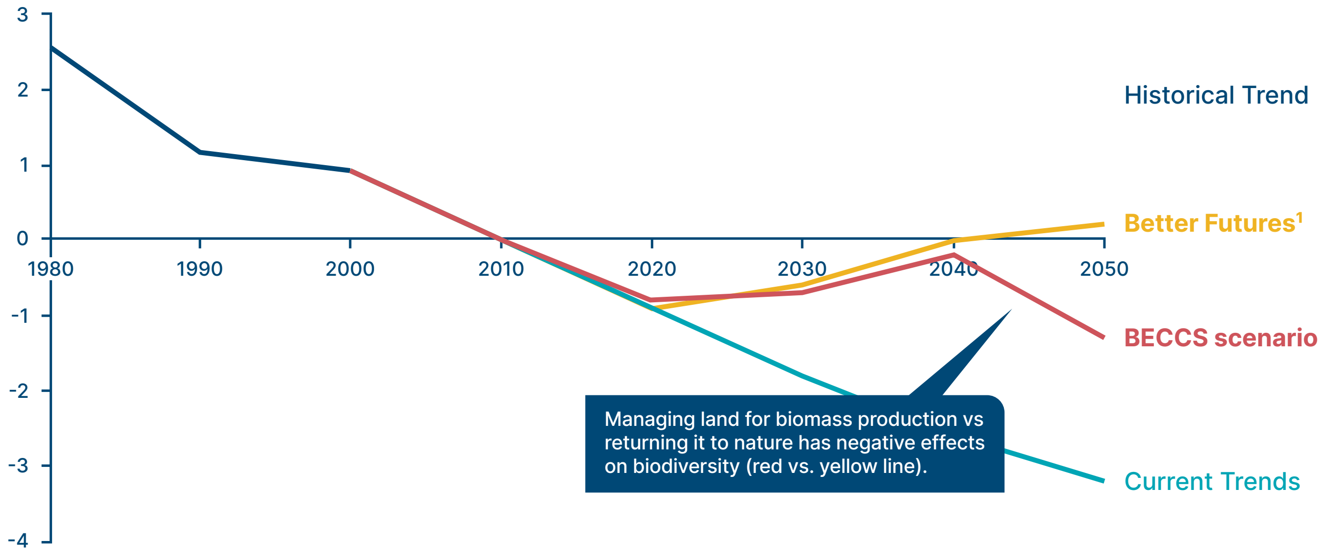


Exhibit 1.15

[1] Refers to the Better Futures scenario in the FOLU Growing Better 2019 report.

SOURCES: Food and Land Use Coalition (FOLU) *Growing Better* 2019 Report. IIASA GLOBIOM 2019; Leclère et al. (2018) for historical reconstruction; Bernes et al. (2015), *What is the impact of active management on biodiversity in boreal and temperate forests set aside for conservation or restoration?*

Miscanthus gigantaeus is a fast-growing, lignocellulosic energy crop

1.3 Biomass from waste and residual sources: The biggest potential sustainable supply

Given the constraints on land availability discussed above, the majority of sustainable, low lifecycle emissions biomass supply derives from waste and residual sources that do not require direct use of land. In our prudent scenario, we estimate that these sources could supply approximately 20-40 EJ/year of sustainable biomass globally in 2050.[74] For each of the sources, there are important sustainability criteria [Exhibit 1.16].

Each waste and residue source has its own sustainability considerations

	Potential sources	Key considerations
Waste & residues	**Woody biomass from forestry**	• Less than half of managed forest harvests are used for materials (e.g. timber), **main output is low quality 'fuel wood'** (currently used for heat) which could be reprioritised, alongside residues from forest management and industrial processing. • Sustainable forest management **reduces biodiversity levels** compared to natural land, but good practice can improve biodiversity levels on former agricultural land. • An industrially managed commercial forest can **hold a stable carbon stock while generating an on-going supply of biomass.** • **Supply of biomass** from new managed forests is **delayed** while trees grow.
	Agricultural residues	• Supply of residues depends on the **amount of agricultural land and types of crops.** • Significant fraction (~70%) of **residues must be left on the land** for soil health. • Today ~10% of residues are used for **animal feed and bedding**.
	Municipal & industrial waste	• **Mix of sources:** - Municipal waste is composed of **biogenic (e.g., food, paper)** and **non-biogenic (e.g., plastic, rubber)** waste, generally intermixed. - **Waste oils/fats and livestock manure** are also separately collected from industry. - **Biogas** from anaerobic digestion of manure, organic municipal waste, crop residues, & wastewater sludge. • Priority to **develop a circular economy and minimise waste.** • **Comprehensive waste collection often lacking** and **difficult to separate organics** from high-carbon products (e.g. plastics) in mixed waste streams. • **Waste oils and manure are valuable**, sustainable biomass sources but scale is limited.

Exhibit 1.16

SOURCE: ETC (2021); *UK Committee on Climate Change (2018)*, *Biomass in a low-carbon economy*; International Renewable Energy Agency (IRENA) (2019), *Bioenergy from boreal forests: Swedish approach to sustainable wood use*; IIASA analysis of forestry data from FAOSTAT (2010, 2018); IIASA GLOBIOM; Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

74 Excludes traditional uses of woody biomass (e.g., gathered firewood).

Corn cobs are an example of residual biomass from agricultural production.

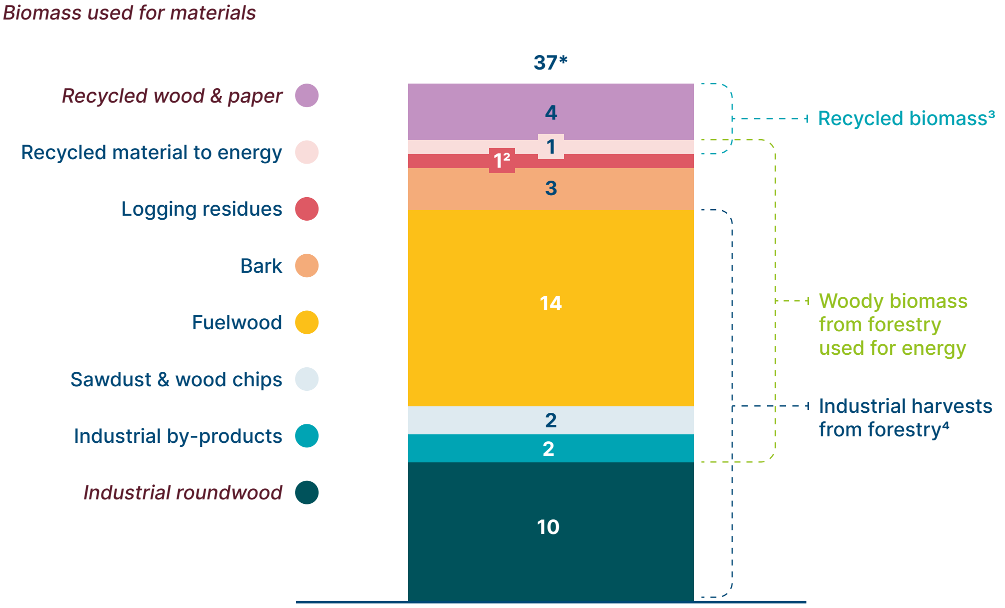
1.3.1 Woody biomass from forestry: a significant potential requiring appropriate management

Trees can be a key source of sustainable biomass for both materials and energy and can also play a pivotal role in climate mitigation. The primary use of land for managed forestry should be for dedicated materials production. Residues from these industrially managed forests can provide a significant source of sustainable biomass for energy, however, extraction needs to be carefully managed. For the carbon balance and biodiversity issues discussed, conversion of natural forests for biomass production is counterproductive; here we discuss managed forests for timber production where the principles of sustainable forestry apply. The overall advantages and disadvantages of forest management are debated and are likely to vary with forest type, management, and context.

About 10 EJ of woody biomass produced each year from managed forests is currently used for materials – whether as timber or converted to pulp and paper – and use of woody biomass for material production can also act as a mechanism of carbon storage when used in long-life products. However, this only accounts for one third of the biomass harvested from managed forests.[75] The largest managed forest output is low-quality 'fuel wood.' This is primarily used for process heat by the timber and wood products industries, or as firewood for building heating [Exhibit 1.17]. These outputs could potentially be reprioritised to other uses or combined with carbon capture and storage for carbon removal via BECCS (see Chapter 3).

Managed forests sequester carbon whilst also producing a stream of biomass which can be used for materials or energy

Total Managed Use of Forest Biomass 2018
EJ year



*A significant volume of additional forest material (~25 EJ/year)[1] is informally gathered for **traditional uses of biomass** (fuelwood, charcoal and dung used in the residential sector, predominantly in developing countries) today. This is expected to decrease substantially with modernisation.

Exhibit 1.17

NOTES: [1] Traditional uses of biomass are not reported, but are estimated by the IEA to account for approximately ~25 EJ/year of primary biomass energy today.
[2] Logging Residue estimate calculated based on demand in 2018, has potential to be greater.
[3] 'Double counted' due to cascading use.
[4] Refers to total roundwood under bark as reported by FAOSTAT.

SOURCE: FAOSTAT (2010, 2018); IIASA GLOBIOM; IEA (2021) *Net-Zero by 2050 - A Roadmap for the Global Energy Sector*.

75 Based on IIASA/GLOBIOM estimates and FAOSTAT (2010, 2018).

In addition, it is possible to harvest managed forest residues. These include 'primary residues' such as treetops, branches, and stumps from timber harvests and 'secondary residues' such as sawdust, bark, and scrap-wood that are produced during the processing of woody biomass. For highly managed, high-yielding forests, thinning is a common practice that serves to maximize the production and harvest of merchantable wood. Today most thinned material is used, typically for pulpwood, but some may be left in forests and contribute to residues, which could be harvested and supply additional biomass for priority uses. If agricultural land is spared in our 'system change' scenario through dietary change and agricultural productivity gains, thinnings of new managed forests may be a good source of additional biomass for materials.

Both overall forest management and the harvest of residues must take into account important sustainability limits:

- **Carbon balance**: As discussed above, given the substantial amount of carbon that is stored in soils and in living plant biomass, pristine forests and other landscapes with significant carbon stocks should not be converted. In addition to the lifecycle carbon footprint, the opportunity cost of harvesting the land must be considered. In the managed forestry context, this opportunity cost can be minimised by respecting the time required for trees to grow to maturity before harvesting them.[76] To conserve carbon stocks, only biomass harvests equivalent to or less than new growth can be considered [Box C].

- **Land/ecosystem health:** Land and ecosystem health considerations also mean that a proportion of managed forest residues need to be left to maintain soil organic carbon levels and topsoil depth, and steep areas should be excluded due to risk of erosion.

- **Biodiversity**: Harvesting of woody biomass in protected forests and other areas of ecological importance should be excluded to safeguard biodiversity. Where land is used for managed forestry, there are steps that can be taken to reduce the impacts of this activity on biodiversity such as avoiding monocultures, favouring native species, and leaving areas of the managed forest intact [Box D].[77] However, compared to leaving land to nature, forest management will inevitably have some adverse impacts on biodiversity levels. It is also important to define carefully what types of residues can be removed and where removal is necessary to mitigate fire risks. Harvesting of residual forest biomass has been shown to decrease population sizes of common forest species (while rare forest species are most sensitive to clearcutting of the forest rather than harvesting of logging residues). But of those residues, coarse dead wood such as stumps are more valuable for biodiversity than other residue types (i.e., branches and tops removed in thinning operations), suggesting that sustainable residue harvest should focus on the latter.[78]

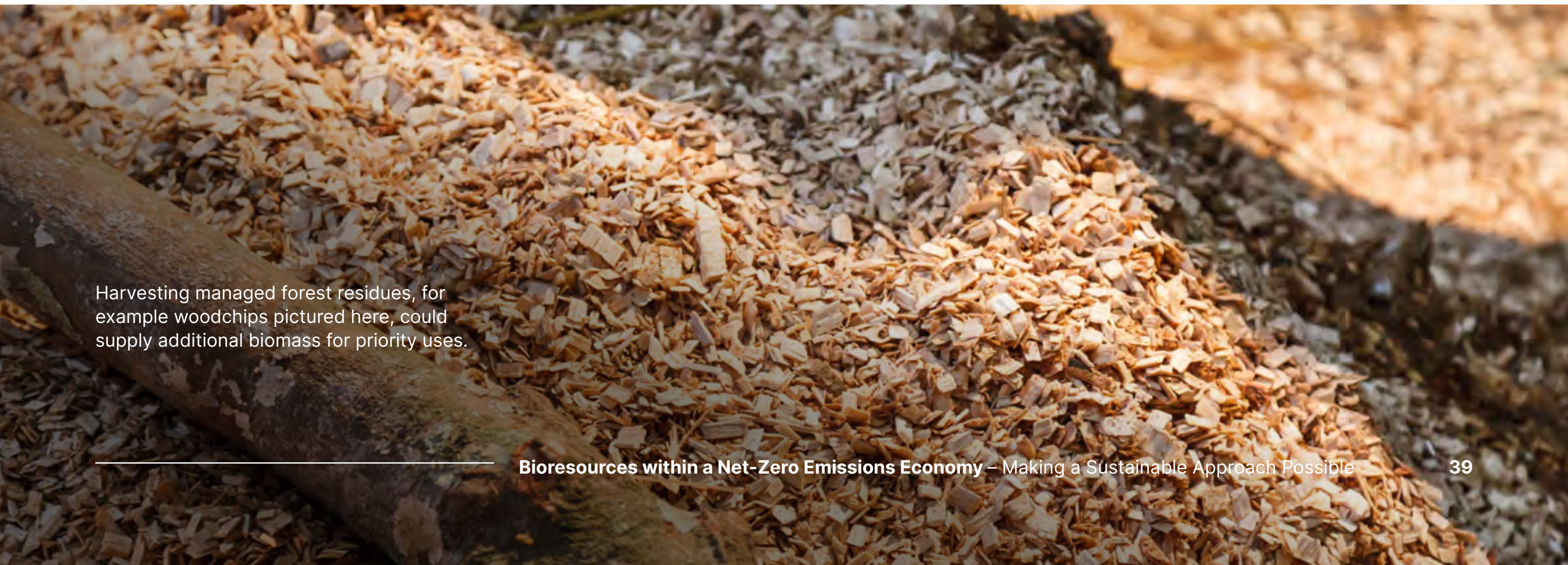
These considerations will become increasingly important as growing biomass demand drives up prices. Favourable economics are likely to result in greater residue extraction from managed forests. Some of this may simply represent exploitation of sustainable biomass that was previously uneconomic, but clear public and corporate policies will be essential to minimise the risk of exceeding sustainable levels of residue collection. In some regions, additional residual woody biomass supply may also come from management of forests for fire and pest prevention.

Our prudent scenario estimate suggests that by mid-century c.10-20 EJ/year of residues could be collected from managed forests. This would be in addition to the c.10 EJ/year of primary biomass for materials currently derived from forestry. Any additional managed forest areas in future would further contribute as would increased growth rates in production forests that reduce rotation age and increase production per hectare.

76 However, as the focus of managed forestry is on materials production, the timings of harvests will also take into account the physical properties of the timber (shape / form) which change as trees mature.

77 As with energy crops, the biodiversity outcomes of less intensive land use should be weighed against the potential for highly productive monoculture plantations to utilise less land and potentially leave available more land for restoration to nature. The location of the land in question (e.g., near or far from existing natural areas) is highly relevant in evaluating this trade-off.

78 Berndes et al. (2016), *Forest biomass, carbon neutrality and climate change mitigation*. From Science to Policy - European Forest Institute.



Harvesting managed forest residues, for example woodchips pictured here, could supply additional biomass for priority uses.

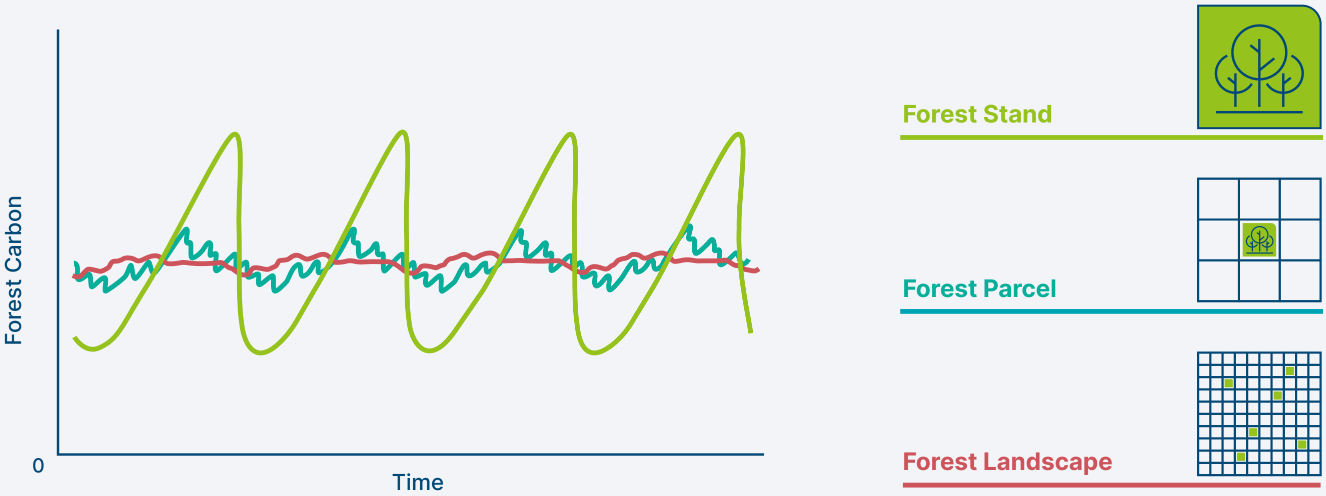
Implications of forest management on carbon balance

Forest management can be a means of increasing the supply of wood on the land managed while also maintaining a store of carbon. An uneven-aged managed forest is made of a series of stands planted and harvested sequentially. The carbon balance of a single stand in a managed forest changes dramatically over time as carbon is sequestered and stored within the stand, and then harvested and lost from the stand. The average carbon balance over a mature, managed forest landscape (collection of stands) can be maintained at a stable level by only harvesting biomass equivalent to new growth of managed forest, i.e., a small number of stands each year [Exhibit 1.18]. Thus, once an area of forest is established, harvesting different stands sequentially can result in a continuous supply of wood while maintaining a level of carbon that represents the carbon stored at the average age of the different trees. The age at which trees reach maturity varies by climate/geography and species from as few as seven years to well over a century [Exhibit 1.19].

Managed forests are designed to increase growth per year of merchantable wood but are also typically harvested at a younger age. As a result, managed forests will tend to supply more wood but store less carbon than unmanaged forests, which are either harvested at a later age or not harvested at all. By supplying more wood per year on average, management can contribute to reducing the pressure to harvest from unmanaged forests and, in that way, contribute to additional carbon storage. But managed forests will typically themselves store less carbon and provide less biodiversity. The overall advantages and disadvantages of forest management are debated but also are likely to vary with forest type, management, and context.

Box C

Managed forests can maintain a stable carbon stock alongside a regular supply of biomass if stands within the forest are harvested in rotation



SOURCE: Adapted with permission from Figure 8 in Janowiak et al. (2017), *Considering Forest and Grassland Carbon in Land Management* from United States Department of Agriculture, Forest Service. Figure designed by Kailey Marcinkowski, adapted from Bowyer et al. (2012) Carbon 101: Understanding the carbon cycle and the forest carbon debate, and McKinley et al. (2011) *A synthesis of current knowledge on forests and carbon storage in the United States.*

Exhibit 1.18

If mature trees that have sequestered carbon are harvested, they can provide products or geological storage – but growth period delays supply

Example of forest management rotation where mature trees are harvested and replaced with new saplings.

Managed forest type	Region	Rotation length[1] (years) = ~ time to maturity
Eucalyptus	South America	7
Loblolly pine	South-eastern USA	20 (max growth rate) to 40[2]
Nordic boreal	Southern Sweden	70-90
Nordic boreal	Northern Sweden	120-150

It takes time for trees to reach maturity, thus the potential **supply of low lifecycle emissions biomass from forestry may be delayed by decades** after planting.[3]

[1] The time period from planting to harvest is called a rotation. [2] Carbon uptake in these forests peaks at 20 years, but unharvested stands have higher biomass for 40-100 years; so, rotation lengths of less than 40 years can transfer carbon from biomass to the atmosphere. [3] Refers to the main harvesting event; in a managed forest, one may choose to thin a forest stand 2-3 times during the rotation period to optimize timber production, which will also yield a modest supply of biomass before the stand reaches maturity.

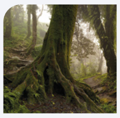
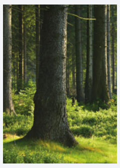
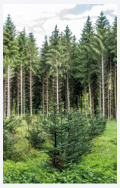
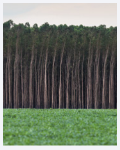
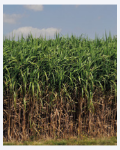
SOURCES: International Renewable Energy Agency (IRENA) (2019), *Bioenergy from boreal forests: Swedish approach to sustainable wood use*; Ter-Mikaelian et al. (2015), *The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting*; Schlesinger (2018), *Are wood pellets a green fuel?; Sveaskog (2021), Forestry the Swedish Way: Brief facts 6 - If Swedish forestry did not exist.*

Exhibit 1.19

Ecological impacts of forest management

The ecological impacts of forest management depend on the region and type of forest as well as the systems of management used [Exhibit 1.20]. In general, management optimising for industrial output is inversely correlated with minimisation of ecological impacts, implying a trade-off.

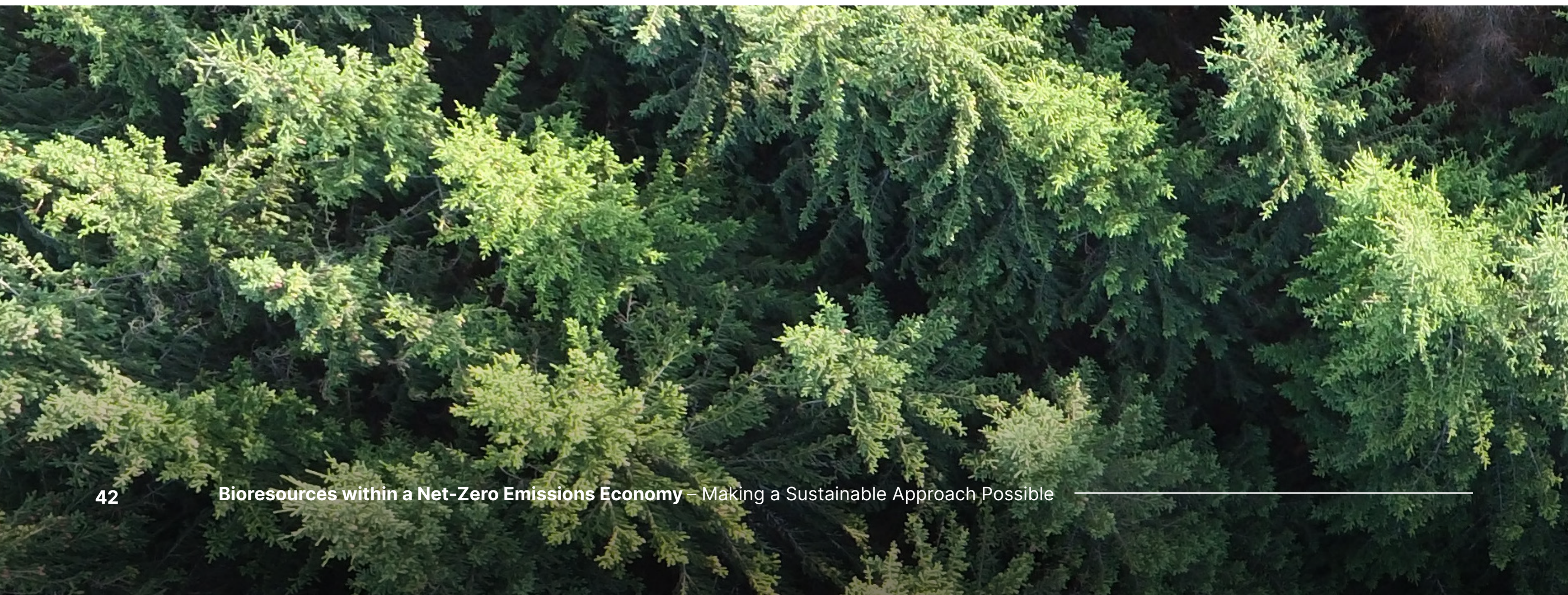
While plantation and cultivated land foster more biodiversity than urban land, they are detrimental compared to protected and even moderately used land and rarely better than degraded land [Exhibit 1.21].

Illustrative Examples	Description	Carbon Balance[1]	Ecological Impacts	Materials and energy outputs	Timeline
 **Old Growth Forest**	• **Pristine, long established forest.** • **Critical to avoid conversion** of intact forests for biodiversity and to avoid release of carbon stocks	**Very high** carbon stocks within above and below ground forest	Abundant biodiversity, pristine habitat, soil quality and water quality.	No industrial outputs; traditionally gathered firewood.	10,000s of years
 **Actively Regenerated Forest**	• **Depleted forests which are being actively regenerated** through planting • Aim of re-establishing forest habitat, not primarily for energy or materials use.	**Carbon stock growing** over time as forest matures	Soil quality restoration; Biodiversity habitat restoration.	Limited industrial outputs (e.g. high value timber removal); traditionally gathered firewood.	>100 years
 **Managed Forest – Uneven-Age and multiple species**	• **Stand age is uneven.** Uneven selection of trees are removed in one harvest. Complex management.[2] e.g. 'cut-to-growth' selected felling • **Cultivating diverse species and sustainable harvesting techniques** can limit impact on biodiversity	Carbon is sequestered as forest grows but **stock depends of level and timing of timber removal.** Potential to reach stable balance if forest stands equal to new forest growth are harvested in rotation	Ecological impact as not pristine habitat, level of impact depends on forestry cultivation and harvesting techniques	Timber, pulp, residues. ~2-10 m³/ha/yr[3]	15-45 year rotations
 **Managed Forest – Even-aged and mono-culture**	• **Stand age is even:** The range of tree ages within a stand do not vary by more than ~20%.[2] • **Single species** limits biodiversity and increases vulnerability to pests		Poor ecological benefits, reduced habitat and vulnerable to pests.	Timber, pulp, residues. Higher volume productivity than uneven aged. ~3-15 m³/ha/yr[3]	15-45 year rotations
 **Woody Biomass Energy Crops**	• **Fast-growth woody biomass plantations.** e.g. miscanthus, bamboo, Short rotation forestry for energy	**Limited** storage in biomass; but can be combined with **bioenergy, CCS and geological storage**[5]	Equivalent to agricultural land.	Woody biomass for fuels; high productivity ~80-140 m³/ha/yr[4] (e.g. miscanthus)	Perennial 1-3 years to 15 year rotations

NOTES: [1] OECD (2001) *Forestry Projects: Permanence, Credit Accounting and Lifetime*;
[2] Savilaakso., et al (2019), *What are the effects of even-aged and uneven-aged forest management on boreal forest biodiversity in Fennoscandia and European Russia? A systematic review protocol*;
[3] British example. Matthews et al., (2016) *Forest Yield: A handbook on forest growth and yield tables for British forestry*; Productivity of industrial forests varies by region and may be as high as c.70 m3/ha/yr in best-in-class tree farms in Brazil, or nearer 20-25 m3/ha/yr in Indonesia with corresponding cost effectiveness of around $2/tonne CO_2.
[4] Agri-Food and Biosciences Institute (2011), *Miscanthus Best Practice Guidelines*.
[5] Some carbon may be stored underground (e.g., in root systems).

Box D

Exhibit 1.20



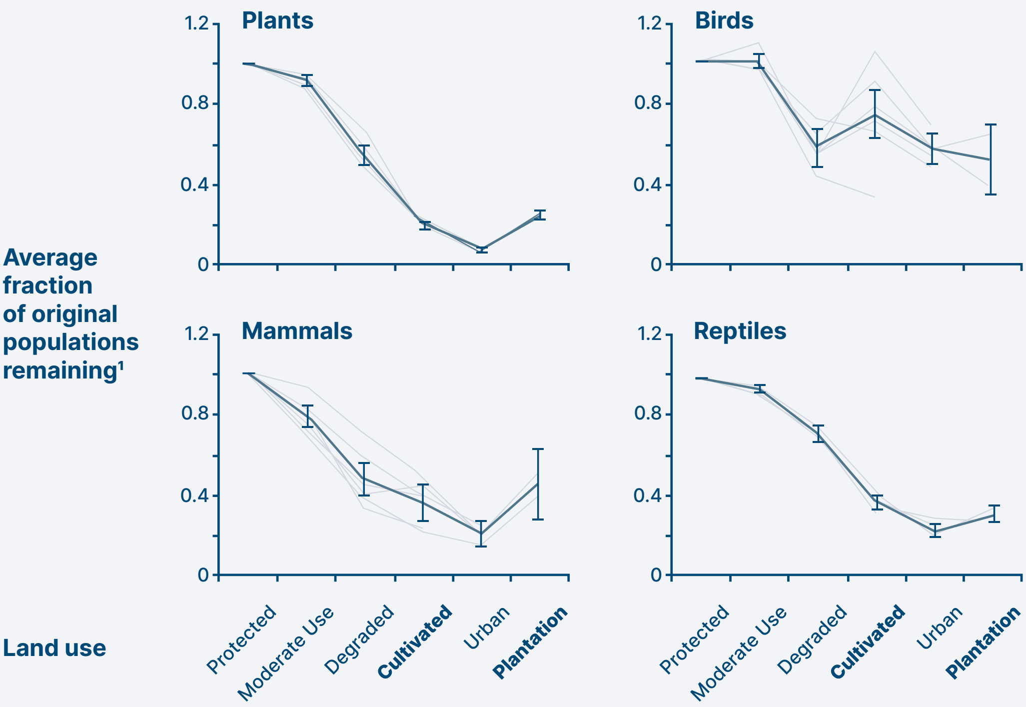
Box D *continued*

Nevertheless, sustainable forest management practices can improve the biodiversity outcomes of managed forests. These include:

- Maintaining a fraction of intact land between managed areas (e.g., 25% of the estate).
- Planting diverse and non-invasive species rather than a monoculture and including native species.
- Thoughtful land management minimising fertiliser and herbicide use, incorporating longer rotation lengths, and operating with mindful thinning and harvest practices.

Climate-Smart Forestry is an example practice focused on increasing carbon storage in forests while providing other ecosystem services, using adaptive forest management to enhance health and resilience, and using wood to substitute carbon-intensive materials.[79]

Plantation forestry can have severe consequences for nature, but sustainable land management practices can help mitigate the impact



Sustainable land management practices can help mitigate the impact on biodiversity on land which is being used for plantation forestry, or is heavily cultivated.

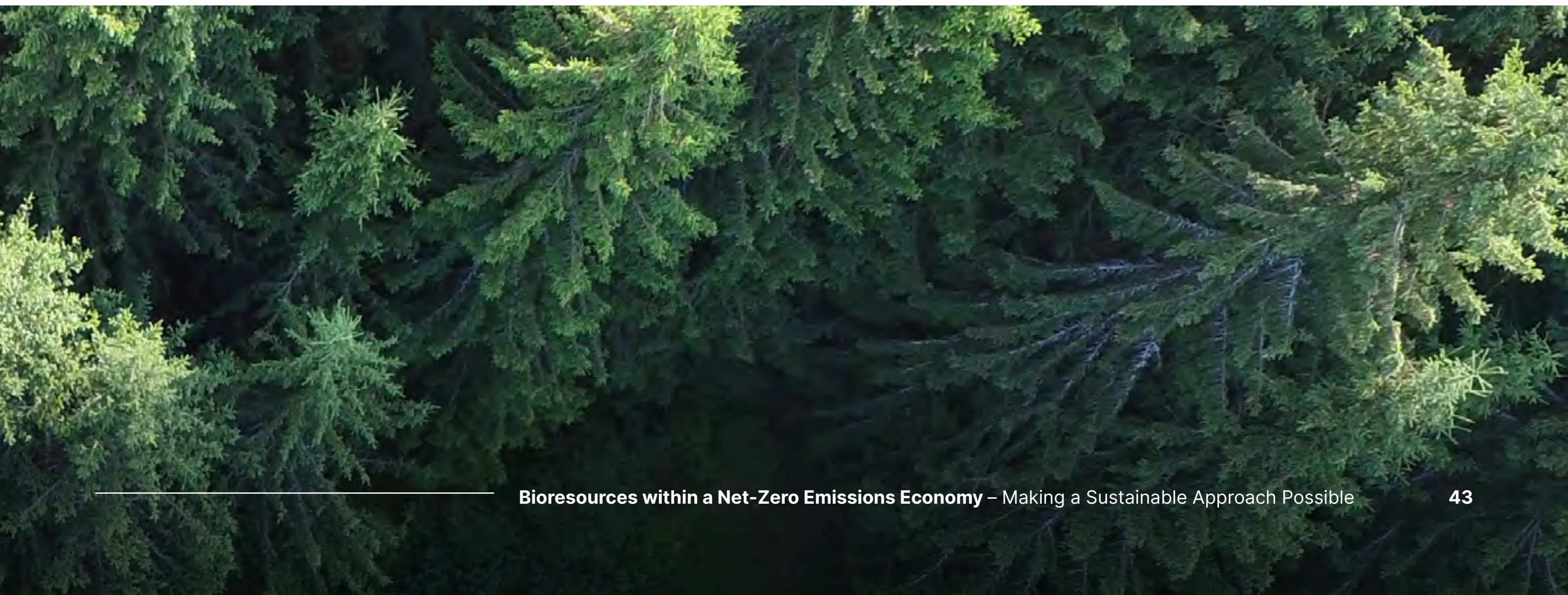
Protected land, or moderately used / degraded natural forest should not be converted to managed commercial forestry, regardless of management, to avoid negative impacts on biodiversity and carbon stocks.

¹ Expert estimates of species-by-species population reduction were made relative to populations in large, protected areas of the same ecosystem types. Data shown is for southern Africa.

SOURCE: Reprinted by permission from Springer Nature: Nature - A biodiversity intactness index, R. J. Scholes et al., © 2005.

Exhibit 1.21

79 Verkerk et al. (2020) *Climate-Smart Forestry – the missing link.*



1.3.2 Agricultural residues: a meaningful supply, but collection must respect soil health

Agricultural residues come in many forms, encompassing both field residues (such as straw, stalks, and leaves left after harvest) and process residues (such as husks, bagasse, and roots).[80] Availability therefore varies greatly by region, reflecting the mix of crops grown.

Estimates of total potential global supply range from 5 to upwards of 30 EJ/year, but in studies which apply strong sustainability criteria the range narrows to between 5-12 EJ/year.[81]

Among the most important criteria applied is the assumption about what proportion of residues can be extracted. In the sustainability focused studies on which we focus, it is assumed that around 50-70% of residual agricultural biomass will typically need to be left to maintain soil health, preventing nutrient loss and soil erosion, and preserving soil organic carbon [Exhibit 1.22].[82]

The amount of residual biomass that can be extracted without compromising soil health is limited; most biomass left on land

Fraction of agricultural biomass left on the land
% Total Available Biomass

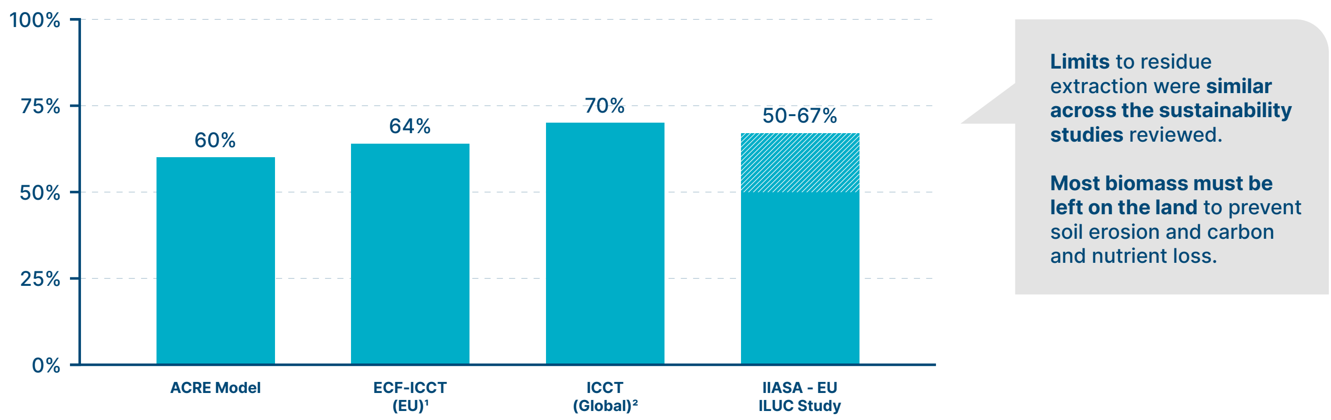


Exhibit 1.22

NOTES: [1] Assumes yield of 5.8 tons/ha for ECF figures. Biomass assumed removed is considered baseline assumption depending the region.
[2] Approximately 90% of residue produced is considered to be physically harvestable of which approximately 10% is used for animal bedding and horticulture and 70% should remain in the field to prevent soil erosion and carbon and nutrient loss, leaving 20% available for sustainable use.

SOURCES: ACRE Satellite Model, ECF-ICCT EU model; ICCT global model; IIASA EU ILUC study; Hanssen et al. (2019) *Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models*; Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

80 BP, Energy Biosciences Institute (2014), *Biomass in the Energy Industry – an Introduction.*

81 Estimates in excess of 30 EJ/year from an assessment of a large number of studies with various sustainability constraints are presented in Creutzig et al. (2015) *Bioenergy and climate change mitigation: an assessment* and Hanssen et al. (2019), *Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models.* Most of the studies compared evaluated the maximum possible residue availability. Those with stricter sustainability constraints are estimated to be 80% below the average, landing at 12 EJ/year in 2050. An assessment by Searle et al. (2014), *A reassessment of global bioenergy potential in 2050* suggests 8 EJ/year of total crop residue would be available after accounting for harvesting losses, soil quality, and other uses which is further reduced to 5 EJ/year after adjusting for economics and governance quality.

82 According to one estimate, approximately 90% of residue produced is considered to be physically harvestable of which c.10% is used for animal bedding and horticulture and 70% should remain in the field, leaving 20% available for sustainable use. Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

1.3.3 Biomass from municipal and industrial wastes: upsides and downsides from recycling and sorting

A third source of biogenic waste and residues is municipal wastes and separately collected wastes from industry. Municipal wastes are composed of biogenic (e.g., food, paper, wood) and non-biogenic (e.g., plastic, rubber) wastes, generally intermixed. Separately collected wastes from industry include waste oils and fats, and livestock manure. Biogas can be created from the anaerobic digestion of animal manure, the organic fraction of municipal solid waste (MSW), crop residues, and wastewater sludge, and can be upgraded to biomethane.[83]

We estimate that supply from municipal and industrial waste sources can provide c.6-9 EJ/year of sustainable biomass supply by mid-century. At current recovery rates, annual municipal and biogenic waste streams from industry, after recycling, contain approximately 25 EJ/year of potential energy [Exhibit 1.23].[84] Supply in 2050 in our prudent case is estimated as below:

- **Waste oils and fats**, currently c.1.5 EJ/year, are expected to somewhat increase over time and are of significant value (e.g., for sustainable aviation fuels), leading to high recovery rates. However, total potential of this source is limited.

- **Manure** from livestock today has the potential for c.7.5 EJ/year to be collected for energy purposes primarily in the form of biogas; however, manure is often used for fertiliser, providing nutrients for the soil, enhancing soil stability and moisture retention, and preventing erosion.[85] While biogas could be produced from dung and the digestate returned to the field, this may not always occur in reality.[86] Some estimates suggest a maximum theoretical potential from manure of 17-19 EJ/year in 2050, but when considering sustainability and feasibility criteria (e.g., limiting collection to intensive, indoor livestock systems), c.4-5 EJ/year is more credible.[87] As dietary shifts away from animal products could reduce this potential even further, our prudent estimate only relies on c.1-4 EJ/year being available from this source in 2050.

- **Municipal waste** (i.e., what remains after recycling) is currently estimated to have an energy content of about c.16 EJ/year including biogenic and non-biogenic fractions. While residual MSW contains significant biomass, today more than half of its energy content is non-biogenic – plastics alone account for more than c.7 EJ/year.[88] An estimated c.3.5 EJ/year of sustainable supply is expected from this source in 2050 after excluding areas without sufficient collection infrastructure, or with insufficient governance to ensure quality of waste streams.[89] Where biogenic waste is used rather than landfilled, there is an added benefit of avoiding methane emissions which, if not captured, significantly accelerate climate change.

Increasing supply of biomass from municipal and industrial waste sources will require significant investment in and expansion of waste management systems. Municipal waste, in particular, has considerable further potential due to the amount of waste which is uncollected today, combined with population growth trends and growing waste generation per capita. In our 'maximum potential' scenario we assume an additional c.5 EJ/year from this waste source, bringing the maximum potential to c.14 EJ/year. Achieving this would require:

- Development of comprehensive waste management systems, particularly in regions lacking sufficient collection infrastructure.[90]

- Improvements in waste sorting and processing to separate recyclable waste for material recycling and prepare residual waste for energy recovery.

- CCS technology development and addition of CCS infrastructure to waste-to-energy plants to capture GHG emissions from incineration of biogenic and non-biogenic waste.

83 IEA (2020), *Outlook for biogas and biomethane: Prospects for organic growth.*

84 ETC Analysis; IEA; World Bank (2018), *What A Waste 2.0*; World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*; IEA (2020), *Outlook for biogas and biomethane: Prospects for organic growth;* Kalt et al. (2020), *Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different food system pathways;* Ozbay et al. (2013), *Energy content of municipal solid waste bales;* Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

85 Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

86 Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

87 Kalt et al. (2020), *Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different food stem pathways.*

88 ETC Analysis; IEA; World Bank (2018); World Economic Forum – Clean Skies for Tomorrow Analysis (2020).

89 Poor governance is linked to poor infrastructure, reducing feasibility of collection and resulting in questionable sustainability of sources due to lack of regulatory control. Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

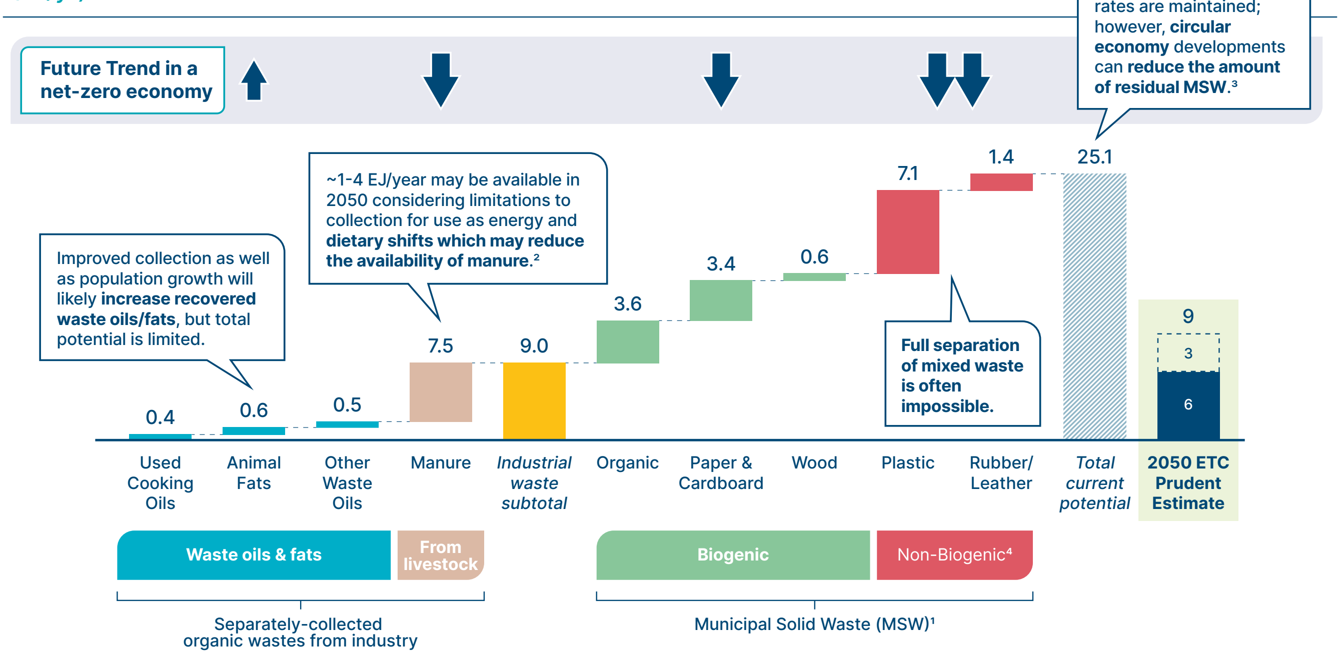
90 An estimated 500,000 people would need to be connected to waste management systems every day until 2040 to close the collection gap. The Pew Charitable Trusts and SYSTEMIQ (2020), *Breaking the Plastics Wave.*

Actual volumes and composition of waste produced by mid-century will, however, reflect several competing trends:

- Population growth, urbanisation, expanded waste collection and improved separation of materials will increase the availability of organic waste.[91]
- If efforts to establish a more circular economy (where waste is minimised through efficient material use and recovery) are successful this would reduce biomass supply from municipal waste over time, particularly in the Global North.
- Efforts to reduce food waste and/or the growth of decentralised organic waste management (e.g., home composting) would reduce food waste collection.
- Shifts towards bio-based materials (e.g., away from single use plastics) could increase the organic fraction of municipal waste streams, however, this is unlikely to meaningfully increase volumes.[92]
- Dietary changes could go in either direction. Meat consumption could increase with rising prosperity, increasing the dietary of animal manure (of which the IEA estimates 2.5% p.a. growth).[93] But, if the reductions in meat consumption or the shift to cultured meat considered in section 1.2 occurred, the supply of manure would fall significantly.

Current waste streams from municipal & industrial sources contain ~25 EJ potential energy but most not utilised; in a net-zero economy there could be a significant reduction

Current energy potential from industrial sources and municipal solid waste (MSW)[1] (EJ/yr)



[1] Excludes the proportion of MSW that is recycled (using a regionally-weighted global average of ~17% of total MSW). MSW energy content excludes that of glass, metal, and 'other' wastes.
[2] In 2050, the global potential for sustainable energy from manure from intensive, indoor livestock systems is estimated to be ~4-5 EJ/year under business-as-usual dietary choices, and significantly less under a 'healthy reference diet' scenario based on Kalt et al. (2020).
[3] Overall, MSW for sustainable energy use in 2050 is estimated to be ~3.5 EJ/year in 2050 from areas with collection infrastructure and good governance based on Searle et al. (2015).
[4] Approximately 20-40% of carbon in MSW is derived from fossil fuels; due to their high energy density, these wastes contribute a higher proportion of the energy content than biogenic wastes. Energy content of organic (912 Mt/year), paper & cardboard (327 Mt/year), wood (37 Mt/year), plastic (223 Mt/year), and rubber/leather (41 Mt/year) assumed to be 4.8, 12.5, 19, 38.5, and 42 MJ/kg, respectively.

SOURCES: IEA; World Bank (2018), *What A Waste 2.0*; World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation;* IEA (2020), *Outlook for biogas and biomethane: Prospects for organic growth;* Kalt et al. (2020), *Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different food system pathways;* Ozbay et al. (2013), *Energy content of municipal solid waste bales;* Searle et al. (2014), *A reassessment of global bioenergy potential in 2050.*

Exhibit 1.23

91 The Pew Charitable Trusts and SYSTEMIQ (2020), *Breaking the Plastics Wave;* IEA (2021) *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.*
92 Even if bio-based biodegradable plastics reach 20% of plastic packaging by 2050, this would be very small (e.g., <5% of waste) compared to overall organic waste production.
93 IEA (2021) *Net-Zero by 2050 - A Roadmap for the Global Energy Sector;* IEA (2021), *What does net-zero emissions by 2050 mean for bioenergy and land use?*

1.4 Biomass from aquatic sources: Promising but not yet technologically ready for bioenergy

There are two main sources of aquatic biomass relevant to this discussion: macroalgae and microalgae [Exhibit 1.24]. Macroalgae, more commonly known as seaweed, can be cultivated in the ocean and can contribute to biomass supply either directly as a source of energy (e.g., biofuels or biogas) or materials (e.g., bio-based packaging), or indirectly by providing an exceptionally land-efficient alternative to crop-based animal feed cultivation, enabling a release of crop- and pastureland for other uses. Microalgae, typically cultivated on land, is less relevant as a direct source of energy due to costs and scale but can similarly increase biomass supply indirectly. These systems are very promising: macro- and microalgae are extremely land efficient, requiring either no land at all or utilising otherwise unproductive land, and they grow faster than terrestrial plants due to their high photosynthetic efficiency.[94]

Significant research and investment in the cultivation of seaweed in coastal regions could help scale this promising source of biomass in the coming decades. Some estimates suggest a seaweed economy at scale could provide c.7-18 EJ of biomass annually;[95] however, given the limited scale of seaweed cultivation for energy today[96] and other potential uses of this biomass, we have included only c.0-1 EJ/year in the prudent supply scenario. In our maximum potential scenario we add another c.10 EJ/year by 2050.

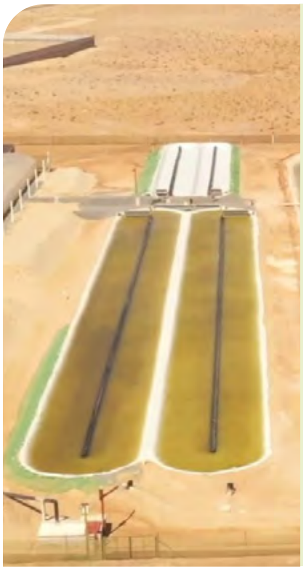
Exhibit 1.24

Two main sources of aquatic biomass: macro- and microalgae

A Macroalgae (seaweed)

- **No need for land**
- Requires no inputs to grow
- No need for fresh water
- Grown in uncontrolled ocean environment
- No need for energy-intensive, synthetic nitrogen fertiliser
- Creates habitats for marine life
- Sequesters carbon and absorbs excess nitrogen

B Microalgae



- Grown in open ponds or photobioreactors **on land**
- Requires energy and nutrient inputs to grow
- Grown in controlled environment
- High lipid content under certain growth conditions
- Globally produced in small volumes today

SOURCE: Microalgae image courtsey of SuSeWi (2021).

Macroalgae

Seaweed has a number of benefits unrivalled by other biomass sources: it does not require land, fresh water, or fertiliser. Instead, it grows in an uncontrolled ocean environment, requiring no exogenous inputs other than a physical anchoring point (i.e., a suspended longline or net). In addition to sequestering carbon, seaweed absorbs excess nitrogen in the ocean and creates habitats for marine life.[97]

94 Microalgae can produce an equivalent amount of biomass with 1/10th the land (based on research by SuSeWi, 2020).
95 Lehahn et al. (2016), *Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability.*
96 Approximately 100,000-fold less seaweed by mass is cultivated in comparison with biomass supply from terrestrial crops, grasses, and forests. Lehahn et al. (2016), *Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability.*
97 Seaweed for Europe (2020), *Hidden champion of the ocean – seaweed as a growth engine for a sustainable European future.*

Global seaweed production today is around 30 million tonnes per annum, >95% of which is in seaweed farms, mostly in Asia.[98] To put this in context with other ocean-based biomass, approximately 100 million tonnes of fish is captured globally each year (with another 80 million farmed).[99] The seaweed market has tripled in the last decade,[100] but relative to the energy value of total global biomass production it remains very small (about 0.1-0.2 EJ/year).

Seaweed therefore plays a minimal current role in direct energy uses, and is mainly used as an input to food, hydrocolloids (gels), and cosmetics. Further revenue growth from an estimated $17 billion today to perhaps $30 billion by 2025[101] will also be focused on higher value uses outside of energy, including animal feed, bio-based packaging and textiles, bio-stimulants, and nutraceuticals.[102]

Estimates of future potential as an energy source depends on the relative value of energy versus alternative products, technological readiness in deeper water and further-from-shore locations, and cost-efficient transformation processes:

- **Theoretical and realistic potential in shallow, near-shore waters**: Many coastal regions with cold, nutrient-rich water are well suited to seaweed production (e.g., Europe) [Exhibit 1.25]. And if it were possible to develop all sites considered suitable (e.g., near shore, sufficiently shallow waters), and use all of the biomass created for energy or materials uses, rather than the product applications mentioned above or carbon removals, seaweed production for these uses could reach 18 EJ/year of biomass.[103] But, realistic potential is likely to be somewhat smaller, with several experts suggesting a limit of around 7 EJ/year.[104]

- **Theoretical potential in open ocean waters**: Ongoing research from ARPA-E's MARINER Program[105] suggests an enormous global potential of 140 EJ/year could be realised if cultivation were not limited to near-shore waters.[106] Operating in a high seas environment would require substantial research and development coupled with high capex investments that will make business models challenging. At this point, these very large estimates are therefore extremely speculative.

Developing and scaling a seaweed-for-energy economy will require significant developments in technologies and business models. Key developments include:

- **Cultivation**: cost reductions in offshore locations suitable for large surface area cultivation where conditions are tougher and CAPEX currently high. Careful assessment of impacts of large-scale offshore seaweed farms on marine biodiversity and advancement of engineering in marine environments.

- **Transportation**: reduced collection costs.

- **Production**: economies of scale and cost-efficient transformation process to turn seaweed into biofuel and or biogas.

- **Business models**: business models which can extract higher value products before using by-products for energy applications.

While there is a role for seaweed in bioenergy, efficient biorefinery operations will continue to focus on producing the highest value products (e.g., food, feed, and biomaterials).[107] It is also critical to ensure that too-rapid scaling of large-scale systems does not shortcut the research needed to safeguard marine environments and engineer appropriate cultivation systems. Macroalgae accounts for all of the 0-1 EJ/year which we include in our prudent supply scenario and for all of the additional 10 EJ/year that we include in our maximum potential scenario.

98 Seaweed for Europe (2020), *Hidden champion of the ocean – seaweed as a growth engine for a sustainable European future.*
99 FAO (2020), *The State of World Fisheries and Aquaculture 2020.*
100 Seaweed for Europe (2020), *Hidden champion of the ocean – seaweed as a growth engine for a sustainable European future.*
101 Seaweed is expected to continue to grow at double digit CAGR for the next decade. Markets and Markets (2020), *Seaweed Cultivation Market by Type, Method of Harvesting, Form, Application and Region - Global Forecast to 2025.*
102 Seaweed's high nutritional content makes it a very interesting source of food or feed: seaweed has low fat content but contains omega 3 fatty acids, macro- and micronutrients like for instance sodium, calcium, magnesium or iodine, as well as vitamins B12, A and K. Seaweeds share no diseases with land-based plants but are rich in minerals and carbohydrates making them a performing fertiliser. Seaweed's unique biophysical properties of alginate, carrageenan, and agar explain their use in thickening, gelling, and emulsifying applications.
103 Lehahn et al. (2016), *Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability.*
104 Expert interviews. Practical limitations to cultivation (e.g., difficulties cultivating seaweed at distance up to 400m from shore and depth as great as 100m) would limit global supply.
105 The US Advanced Research Projects Agency – Energy (ARPA-E) Macroalgae Research Inspiring Novel Energy Resources (MARINER) program.
106 Marine BioEnergy predicts that if 0.5% of the total ocean area were under cultivation with farms towed by drone submarines doing depth-cycling, that would represent about 140 EJ/year (and would consume the artificial nitrogen fertilizer runoff from land agriculture).
107 Seaweed for Europe (2020), *Hidden champion of the ocean – seaweed as a growth engine for a sustainable European future.*

There is significant untapped global potential for macroalgae production

High opportunity marine ecoregions for development of seaweed aquaculture
(based on the synthesis of environmental, socioeconomic, and human health factors)

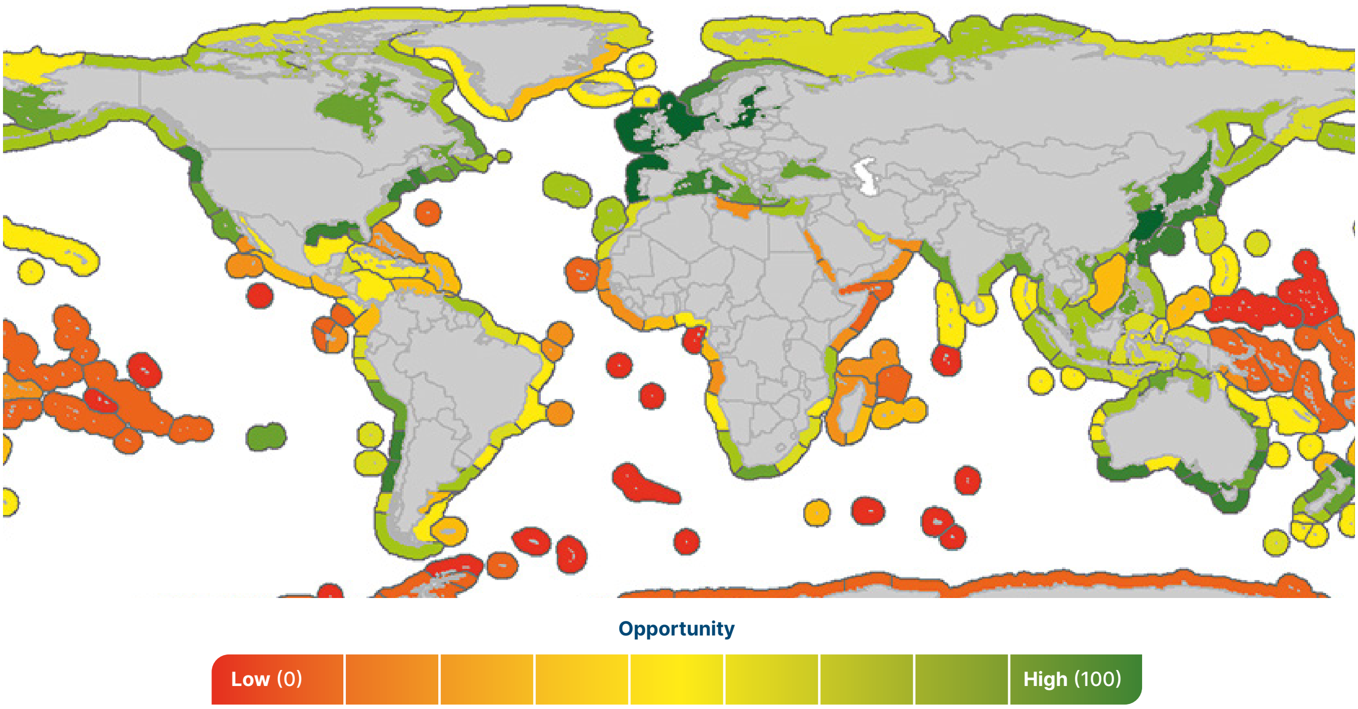


Exhibit 1.25

SOURCE: Figure from Theuerkauf et al. (2019), *A global spatial analysis reveals where marine aquaculture can benefit nature and people*.

Microalgae

Microalgae are the most efficient photosynthetic organisms on the planet. Though aquatic, they are generally grown in raceway ponds or photobioreactors on land. Using microalgae as a potential source of biomass therefore raises similar sustainability issues as biomass from dedicated land. Land use implications (such as carbon trade-offs), ecological factors (such as impacts on biodiversity) and resource requirements (such as the need for nutrients, energy, and fresh water) must be considered.

Production of microalgae today is limited and relatively costly, with growth in a controlled environment (in contrast to the open ocean) adding to the expense. But the potential for cost reduction is large, since algae are fundamentally more efficient than terrestrial plants, exhibiting higher growth rates and higher photosynthetic efficiencies.[108] New technologies are making it possible to grow microalgae with minimal inputs and in a way that sustains the highest growth phase: as a result, only 1/10th the amount of land is needed to produce the same amount of biomass as from terrestrial plants. Algae can also be grown using land unsuitable for agriculture (e.g., deserts) and, in some cases, the production method obviates the need for freshwater or additions of nutrients (with all growth requirements met by pumping nutrient-rich ocean water through the culture).[109]

Microalgae have been of interest in the bioenergy space due to the high oil content of some strains and their natural ability to produce long-chain hydrocarbons (e.g., biodiesel); however, this trait is primarily exhibited under conditions of nutrient stress, when the algae grow slowly. Moreover, there are strong arguments for focusing the use of nutrient rich microalgae on food and other high value products rather than on fuel production.

108 Guedes et al. (2019), *Algal spent biomass – A pool of applications*.
109 The technology developed by SuSeWi has these features.

We do not therefore assume any role for microalgae as an energy source, either in our prudent or maximum potential scenario. But their use for production of food and feed could play a significant role in freeing up crop- and pasturelands for other uses as discussed in Section 1.2.[110]

1.5 Evolution of land use and biomass supply over time

Exhibit 1.3 showed our prudent estimate of sustainable biomass supply in 2050 at 40 to 60 EJ/year; Exhibit 1.4 suggested a maximum potential by then of 120 EJ/year.[111] Some key elements of supply are already available and will remain roughly stable over time. Others either will, or might, grow gradually over the coming decades if ambitious systems changes are achieved.

In our prudent scenario, the supply of sustainable biomass crops on dedicated land or from residues derived from forestry (in total about 25 to 40 EJ/year) is likely to remain broadly constant over time, reflecting constraints on land availability. Available supplies of municipal and industrial wastes and agricultural residues are expected to increase slowly from the current level, but this scenario does not rely on there being significant improvements in waste and residue collection. Additionally, while the seaweed industry is expected to continue to grow, supply from this source for energy uses is assumed to be minimal relative to the total scale of supply (0-1 EJ/year).

By contrast, the additional upside implied by our maximum potential scenario, should any of this become available, will primarily develop late in the path to 2050.

- **The upside for municipal and industrial wastes (+5 EJ/year)** depends crucially on improvements in waste collection and sorting and may be offset by increases in waste recycling.

- **The development of seaweed for energy uses (+10 EJ/year)** will depend on the rapid scaling of still nascent technologies, but could be accelerated by deliberate policy support.

- **The largest potential upside (+45 EJ/year) from either increased energy crops or increased forest products**,[112] remains uncertain and will only emerge if major changes in either diet or technology significantly reduce the land required for animal protein production. If this potential does emerge, it will only develop gradually over time. This is both because the land released from food production would only slowly become available and because, in the case in which that land would be dedicated to managed forestry, it would then take time for newly-planted trees to reach maturity for harvest [Box C].[113]

Divergences between a base case and a maximum potential scenario are therefore not likely to occur until the 2040s [Exhibit 1.26].[114]

Over the next decades, increasing demand for biomass and constrained sustainable supply will likely drive prices up. This will be true during transition even if freed up land and aquatic sources eventually bring supplies closer to the maximum potential level. Higher prices could make other decarbonisation options more economic or spur the development of additional sustainable biomass supply but could also increase the risks of non-sustainable sourcing of bioresources. Stringent sourcing standards combined with effective enforcement systems must therefore be in place.

110 Microalgae can have a transformative impact on food production through delinking food and protein production from energy production and, in particular, reducing the carbon impact of food as they have the ability to be carbon negative (SuSeWi, 2020).

111 With an additional 4 EJ/year in each from recycled woody biomass for materials.

112 As presented in Exhibit 1.14, reflecting either 250 Mha energy crop biomass production, 750 Mha to nature or 800 Mha managed forestry biomass production, 200 Mha to nature.

113 Perennial energy crops or short rotation coppice could be developed more rapidly.

114 Supply availability over time from dedicated use of land reflects modelling from IIASA GLOBIOM (latest GLOBIOM FOLU-Scenario model outputs shared Dec 2020). In a scenario where demand for biomass increases substantially (e.g., to facilitate BECCS to avoid runaway climate change), starting around 2040, biomass from some of the newly reforested land is used. This would be accompanied by significant negative consequences for biodiversity.

In prudent scenario supply of biomass to remain broadly flat; if land can be released from agriculture additional bioresources are likely to become available from late 2030s

Global sustainable biomass supply (2020-2050) – illustrative scenarios[1]
EJ/year (primary energy) excluding stemwood for materials[2] and traditional biomass use[3]

Illustrative

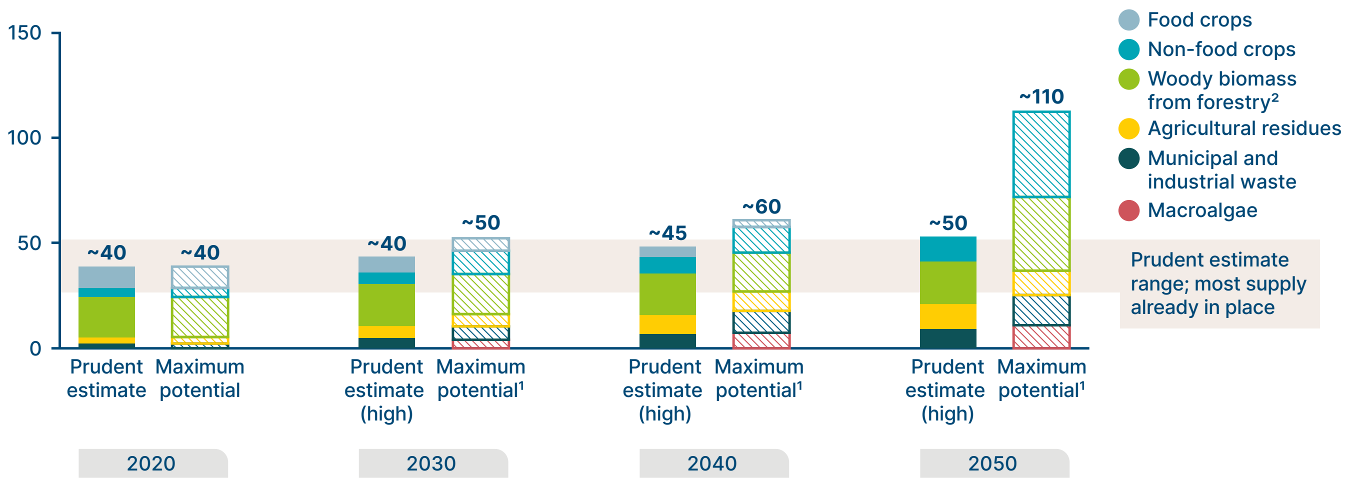


Exhibit 1.26

[1] Illustrative scenario for maximum potential supply over time of non-food crops and woody biomass from forestry is based on modelling by IIASA GLOBIOM / FOLU in an unpublished BECCS scenario. Other sources of biomass were assumed to scale linearly to 2050 maximum potential values. [2] Excludes stemwood for materials uses, estimated to be c.10 EJ/year based on IIASA analysis of FAO industrial roundwood figures after removing by-products used for energy. This could increase if managed forestry practices are expanded. [3] Excludes biomass for traditional uses (i.e., woody biomass and dung used as fuel for cooking and heating purposes, mostly in developing countries). This is estimated to be ~25 EJ of biomass today and is expected to be phased out over time in order to reduce air pollution and deforestation. [4] Maximum achievable only under extremely ambitious systems change scenarios.

SOURCES: IIASA GLOBIOM / FOLU (2019), *Growing Better: 10 critical transitions to transform food and land use*; IEA (2021) *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.*

1.6 Biomass availability and considerations by geographic region

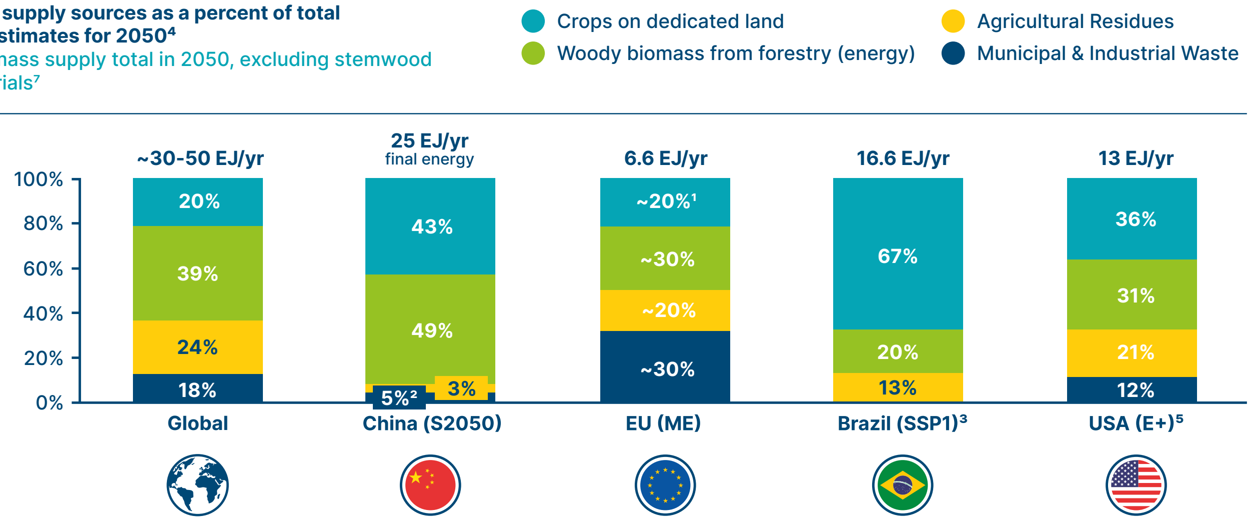
While global sustainable biomass supply is constrained, resources are very unevenly distributed across regions, reflecting:

- The amount and type of bioresources available (woody biomass, agricultural residues, biogenic municipal waste, etc.) given geographical attributes and current land use.
- The ease of collection and suitability for different end uses of those resources.
- Varying levels of pressure from competing uses of land (for food, nature, etc.) driving different opportunity-costs of land.
- Varying potential upside in future sustainable bioresources supply – e.g., from freed-up land, more waste collection, or aquatic sources.
- Pre-existing policies related to bioresources, which may encourage or discourage different sources of supply – in a sustainable or unsustainable way.
- Specific local sustainability risks, e.g., risk of high lifecycle emissions from land use change and biodiversity impacts in the tropical belt.

We consider below the regional supply mix outlined in bioresource studies for four major regions – the USA, Europe, Asia (especially China), and countries located in equatorial regions – to illustrate differences, local implications, and implications for global trade of bioresources [Exhibit 1.27]. Other than for Europe these regional estimates do not include woody biomass for materials.

Estimates of biomass supply across regions vary according to local characteristics and sustainability criteria considered

Biomass supply sources as a percent of total supply estimates for 2050[4]
% of biomass supply total in 2050, excluding stemwood for materials[7]



	Global	China (S2050)	EU (ME)	Brazil (SSP1)[3]	USA (E+)[5]
Sustainability criteria considered[6]	✓	✗	✓	~	~
Regional Supply Drivers	N/A	Targets conversion of 61m hectares of marginal land for energy crops and forestry	Majority of supply from woody biomass; land constraints limit supply; partially driven by EU policy	Dominated by energy crops due to economics on highly productive land	Land currently used for ethanol-corn production converted to other energy crops. Large existing forestry sector
Fraction of global prudent estimate[4]		~50-80%	~10-20%	~35-55%	~25-45%

Exhibit 1.27

[1] Includes both food and non-food crops. [2] Includes animal manure [3] SSP1 Scenario: Technological development follows a progressive trend and environmental policy is based on the NDC agreements of Brazil until 2030. The supply potential of biomass assumes a high productivity increase. [4] Excluding materials. [5]but energy-supply options for minimizing total energy system cost while meeting the goal of net-zero emissions in 2050 are relatively unconstrained. [7] Biomass from forestry for the timber and pulp & paper sectors (~10 EJ/year today + ~4 EJ/year recycled woody biomass, FAO Industrial Roundwood less by-products used for energy).[6] ETC assessment. [7] Biomass from forestry for the timber and pulp & paper sectors (~10 EJ/year today + ~4 EJ/year recycled woody biomass, FAO Industrial Roundwood less by-products used for energy).

SOURCES: Lap et al. (2018), *Pathways for a Brazilian biobased economy: towards optimal utilization of biomass*, ME: Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.* Zhao (2018), *Assessment of potential biomass energy production in China towards 2030 and 2050*. Princeton Net-Zero America (2020), *Potential Pathways, Infrastructure, and Impacts.*

USA

The recent Princeton Net-Zero America study suggested that c.13-23 EJ/year of primary biomass for energy uses could be available by 2050.[115] This would represent an increase of 400-800% compared to today's bioresources consumption and implies a significantly larger role for bioresources than our prudent global scenario suggests.[116] The majority of supply is expected to come from energy crops (e.g., grasses) grown on former ethanol-corn land (c.36%) and from woody biomass from forestry (c.31%), with c.21% from agricultural residues and c.12% from municipal and industrial waste [Exhibit 1.27].

This scale and mix of bioresource differs from our global picture in ways which reflect existing agricultural and land-use policies in the USA:

- **A high reliance on energy crops:** This reflects the existing importance of energy crop production in the US, mainly due to encouraging policies in the 1970s and 1990s – including the *1990 Clean Air Act* and the *Renewable Fuel Standard* which set a minimum use of renewable fuels including ethanol.[117] Today, around 10% of the total volume of finished motor gasoline consumption in the USA is ethanol[118] with c.38% of corn production converted to ethanol.[119]

115 The biomass sources encompass agricultural residues, woody residues, wastes, and both woody and herbaceous energy crops. Highest use of biomass is in scenario E-B+ due to it assuming that some pastures and cropland is converted to energy crops, lowest in scenario E+ as it assumes no increase in land use for energy. Princeton's Net-Zero America Study (2020), *Potential pathways, Infrastructure and impacts.*
116 Princeton's Net-Zero America Study (2020), *Potential pathways, Infrastructure and impacts.*
117 US Energy Information Administration (EIA) (2021), *Biofuel explained: Ethanol.*
118 US EIA (2021), *FAQs: How much ethanol is in gasoline, and how does it affect fuel economy?*
119 Princeton's Net-Zero America Study (2020).

- **A significant role for woody residues from existing commercial forests:** The USA has around 300 million hectares of forest land covering around a third of total land area, of which more than 40% is managed by the federal, state, and local governments.[120] Forestry and the management of forests is therefore expected to yield significant residues, primarily used as an energy source.

- **Significant agricultural residues:** This is due to the USA's comparatively large agricultural production, which represents around 20% of global crop production by volume.[121]

These factors make the USA among the most favourably endowed countries in terms of bioresources, implying that an optimal decarbonisation pathway for the US may involve a larger proportionate role for bioresources than elsewhere. Optimal policies for US biomass development should also however consider.

- Whether the existing energy crop production would be sustained if electrification became the most cost-effective route to most road transport decarbonisation.

- Whether some freed-up agricultural land should be used for afforestation rather than energy crop production, taking into account biodiversity imperatives.

- Whether a stricter approach to forestry and agricultural residues, with a higher proportion left on the soil to sustain soil health, should imply less growth in residue supply.

Europe

A review of estimates of sustainable bioresource supply in the EU conducted by Material Economics suggests that approximately c.5-7 EJ/year of primary biomass could be used in 2050 for industry and energy uses,[122] with an additional c.6 EJ/year used for materials (up from 4 EJ/year today, driven by chemical and plastics demand).[123] Of the biomass available for energy use, municipal and industrial waste and woody biomass from forestry each make up approximately 30% while dedicated crops and agricultural residues each contribute approximately 20% of total [Exhibit 1.27].[124]

These estimates for Europe are broadly in line with the global estimates of sustainable supply presented in this report, representing about 10% of our global prudent scenario. They reflect the following factors:

- **Forestry is Europe's biggest biomass source**, with 161 million hectares dedicated to forestry – primarily in Sweden, Finland, and Spain. Biomass from European managed forestry is optimised for high value solid wood products, followed by pulp and paper production, with forest residues and the by-products from wood-processing industries used for both material production (e.g., particle board) and energy generation.[125] European managed forest harvests are not expected to materially grow over the next 30 years given sustainability constraints, such as soil health and biodiversity. Wildfire risk is also rising.

- **The EU is a global leader in recycling and waste management**, which makes separation of biogenic and non-biogenic waste more feasible.[126]

- **Land constraints** limit supply from dedicated energy crops. Dedicated energy crops currently use only 3.3% of the EU's total cropland. Agricultural residues will play an important but limited role due to their continued use as animal feed, the high collection and handling costs, the requirement for significant changes in farming practices and the benefit to soil health of leaving at least some residues on the land.[127]

Material Economics noted that many studies had a much higher range of bioenergy supply, reaching 12-18 EJ/year available as an energy source by 2050. However, their c.5-7 EJ/year estimate (excluding materials) reflects an equivalent approach to sustainability as that applied in our prudent scenario.

120 USDA Forest Service, 2016 data.
121 OECD (2021) *OECD-FAO Agricultural Outlook (Edition 2020).*
122 ETC analysis of supply estimates from Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
123 Materials uses are expected to be prioritised, with woody biomass allocated to all materials uses first, resulting in c.70% of woody biomass in 2050 used for materials vs. c.40% today.
124 ETC analysis of supply estimates from Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
125 Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
126 Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
127 Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*

Manure from livestock can be collected for energy purposes (i.e., biogas production) and the digestate returned to the soil.

Asia

Asia's large land mass and agricultural sector provide significant opportunity for sustainable bioenergy collected from waste and residues as well as crops and forestry. But assessing potential sustainable bioenergy supply in Asia is constrained by a lack of available research and by limited consideration of sustainability criteria within the research. Several studies that do not consider sustainability criteria suggest considerably higher supply potential than implied by our prudent scenario.

- **One estimate for China foresees c.25 EJ/year of final biomass energy in 2050**, increasing from c.12 EJ/year in 2020, and implying a far greater role for biomass in China than in our prudent global scenario.[128] In this analysis, woody biomass and energy crops together account for over 90% of supply (49% and 42% respectively), with crop residues, animal manure, municipal solid waste and sewage sludge making up the remaining amount [Exhibit 1.27].[129] This implies a smaller role for agricultural residues and municipal and industrial waste and a larger role for dedicated land than in our prudent scenario. The fact that China is a food importer with growing food needs, suggest that most agricultural land should be prioritised for food production. However, many studies rely on the conversion of 'marginal land' to woody biomass or energy crops to meet China's growing biomass demand.[130]

- **Estimates for India vary greatly** as a result of a lack of data on existing biomass supply,[131] together with highly variable climatic and geographical conditions across different regions within the country. Some estimates suggest c.9 EJ of bioenergy could be available from agricultural and municipal waste alone, representing more than 15% of our prudent global supply estimate.[132] Further potential could be delivered through woody biomass and energy crops. Low labour costs could reduce biomass collection costs making growth on marginal land (including around agricultural land) more feasible, but it is difficult to assess the potential impact of this on supply.

- **In many other countries,** significant potential likely exists, but limited research has so far been conducted.

Equatorial Countries

Equatorial regions contain some of the world's most important carbon sinks, including rainforests and peatlands, which are also rich in biodiversity. These ecosystems will come under increasing pressure as demand for biomass for food, materials and energy grows, driven by economic development. For example, in 2019, the tropics lost 11.9 million hectares of tree cover, with 1.4 million hectares of primary forest lost in Brazil alone.[133] Estimates suggest that over 20 EJ/year could be sourced from these areas, equivalent to over a third of global supply in our prudent case, though considerations of sustainability could reduce these estimates substantially.

In equatorial countries with high land-based carbon stocks, strict sustainable sourcing discipline is critical, requiring robust sustainability regulations, governance, and oversight. In these environments, financial incentives to extract biomass could help develop sustainable supplies, but, if not carefully managed, could also incentivise biomass extraction forms that are more harmful to the climate and biodiversity.

128 These c.25EJ are primarily expected to be used for liquid biofuels and for BECCS. Zhao (2018), Assessment of potential biomass energy production in China towards 2030 and 2050. Kang et al. (2020), Bioenergy in China: Evaluation of domestic biomass resources and the associated greenhouse gas mitigation potentials.

129 Zhao (2018), Assessment of potential biomass energy production in China towards 2030 and 2050.

130 Zhao (2018), Assessment of potential biomass energy production in China towards 2030 and 2050.

131 There is a distinct lack of data in India for the country's existing biomass supply as well as information and consensus amongst databases on what meaning and use of different biomass and bio-waste potentials currently is. Joshi et al. (2016), *Assessment of Biomass potential and Current Status of Bio-fuels and bio energy Production in India.*

132 ETC calculations based on estimates by The Energy and Resources Institute (TERI) for current waste volumes in India arising from agriculture, livestock, and municipal sources. Assumes approximately 683 Mt/year agricultural yield from eleven major crops of which approximately 178 Mt/year is surplus quantity (TFIAC, 2018) at 16 MJ/kg, 414 Mt/year of livestock waste at 14 MJ/kg, and 52.5 Mt/year of organic municipal waste at 6 MJ/kg. TIFAC & IARA (2018), *Estimation of surplus crop residues in India for biofuel production.* Kaur et al. (2017), *Potential of Livestock Generated Biomass: Untapped Energy Source in India;* Kaur et al. (2014), *Estimation of large animals dung for power generation- A case study for district Bathinda, Punjab;* MoHUA (2020), *Swachhata Sandesh Newsletter.*

133 WRI (2020), We Lost a Football Pitch of Primary Rainforest Every 6 Seconds in 2019.

It is critical to prevent the use of this type of biomass, which undermines rather than contributes to climate mitigation goals. Case studies in Brazil and Indonesia highlight the risks:

- **Some Brazilian studies suggest biomass supply could be 11.4-16.6 EJ/year in 2050,**[134] up to a third of global supply in our prudent supply case.
    - Brazil currently has an active bioenergy sector with c.6 EJ/year of primary biomass produced in 2010,[135] largely producing sugar cane biofuels which is used in motor vehicles, accounting for c.25% of Brazil's primary energy supply.
    - Studies suggest that future biomass supply will continue to be dominated by dedicated crops such as sugar cane (c.70%) [Exhibit 1.27].
    - However, Brazil is home to the largest rainforest on earth, and, if biomass is produced on deforested land or unsustainably harvested, it has a very high carbon footprint.[136] Expansion of sugar cane into rainforest land would therefore carry a very high carbon penalty and should be discouraged.
- **Bioenergy expansion in Indonesia** risks releasing large volumes of carbon stored in tropical peatlands, but could be sustainably expanded through coastal algae cultivation. Some studies suggest up to 11 EJ/year in primary biomass supply but estimates applying strict sustainability criteria suggests a much lower 3-4.5 EJ/year, with the majority produced from woody biomass and agricultural residues.[137, 138]
    - In recent years forest land in Indonesia has been converted to palm oil plantations, releasing carbon in the process. Further land use change in Indonesia comes at high risk, given that Indonesia peatlands alone are estimated to store around 55-61 Gt of carbon which could be released.[139] Estimates of sustainable bioenergy supply in Indonesia are based on no additional land becoming available for palm oil plantations.
    - With thousands of islands, long coastlines, shallow waters and abundant sunlight, Indonesia is highly suitable for algae cultivation. However, as discussed in Section 1.3.4, algae for bioenergy are still at the research stage.

Implications for international trade of bioresources

Bioresources are most economical when used locally. Collection and transportation of biomass is costly, especially where the biomass is moved in a bulky, low energy density form (such as wood or industrial residues).[140] In addition, many regions are limiting biomass use to that which is locally produced, in order to ensure sustainability criteria are respected through more transparent local supply chains.[141] Therefore, in regions with abundant local bioresources, bio-based emissions reductions routes are likely to be more prevalent, and possibly applied to a wider range of use cases. Regions with less access to biomass are likely to rely more heavily on alternative decarbonisation routes such as electrification, clean hydrogen or fossil fuels combined with CCS.

However, as the application of sustainability criteria constrains the supply of biomass, its value is likely to rise, in some cases sufficiently to overcome the barrier posed by collection and transportation costs, stimulating longer trade. Indeed, a transatlantic trade in bioenergy exists today, with North American wood pellets exported to Europe, driven by the EU's renewable energy policies. Over time, constraints on supply, combined with the uneven global distribution of bioresources could encourage a greater role for national and international trade, directing scarce sustainable bioresources to the highest value use cases. International standards on sustainability will therefore be essential.

134 11.4 EJ (SSP3 pathway) and 16.6 EJ (SSP1 pathway) from Lap et al. (2019), *Pathways for a Brazilian biobased economy.*

135 Lap et al. (2019), *Pathways for a Brazilian biobased economy.*

136 As discussed in Section 1.2, biomass produced on deforested land has very high lifecycle carbon emissions, and conversion of tropical rainforest entails a 100+ year carbon payback period [Exhibit 1.10].

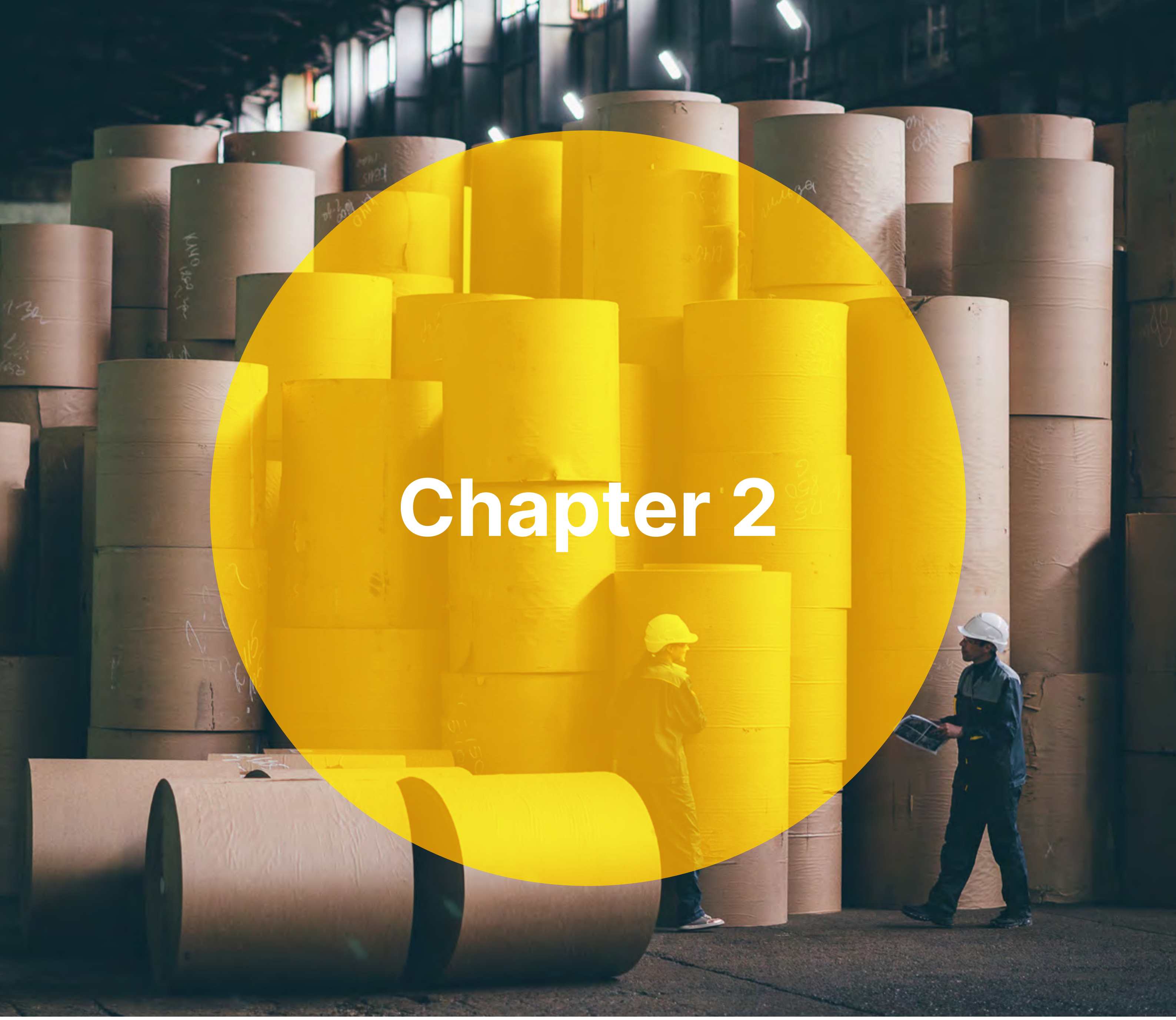
137 IRENA (2017), *Renewable Energy Prospects: Indonesia.*

138 IRENA (2017), *Renewable Energy Prospects: Indonesia.*

139 Siegert and Jaenicke (2019), *Estimation of carbon storage in Indonesian peatlands.*

140 Costs can be reduced by creating supply chains with a hub-and-spoke network structure for biomass and by utilising a multi-objective, mixed integer linear programming model to design and manage the supply chain for biofuels. Roni et al. (2016), A multi-objective, hub-and-spoke model to design and manage biofuel supply chains.

141 A US biomass market study shows that such a hub-and-spoke network structure would work by allowing depots to serve as shipment consolidation points where small shipments of biomass from reprocessing facilities are consolidated into high-volume shipments, which are then delivered to biofuel plants by rail. Such a system positively impacts transportation costs, and consequently, the delivery cost of ethanol, and CO2 emissions. Roni et al. (2016), A multi-objective, hub-and-spoke model to design and manage biofuel supply chains.



The optimum role for biomass in a net-zero economy – prioritising the use of bioresources across sectors

Many companies, sectors and countries consider biomass use as a crucial route to decarbonisation. Additionally, bioenergy development has been encouraged by a variety of public policies including in transport, residential heating, industrial heat, chemical feedstocks, and thermal power generation. But as Chapter 1 described, the supply of sustainable biomass is tightly constrained. As a result, total potential demands are far higher than sustainable supply. Total global final energy consumption is currently 430 EJ per annum[142] and for illustration, if all of this were met with biomass, total primary energy supply would have to be at least 610 EJ/year.[143] In addition, total material uses could add a further 36 EJ. Clearly sustainable biomass supply, as estimated by the ETC at c.40-60 EJ/year,[144] can therefore meet only a very small proportion (e.g., 5-8%) of total energy demand [Exhibit 2.1].

ETC analysis suggests that by 2050, final energy supply could grow to around 495 EJ per year, though there are significant opportunities to reduce this demand through efficiency and energy productivity improvements. If maximum potential improvements were realised, final energy consumption could be around 355 EJ in 2050, allowing bioenergy to take up a greater share of overall energy supply.[145]

In this chapter and in Chapter 3 we therefore assess the optimal use of a limited sustainable biomass supply. This chapter assesses prioritisation if supply were limited to the 40 to 60 EJ/year which our prudent case suggests is highly likely to be sustainable. It concludes that the highest value uses are where biomass is used as a material or feedstock – in wood products, pulp and paper, and plastics production – with the use of biomass as an energy source concentrated on aviation.

Chapter 3 considers how this prioritisation changes if bioenergy with carbon capture and storage (BECCS) could be used to deliver carbon dioxide removals (sometimes called 'negative emissions'), and how changes in diet or food production technology could unlock the significant additional supply considered in our 'maximum potential scenario'.

We cover, in turn, below:

- The various potential uses of biomass as source of biomaterials or bioenergy.
- Key conclusions on sectoral prioritisation, given the alternative decarbonisation options.
- An illustrative scenario for the allocation of constrained sustainable biomass supply.[146]

142 Global final energy demand, 2019. IEA (2020), *Energy Technology Perspectives*.
143 Assuming 70% efficiency; with c.60% efficiency (as described in Box A) this would be closer to 720 EJ/year.
144 Not including an estimated additional c.4 EJ/year of recycled woody biomass for materials.
145 ETC (2020) *Making Mission Possible*.
146 Energy Transitions Commission, *Bioresources in a net-zero economy – Technical appendix* (to be published in 2021).

Bio-based decarbonisation can only be a small share of the decarbonisation technology mix

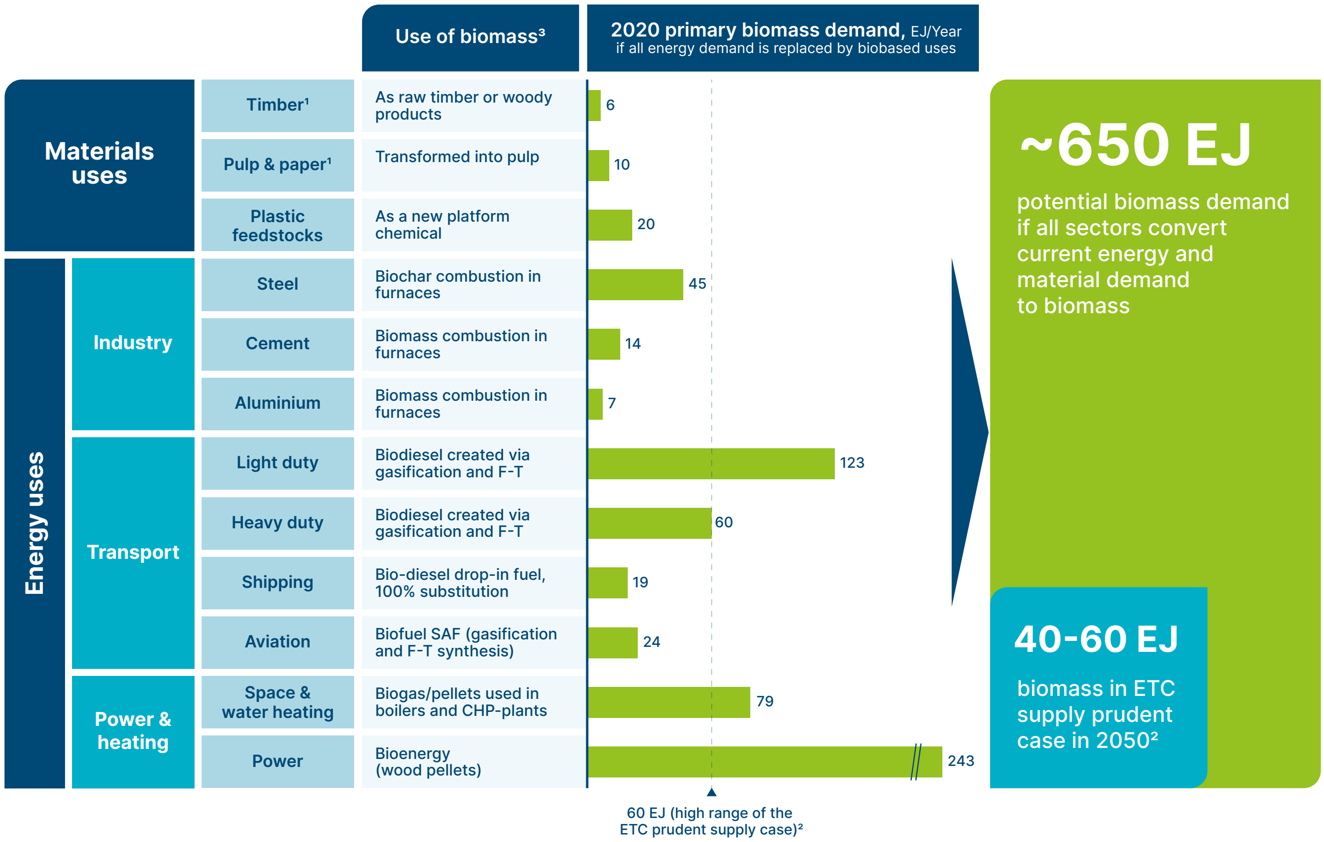


Exhibit 2.1

NOTE: F-T: Fischer-Tropsch. ¹ Wood resource balances show a ~13% gap between FAO sources (c.14 EJ/year, primary and secondary resources) and uses of woody biomass; ² Excludes c.4 EJ of recycled woody biomass. ³ Example bioresource for comparison; not exhaustive.

SOURCE: IEA ETP 2017 & 2020; Material Economics

2.1 The various uses of biomass in a net-zero economy

Biomass is considered as a key route to decarbonisation with potential application in almost all sectors. In assessing these potential uses, it is useful to distinguish two overall categories – using biomass as a material or feedstock and using it as an energy source.

Biomass can be used as a material in its raw form or as a feedstock for transformation into other forms of material. In all cases, extending the life of materials being used, and increasing recycling of materials at the end of their lifetime, will reduce demand for biomass. Biomass can be used as:

- **Timber and other stemwood products** from forestry which constitute the traditional raw use of biomass as a biomaterial, used in applications such as construction or furniture. Pulpwood is the basis of the paper industry and can substitute for fossil-fuel-based packaging when beneficial.
- **Fibres** in the textile or construction industries (e.g., using cellulosic biomass such as hemp).
- **A chemical building block**; biomass can be converted into:
    - Plastics, from the transformation of the starch, sugar, or cellulose contained in plants into high-value chemical building blocks such as light olefins (ethylene and propylene), methanol, and aromatics;
    - Other chemical feedstocks and products (e.g., solvents, paints, additives, pharmaceuticals) that are used in industry, transportation, textiles, food supply, and housing.

When biomass is used as a material or feedstock, atmospheric carbon that was captured during plant growth is stored for the duration of use. Using biomass as a material thus achieves a temporary 'carbon removal' effect.

Biomass used for its energy content can be transformed for use as follows:[147]

- **Direct combustion to produce heat:** all dry biomass can be burned directly for heating buildings and water, for industrial process heat, or for generating electricity via steam turbines.
- **Thermochemical conversion to produce solid, gaseous, and liquid fuels via:**
    - **Pyrolysis** to produce fuels such as charcoal, bio-oil, renewable diesel, methane, and hydrogen.
    - **Gasification** to produce syngas (a combination of carbon monoxide and hydrogen) which can be transformed into a fuel for diesel engines, airplane turbines, or heating. Biomass gasification can also be used to produce hydrogen which can, in turn, be used either as a flexible energy source or as an input to chemical or steel production.
- **Chemical conversion to produce liquid fuels**, e.g., converting vegetable oils and animal fats into biodiesel or sustainable aviation fuels.
- **Biological conversion to produce liquid and gaseous fuels**, using microorganisms to convert biomass into products such as ethanol, used as a transportation fuel, or into renewable methane, which has the same uses as fossil fuel natural gas.
- **In the steelmaking industry,** the use of biomass (often transformed first into charcoal) is a hybrid use case between material and energy, as it acts both for heat production and as a reducing agent in a blast furnace.

When sustainable, low lifecycle emissions biomass is used as an energy source, net carbon emissions are much lower than if fossil fuels are burned, since CO_2 is absorbed during plant growth. Unless combined with carbon capture and storage, the combustion of biomass (or biomass derived fuels) also creates local air pollution, emitting particles and other greenhouse gases.

147 US Energy Information Administration (2002), *Biomass explained.*

2.2 Prioritising the uses of biomass

The optimal allocation of sustainable biomass by sector should reflect the extent to which alternative decarbonisation options are available, and the relative merits of biomass versus these options along four dimensions;

- **Costs**, where it is important to focus not just on costs today but on how the costs of different decarbonisation options are likely to compare in 2050. In many areas where biomass could be used for energy, the cost of alternative low-carbon technologies is projected to fall substantially by 2050 [Exhibit 2.2]. Exhibit 2.3 and Box E set out a summary assessment of how bio options compare to alternatives, and shows at what price of biomass feedstock the biomass route would be more economic, with applications towards the right of the chart only economic if bio-feedstocks costs were negative.

- **Resource efficiency**, and in particular the use of land, which in all cases argues in favour of electrification-based routes if these are available [Exhibit 2.4].

- **Technical readiness** of both bio and non-bio-based routes, which in some cases raises the complex issue of whether an already feasible bio-based technology should be deployed as a transition solution, even if the non-bio-based route is likely to be more economic in the long term [Exhibit 2.5].

- **How much carbon abatement can be achieved**: in general, this also favours electricity-based routes where feasible, since these can eventually be made zero-carbon, while lifecycle emissions from bio routes, when not combined with CCS, can be low but not zero [Exhibit 2.5].[148]

This analysis leads to the following conclusions:

The highest priority use of sustainable biomass supply is as a material or feedstock, not an energy source. When used in its raw material form (e.g., wood), biomass is already clearly cost advantaged versus other materials. In the chemicals industry, recycling can reduce primary demand; but, for the remaining primary production, bio-feedstocks are highly likely to be competitive against other decarbonisation options. Use as materials also achieves temporary carbon sequestration and has a lower air pollution impact than bioenergy uses.

Most current applications of bioenergy – in particular in road transport and bulk power generation – will be uneconomic versus electricity or hydrogen in the coming years.

Bioenergy uses might be cost-competitive – at least initially – in shipping, seasonal power balancing, residential heating in some locations, and industrial heat and steelmaking. But its use in these sectors should still be tightly limited, and initially higher-cost electricity-based options, where the energy can be provided through renewables, should be favoured to keep total demand within sustainable supply constraints and accelerate cost reduction of the electricity-based options. Long-term use will therefore tend to be limited to specific niches where the bio route is highly advantaged, or locations where bioresources are locally abundant.

Aviation is one sector where biofuels should play a major transitional role and may be a significant use of biomass even in the long term, as the alternative option (power-to-liquid) may not reach cost-competitiveness and scale fast enough to achieve necessary emission reductions.

Hydrogen production via biomass gasification will not be cost competitive versus green hydrogen production from electrolysis unless it is combined with CCS to achieve net carbon removals. Its potential role is therefore considered alongside other carbon removal options in Chapter 3.

148 The cost comparison between bio-based decarbonisation and other decarbonisation routes is based on a set of cost assumptions for the energy sources in 2050 (global numbers). In particular:
- Hydrogen: electrolyser capex decreases from $1,200 in 2020 to $200/MW in 2050.
- Power: global LCOE estimate of $20/MWh in 2050.
- Bioenergy: we consider a 15% reduction in non-feedstock costs from 2020 to 2035 and an additional 15% reduction from 2035 to 2050.

Falling costs of renewables and batteries, and prospects for much lower-cost green hydrogen, means these options are likely to be more cost-effective in most applications

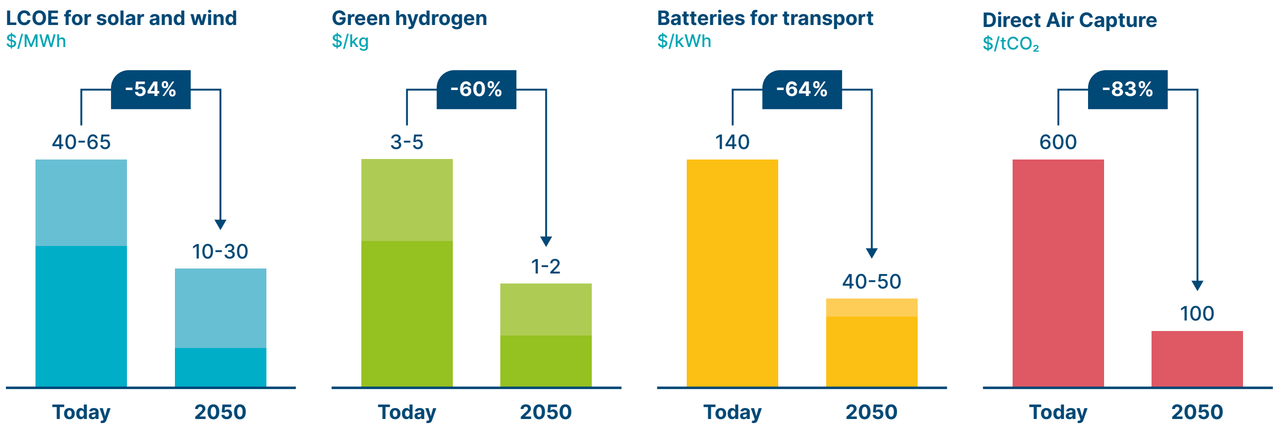


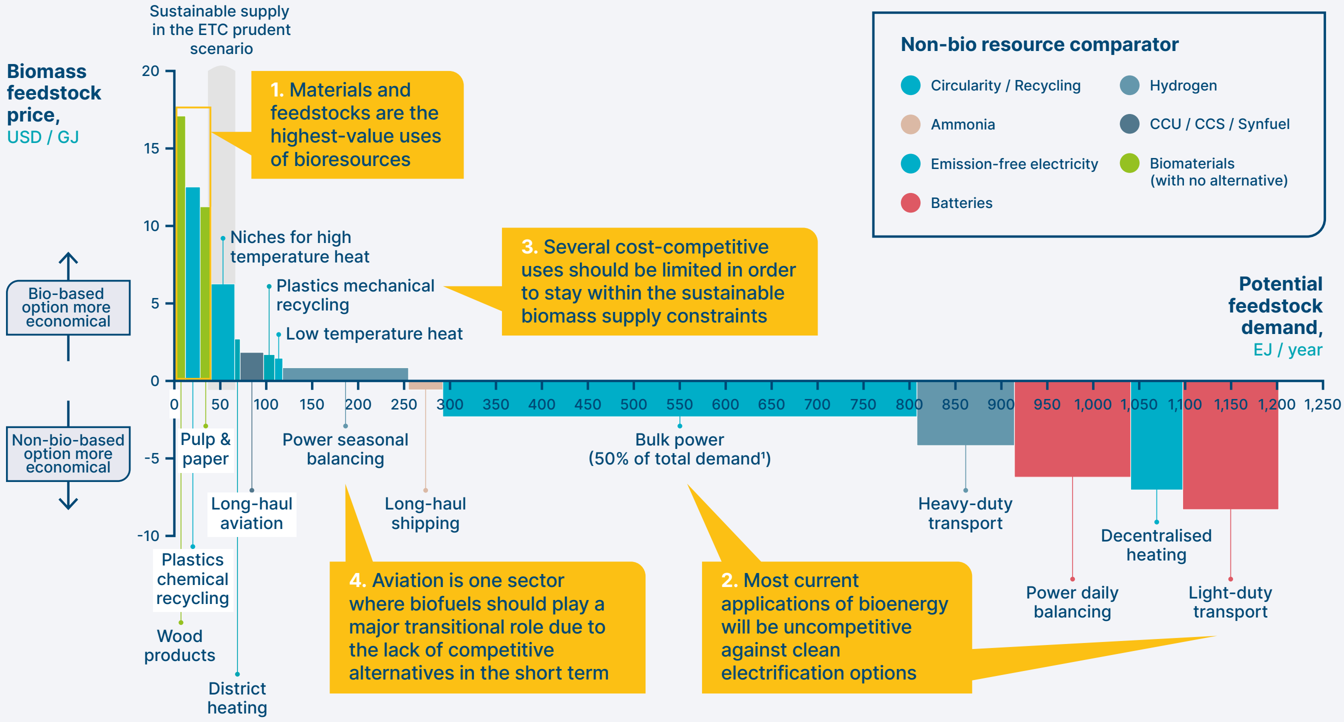
Exhibit 2.2

NOTES: Ranges for cost numbers show that costs are likely to vary by location with lower bound being most favourable locations, and upper bounds representing a global average.

SOURCES: SYSTEMIQ analysis for the ETC, based on ETC (2020) *Making Mission Possible* and Material Economics (2021) *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU biomass.*

Global biomass cost-parity curve for 2050

Cost-parity curve – Breakeven biomass cost vs. alternative leading non-biogenic solution; global (2050 outlook)
"At what biomass feedstock price is the bio option cost effective?"



NOTE: Currently excludes carbon removal applications.
¹ We limit the potential demand for biomass for bulk power to 50% of the demand of the segment in order to make the graph readable.

SOURCE: Material Economics and ETC analysis (2021).

Exhibit 2.3

Methodology: How to read the cost-curve?

This cost curve parity tool is used to identify priority uses of biomass by sector. It assesses the relative cost of biomass feedstock compared to non-bio alternatives across a range of uses and the relative size of demand for biomass feedstock that could be required to service those uses.

- **Each block represents a potential application of biomass in a sector**. The colour of the block indicates the non-bio option with which the bio option is compared. For example, power generation from biomass (i.e., wood pellet combustion in thermal plants) is compared with bulk power generation from variable renewables.
- **The height of the block shows the price of the biomass feedstock** at which both bio and non-bio options are at cost parity. If the market price of biomass is below this value, the bio-route will be the most cost-competitive route.
- **The width of the block shows the size of the demand from this sector if biomass is used to decarbonise the whole sector** (except in the case of bulk power where 50% of total demand is shown).

Box E

Exhibit 2.4

Resource efficiency: bio-based options are ~8-70x more land intensive than all alternative decarbonisation options

			Resource requirements of the non bio-based route: Route	Land use ha/TJ output/yr	Resource requirements of the bio-based route: Route	Land use[1] ha/TJ output/yr	Is the bio option more land efficient than the alternative?	
Materials uses		Timber, pulp & paper	None	n/a	Timber	5	✗	No alternative
Materials uses		Plastic feedstocks	Mechanical recycling	~0	Bio-based feedstock	6	✗	Bio feedstock more applicable than CCS/recycling
Energy uses	Industry	Steel	H2-based primary steel	0.3	Biochar reduction/heat	5	✗	Biochar less land efficient than direct/indirect electrification or CCS
Energy uses	Industry	Industrial heating	Heat pump	0.1	Biomass boiler	7	✗	Biomass more land intensive and process less efficient than power
Energy uses	Transport	Light duty	BEV	0.6	Biofuels	17	✗	Biofuels more land intensive than power and BEV
Energy uses	Transport	Heavy duty	FCEV	1.3	Biofuels	17	✗	FCEV less efficient than power/ hydrogen engine
Energy uses	Transport	Shipping	Ammonia in ICE	2.1	Biofuels	17	✗	Biofuels more land intensive than ammonia
Energy uses	Transport	Aviation	Synfuels	3.8	Biofuels	21	✗	Biofuels more land intensive than synfuels
Energy uses	Power & heating	Power bulk generation	RE	0.5	Biomass plant	14	✗	Biomass more land intensive than RE
Energy uses	Power & heating	Power intraday	RE + batteries	0.5	Biomass plant	14	✗	Biomass more land intensive than RE + batteries
Energy uses	Power & heating	Power interday	Hydrogen storage	0.8	Biomass plant	14	✗	Biomass more land intensive than hydrogen production and storage
Energy uses	Power & heating	Residential Heating	Electric heat pump	0.4	Biomass boiler	25	✗	Biomass more land intensive than power and boiler less efficient than HP

NOTES: RE: renewable electricity (e.g., from solar or wind). BEV: battery electric vehicle. FCEV: fuel cell electric vehicle. [1] Using a land efficiency of 200 GJ biomass per ha per year (middle case).

SOURCES: SYSTEMIQ analysis for the Energy Transitions Commission (2021); Materials Economics (2021).

Exhibit 2.5

Bio-based routes have higher technology readiness levels today but face carbon abatement and transition issues by mid-century

- Criteria favourable to bio (green)
- Bio & non-bio are equivalent (generally or in specific locations / timelines) (yellow)
- Criteria favourable to non-bio (red)

			Key decarbonization route: Bio	Non-bio	How does the bio-route compare with the non-bio options in terms of… Feasibility today	Carbon abatement
Material uses		Timber	Timber	None	No non-bio alternative	No non-bio alternative
Material uses		Pulp & paper feedstock	Pulp	None	No non-bio alternative	No non-bio alternative
Material uses		Plastics feedstocks	Chemical feedstock	Recycling	Mechanical recycling at commercial scale; primary routes have low TRLs	Non-bio route based on clean electrification technologies is zero carbon (even at point of use). The bio route CO_2 abatement potential: • Is highly dependent on source and supply chain of biomass • Emits carbon at point of use, except if combined with CCS (not feasible in transport sectors). This also adversely affects local air quality.
Energy uses	Industry	Steel	Biochar reduction / heat	Electrification / CCS / Hydrogen	Non-bio routes at pilot stage	
Energy uses	Industry	Cement	Biomass combustion	CCS	CCS not applicable to process emissions	
Energy uses	Industry	Industrial heating	Biomass boiler	Heat pump	Heat pumps not applicable to high temperatures	
Energy uses	Transport	Light duty	Bioethanol	BEV	BEVs and biofuels at commercial scale	
Energy uses	Transport	Heavy duty	Biodiesel	FCEV	FCEV trucks close to commercial stage	
Energy uses	Transport	Shipping	Biofuels	Ammonia in ICE	Ammonia ships at pilot stage	
Energy uses	Transport	Aviation	Bio jetfuels	Synfuels	Synfuels production at pilot stage	
Energy uses	Power & heating	Power bulk generation	Biomass plant	RE	Renewables deployed at scale	
Energy uses	Power & heating	Power intraday	Biomass plant	RE + batteries	Battery storage starting its commercial deployment	
Energy uses	Power & heating	Power interday	Biomass plant	Hydrogen storage	Hydrogen storage at pilot stage	
Energy uses	Power & heating	Residential heating	Biomass boiler	Electric heat pump	Heat pumps deployed at scale	

SOURCE: ETC analyses (2021).

2.2.1 Materials over energy – materials and feedstocks are the highest-value uses of bioresources

In studies of bioresource demand, both traditional and potential new uses of bioresources as materials are often overlooked. As a result, available bioresources for energy applications may be overestimated and policies directing biomass resources towards energy applications may risk a misallocation of valuable resources.

Timber and pulp: the highest-value use of woody biomass

Biomaterials such as solid wood and pulp and paper products are among the highest-value applications of biomass, utilising the intrinsic characteristics of bioresources: versatility, lightness, recyclability, and robustness. Biomaterials also include fibre materials derived from biomass residues, which are natural by-products of commercial forestry (see Chapter 1.3.1). There are few alternatives to the use of timber, pulp, and fibres where they are used today, which makes those applications high priority. In addition, material applications result in lower energy and material losses than conversion of biomass to feedstock or fuels.

This higher value of biomass use as material is already reflected in market prices. In energy-equivalent terms, the price (excluding transport) of sawn wood in the US over the period 2017-2018 was around $28-42/GJ; over the same period, wood pellets sold as an energy source were priced around $13-15/GJ.[149]

Moreover, the use of biomass as material could rise to reach 23 EJ/year versus around 16 EJ/year today.[150]

- **Timber used in construction** could account for 7 EJ (compared to around 6 EJ today).[151] ETC estimates suggest that decarbonising concrete and steel could respectively increase their costs by 30% and 20%,[152] improving the cost competitiveness of wood (which also serves as a medium-term carbon store). Cross laminated timber is likely to play an increasing role in construction, and some case studies for Europe suggest that sawn wood demand could double by 2050.[153, 154] Increased demand for sawn wood could decrease the amount of biomass available for non-material applications, although residues associated with managed forests and sawn wood production processes would increase.

- **Pulp and paper** could account for 16 EJ of wood demand, up from around 10 EJ today.[155] Decarbonising this sector will require a mix of solutions, including greatly increased collection and recycling with a decreasing proportion of pulp made from virgin feedstocks. Material Economics estimates that by 2050, recycled paper could account for 50% of pulp supply.[156] However, shifts away from plastics packaging could drive increased overall demand for pulp and paper.[157]

- **Bio-based fibre applications** are being developed (e.g., bio-composites in insulation materials, automotive, medical, and packaging) to substitute for petroleum-based solutions. Notable uses include manmade cellulosic fibres in place of the polyester, or bio-based materials used as cathodes in batteries for utility-scale energy storage. These uses could represent a significant extra demand for biomass if deployed at scale.

149 Futuremetrics (2018), *North American Pellet Quarterly.*
150 Wood resource balances show a ~13% gap between FAO sources (c.14 EJ/year, primary and secondary resources) and uses of woody biomass. Material Economics analysis (2021).
151 Buongiorno, et al. (2012), *Outlook to 2060 for world forests and forest industries: a technical document supporting the Forest Service*; U.S. Department of Agriculture Forest Service (2010) *RPA assessment;* Tian et al. (2016), *Global climate change impacts on forests and markets.*
152 ETC (2020), *Making Mission Possible.*
153 Material Economics analysis (2021).
154 International Resource Panel (2020), *Resource Efficiency and Climate Change 2020.*
155 Assumes 80% pulp yield per ton feedstock and 0.01 EJ/Mt. IEA (2017), *Energy Technology Perspectives;* ETC and Material Economics analysis (2021).
156 Material Economics modelling based on scenarios included in Material Economics (2019), *Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry and* SIFE (2017), *Global Foresight 2050 – Six global scenarios and implications for the forest sector.*
157 McKinsey & Company (2019), Pulp, paper, and packaging in the next decade.

Plastics and chemicals: the importance of bio-feedstock alongside other decarbonisation options

Plastics decarbonisation is a crucial challenge due to its scale, environmental impact, and complexity:

- Global demand for plastics could increase from c.390 Mt in 2020 to c.820 Mt of plastic per year by 2050, mainly driven by the Middle East, Africa and developing Asia. This would roughly lead to a doubling of emissions from plastics production under a business-as-usual scenario.[158]

- Plastics result in two streams of CO_2 emissions: the production process produces on average 2.5 tonnes of CO_2 per tonne of plastics, while the decomposition of plastics at end-of-life (in particular if it is incinerated) produces about 2.7 tonnes of CO_2 per tonne of plastics.[159]

- Apart from CO_2 emissions, the end-of-life disposal of plastics can produce numerous other forms of environmental harm, including dangerous pollution of soils and oceans, with potentially serious implications for biodiversity and human health.

Addressing the environmental impact of plastics will therefore require a combination of:

- **Reducing the need for virgin production** and mitigating pollution issues related to end-of-life disposal through both:
  - Reduced end-use of plastics products as a result of more efficient plastics use or the substitution of other products or materials.
  - Greater mechanical or chemical recycling.

- **Decarbonisation of primary production** via either:
  - Applying CCS to capture the exhaust gases from furnaces.
  - Replacing heat input from fossil fuel combustion with low-emission heat sources (zero-carbon hydrogen, sustainable biomass, or sustainable biogas).
  - Electrification of heat input, which is technically feasible but at an early stage of development.

- **Using a renewable feedstock** so that end-of-life emissions in non-recycled plastics are offset by CO_2 absorbed during plant growth. This could be via either:
  - Biodiesel, which can be converted into bio-naptha and then used in existing furnaces.
  - Bioethanol dehydration to produce ethylene.
  - New zero-carbon electrochemical processes,[160] combining zero-carbon green hydrogen with CO_2 captured from the atmosphere via direct air carbon capture (DACC).

Bioresources could therefore play two roles in the decarbonisation of plastics production and use:

- **As a bio-feedstock** to deliver not only zero-carbon monomer production but very low emissions across the entire product lifecycle, even if plastic is incinerated at end-of-life.

- **In the form of fibre-based materials** used in place of plastics. Recent studies suggest that 17-25% of current plastics used in packaging could, in principle, be substituted with fibre-based alternatives without compromising on the unique properties of plastics (e.g., barrier properties, formability, transparency).[161]

158 Material Economics (2018), *The Circular Economy.*
159 Material Economics (2018), *The Circular Economy.*
160 New research-stage processes based on electro-technology substitutes for distillation (including adsorption and membranes). ETC (2019), *Mission Possible.*
161 Low range: The Pew Charitable Trust and SYSTEMIQ (2020), *Breaking the Plastics Wave.* High range: analysis from Material Economics analysis (2021).

The optimal role of bioresources as feedstocks will reflect the principles outlined at the beginning of Section 2.2:

- **Technical readiness:** Bioresources can already be used as a chemical feedstock and as a substitute material (with technology readiness levels (TRLs) of 5 to at least 9 for those applications). Comparatively, chemical recycling and synthetic chemistry to produce plastics from hydrogen and DACC are at earlier stages of commercial development (TRLs of 7-9 and 5-7, respectively).[162]

- **Energy and land use intensity:** Using biomass as a feedstock is an energy-intensive decarbonisation route requiring 14 MWh (50 GJ) of biomass per tonne of plastics, in addition to 1.4 MWh electricity per tonne, while mechanical and chemical recycling only require 4 MWh and 1.1 MWh electricity per tonne, respectively.[163] As a result, bio feedstocks impose a much larger demand for land – about 0.1 hectares per tonne versus negligible land footprints for recycled or synthetic feedstocks.[164]

- **Cost competitiveness versus alternatives**: Material Economics estimate that the 2050 cost of using bio feedstocks could be close to other low-CO_2 technologies [Exhibit 2.6]. Depending on fuel prices (e.g., electricity and bio-feedstock prices) and technology developments, the bio-route may be the cheapest in the long term.

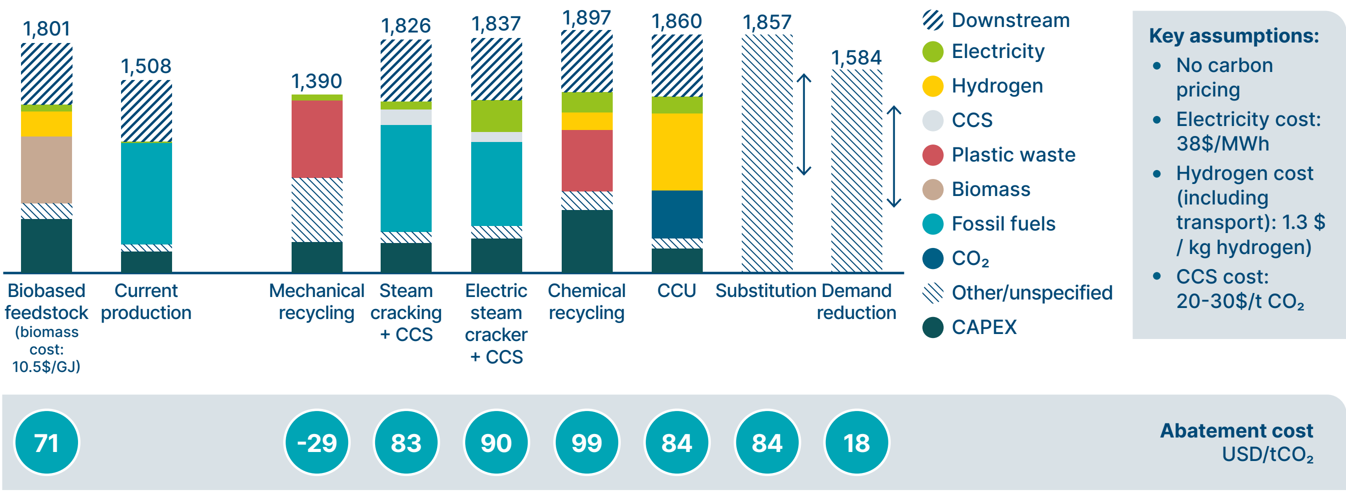
The optimal balance between different decarbonisation routes for plastics (and other chemicals) is inherently uncertain, but bio-feedstocks are highly likely to be a priority use of biomass. If recycling, more efficient materials use, and product substitutes could reduce virgin feedstock demand by c.20% by 2050, 34 EJ of biomass would be needed globally if all virgin plastics in 2050 was produced with bio-feedstock.[165] This compares with the total 40-60 EJ/year of sustainable supply estimated in our prudent scenario.

It is therefore essential to accelerate the development of alternative decarbonisation technologies in this area, alongside treating plastics production as a priority use of bioresources.[166]

Exhibit 2.6

The production of bio-based feedstock is slightly more expensive than mechanical recycling and similar in cost to other techs

Cost breakdown of technologies, global prices
USD per tonne plastics, 2050 (Indicative)



NOTE: Abatement cost calculated assuming zero-carbon electricity.

SOURCE: Material Economics modelling for the report "Industrial Transformation 2050"; Dechema, "Low carbon energy and feedstock for the European chemical industry" (2017).

162 TRL reference scale of 1-11 from concept to maturity. DACC: direct air carbon capture. Material Economics analysis (2021); IEA (2020), *ETP Clean Energy Technology Guide*.
163 Material Economics analysis (2021).
164 Energy Transitions Commission and Material Economics analysis (2021).
165 Material Economics analysis (2021).
166 Analysis by Material Economics suggests that materials efficiency, substitution and demand reduction can reduce total 2050 plastics demand by 20% and chemical and mechanical recycling by 40%. For comparison, in the report Breaking the Plastics Wave (reference above) all demand-side levers add up to 57% of total demand (20% from reuse and demand reduction, 17% from demand substitution, 20% from recycling).

2.2.2 Current applications of bioenergy – many are set to become uncompetitive against clean electrification

The last decade has seen the cost of renewable electricity and battery technologies plummet. As a result:

- Electrification (whether direct or via the use of hydrogen) will dominate road transport.
- Variable renewable sources (solar and wind) plus hydropower and, in some countries, nuclear power will dominate power generation.

Road transport

By 2050, zero-emission road transport can be achieved without any need for biofuels: previous and expected technological improvements in battery electric vehicles (BEV) and hydrogen fuel cell vehicles (FCEV) mean that nearly 100% of vehicle-km in 2050 can be driven with electric drivetrains in nearly all subsegments of road transport:

- Improvements in battery energy density and recharging capability are projected to allow BEVs to travel upwards of 400km on a single 30-minute charge, allowing BEVs to cover all road transport segments apart from long-distance, heavy-duty trucking.
- Declining costs of fuel cells together with reductions in the cost of hydrogen allow FCEVs to be the most cost-effective way to cover the long-haul segment, with synfuels able to cover the longest and heaviest segment.
- BEVs and FCEVs do not to produce any gas or particles at the point of use, which represents a major advantage over biofuels from an air pollution point of view, especially in urban areas.

In addition, from a cost perspective, bioresources are not projected to be competitive for any road transport segments by 2050:

- Biofuels are limited by the inefficiency of internal combustion engines (ICE) compared to electric engines, with an ICE typically consuming about 4 times as much primary energy as a BEV.
- While biofuels are likely to be cost-competitive as a low-emissions road transportation fuel in the short to medium term, they will not be cost-competitive with BEV and FCEV in 2050 [Exhibit 2.7].
- Limits to the supply of cheap green hydrogen may make biofuels cost-competitive for long distance trucking in a transition period, but this advantage will diminish over time.

The long-term role for biofuels in global road transport will therefore be very limited. It is possible that there will be a role for the last c.5-10% of very long road freight journeys, but better infrastructure of high-speed battery charging and/or hydrogen refuelling is likely to squeeze out even that role.

Other non-bio alternatives are possible if cost reductions and technology improvements do not proceed as anticipated in FCEV and BEV. Road electrification via overhead wiring remains a possibility for heavy transport fleets, especially those operating in limited areas (such as mines), though it is likely to be a secondary option to a successful hydrogen breakthrough. Synfuels, developed primarily for aviation fuel but with a product fraction viable for road transport,[167] could be used for extremely long-distance trucking applications but will not have a cost advantage over biofuels due to similar internal combustion engine efficiencies and higher costs of production.

The key strategic priority in road transport is therefore to drive electrification via the BEV route for autos, vans, and light-, medium-, and some heavy-duty trucks, as well as to develop hydrogen FCEVs for heavy-duty trucks traveling very long distances and on routes with limited charging infrastructure. This needs to be supported by the massive growth in clean electricity generation described in the ETC's recent report on *Making Clean Electrification Possible*. The issue of whether there is a transitional rather than permanent role for biofuels in road transport is considered in Box F.

167 Approximately 20%. World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.*

Is there a transitional role for biofuels in road transport?

Biofuels could be used immediately in medium and long-duty road transport applications where electric options are still at an early stage of development. Furthermore, biofuels can act as 'drop-in' fuels to decarbonise vehicles that are already on the road today. As a result, many voices argue that biofuels should play a significant transitional role in road transport. But this strategy could create stranded assets and delay a more complete transition for the sector.

Biofuels are already used, to a limited extent, in road vehicles in certain geographies today. A key question is therefore whether road biofuel production assets – which typically have 15 to 20-year lifetimes – can transition to other uses. The challenge differs by specific conversion technology:

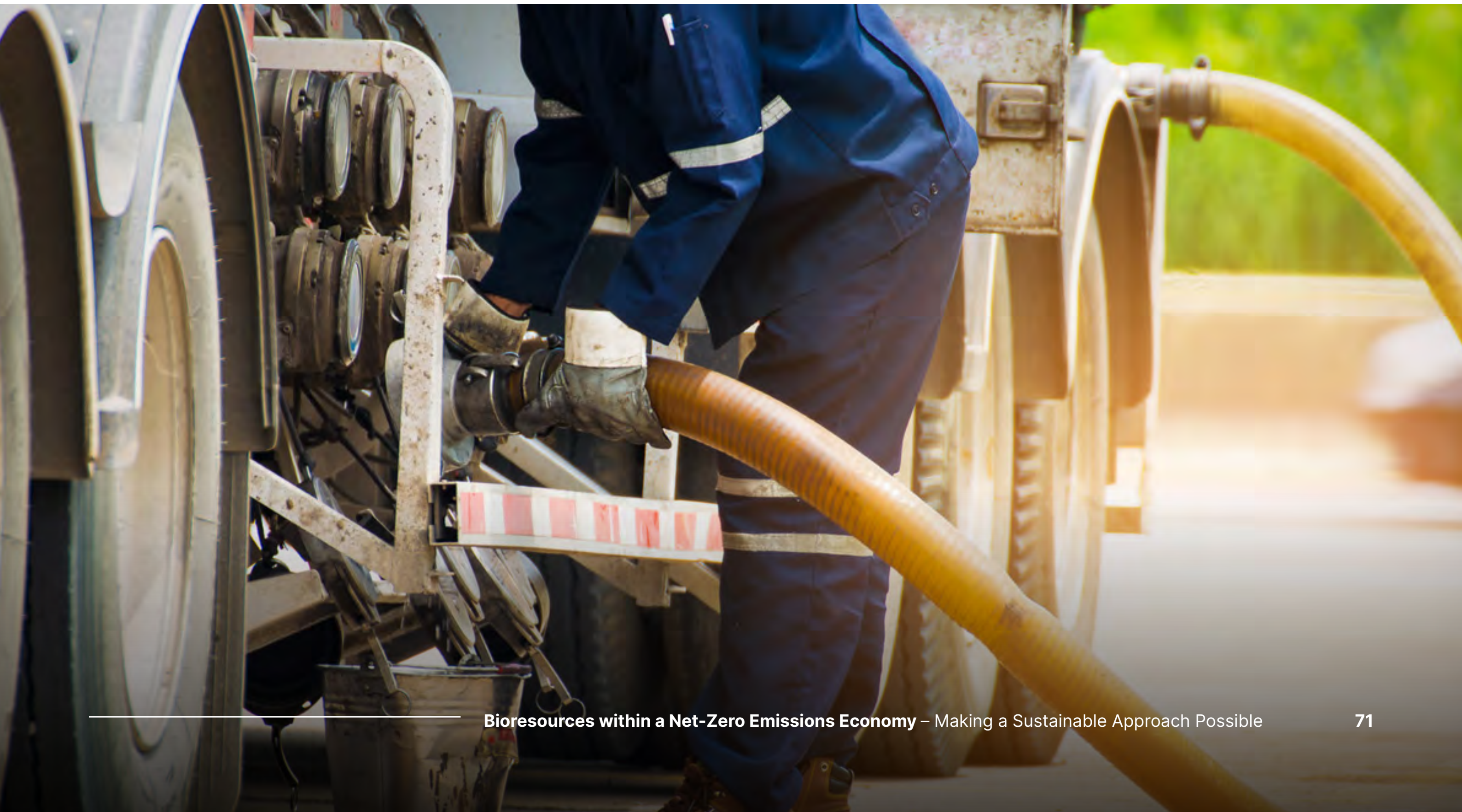
- Most existing facilities for road biofuels produce short chains hydrocarbons from enzymatic routes which can only be used in light-duty road transport fuels. But most of the plants (e.g., facilities producing ethanol) could be converted to produce Sustainable Aviation Fuels (SAF) through the 'Alcohol-to-Jet' process.[168]
- The more versatile process (thermochemical gasification) is not currently competitive or deployed on a commercial scale. Future cost reductions are expected to be more limited since equipment and feedstock costs represent a large share of total production costs.
- Nevertheless, targeted policy support should be used to bring the technology to scale.

Existing policies which support road transport applications (such as the EU RED mandate for renewable energy in transport) create a significant stranded asset threat, driving inefficient investment allocation and creating a powerful lobbying group in favour of the existing policy. To avoid lock-in effects, future policy should reflect the following principles:

- Support for road transport biofuels should be gradually phased out or focused entirely on the long-distance trucking sector.
- Existing production facilities which can produce aviation jet fuel should shift their production towards maximising production of bio jet fuel whilst reducing production of lower energy-density biofuels used in other sectors (e.g., shipping or road transport).
- Production facilities that cannot be converted to jet fuel should retire early or be dedicated to ultra-long heavy-road transport or shipping.

Box F

168 World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.*



Biodiesel will not be cost-competitive versus BEV and FCEV in road transport

Estimated total cost of ownership, zero emission road transport in 2050
USD/100 km

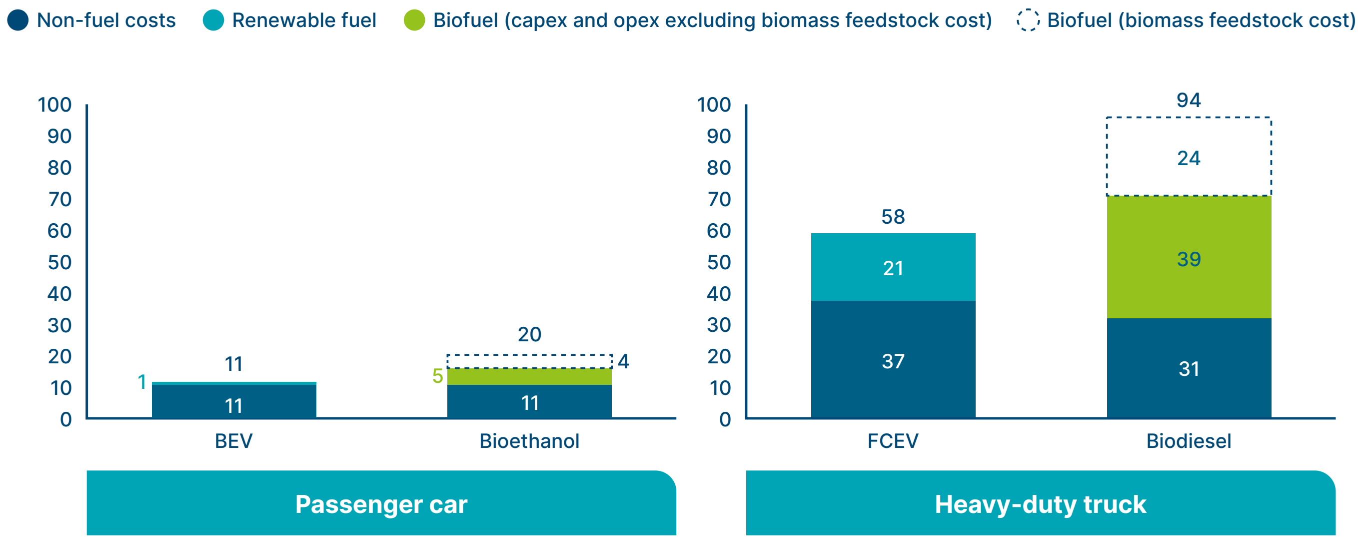


Exhibit 2.7

BEV: battery electric vehicle; FCEV: fuel-cell electric vehicle.
Assumes a 2050 global levelized cost of electricity of $20/MWh and hydrogen at $1.4/kg. Biofuel assumes a cost reduction by 2050 of 28% on non-feedstock OPEX/CAPEX costs from current figures (-15% 2020 to 2035, -15% 2035 to 2050).

SOURCES: Material Economics modelling based on IEA Renewable Transport Fuels (2020), Hydrogen Council "Path to Hydrogen Competitiveness", Transport and Environment "Comparison of hydrogen and battery electric trucks" (2020), IEA Global EV Outlook (2020), EAFO: The transition to a ZEF fleet by 2050 (2017).

Bulk power generation

Bulk power generation from biomass has been incentivised in many geographies. In the EU, the policy framework set by the 2018 Renewable Energy Directive (REDII) sets an overall binding renewable energy target of 32% of total energy consumption by 2030, including biomass for power generation as a renewable source, as long as it meets a number of sustainable criteria. Many recent scenarios continue to foresee a large role for biomass in power generation, with, for example, the 2020 IEA Sustainable Development Scenario forecasting that bioenergy will increase from 4% in 2019 of the global primary energy used for power generation to 13% in 2050 (from 9 EJ/year to 41 EJ/year).[169] The IEA's recent Net Zero scenario also notes that a role for biomethane in power generation is likely to become economic, which could help decarbonise existing gas generation assets in the 2020s ahead of the period when hydrogen combustion in gas turbines can compete.[170]

However, as the latest ETC report on *Clean Electrification* describes, the use of biomass for bulk power generation will be increasingly uncompetitive compared with variable renewable sources (wind and solar) and its role in providing daily power system flexibility will not be competitive compared with battery-based services.[171] Well before 2050, the cost of biomass feedstock would need to be negative (e.g., minus $2 per GJ) for bulk power generation by biomass to be competitive with solar generation.

Only if coupled with CCS, and with a carbon price to remunerate carbon removal, can biomass be cost competitive with renewable generation for bulk power generation. The relative economics depend on the cost of renewables, the price of carbon, and the cost of CCS. If renewables were available at $40 per megawatt hour, bio-based bulk power generation would be economic if the 'CCS profit' (i.e., the carbon price minus the CCS cost) were greater than $65 per tonne of CO_2. A carbon profit of $85 per tonne would be required if renewables were available at $20 per megawatt hour.

The crucial questions for biomass in bulk power generation are therefore:

- Whether there would still be a role for bio-based power plants for seasonal peak power provision (see Section 2.2.3).
- Whether CCS can be added to the process at a cost significantly below the price that will in future be paid for carbon sequestration (this is considered in Chapter 3).

169 IEA (2020), *Energy Technology Perspectives.*
170 IEA (2021) *Net Zero by 2050: A Roadmap for the Global Energy Sector.* In the IEA's analysis, plants that convert to biomethane in the 2020s continue to use biomethane in 2050.
171 Energy Transitions Commission (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy.*

2.2.3 Applications where other options are close to cost-competitiveness – bioresources use still needs to be constrained

In some sectors of the economy, bioenergy is either more technologically ready than alternative options or may initially be lower cost. Nevertheless, bioenergy use should still be limited in order to stay within sustainability constraints on supply. Public policy and private investment should therefore seek to drive rapid technological development and cost reduction of alternative non-bio-based decarbonisation routes in sectors such as:

- **Shipping,** where electricity-to-hydrogen based fuels such as ammonia or methanol will likely dominate in the long term.[172]
- **Seasonal power balancing**, where a range of non-bio-based options are possible.
- **Residential heating**, where electrification is likely to be the most efficient long-term solution, except in specific circumstances.
- **High-temperature industrial heat**, where the balance between direct electrification, hydrogen, and carbon capture technologies is still unclear, but any use of bioenergy is likely to be local and relatively small.

Shipping

Biofuels have long been considered a potential decarbonisation route for shipping, providing a drop-in alternative to existing fossil fuels (heavy fuel oil, marine diesel oil, or very low sulphur fuel oil), with very little or no need for engine retrofits. But with renewable electricity, battery, and hydrogen production costs falling rapidly, shipping companies are increasingly considering alternative decarbonisation options:

- **For short distances**, electric motors supplied with renewable electricity stored in batteries or from green hydrogen via fuel cells can be used.
- **For long-haul shipping** (83% of the maritime sector emissions),[173] electricity-based fuel alternatives like green ammonia, green methanol, or green hydrogen can be used.[174] Each would require increased storage space but could be burned in internal combustion engines that have been retrofitted to use clean fuels.

None of these alternatives for long-haul shipping are yet commercialised at scale; in contrast, biodiesel produced through gasification and catalytic synthesis of lignocellulosic biomass is already used in some existing ships. However, methanol burning engines are commercially available and the first commercial-scale carbon-neutral vessels are due to be launched by 2023-2025, utilising green methanol.[175] Additionally, significant commitments to the early development of ammonia burning engines and to fuel handling facilities have already been made,[176] and it is certain that ammonia and other non-bio options will be developed on a large-scale.

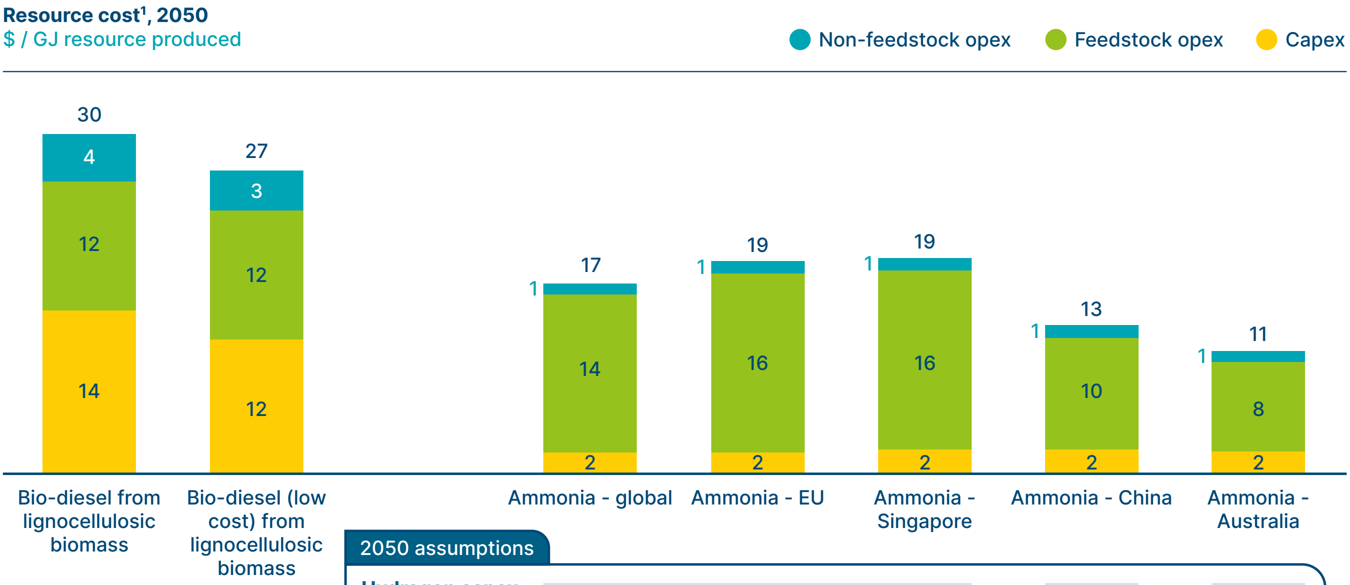
Cost estimates for 2050 suggest that, by then, ammonia will be the cheaper solution in all regions compared to biodiesel, and far cheaper in locations which enjoy low-cost renewable electricity [Exhibit 2.8]. The most important assumption within these cost estimates is the cost of producing green hydrogen. Ammonia will become cost-competitive if green hydrogen can be produced at less than $1.6 per kg, a level likely to be reached in some regions within the next 10 years and in almost all by 2050, as the recent ETC hydrogen report describes.[177]

During a transitional period and in some locations, however, biofuels are likely to be the lower-cost solution, and, if applied at scale, would use a large share of the available sustainable biomass. As an illustrative reference, 31 EJ of primary biomass would be required to meet 100% of the projected energy requirements for the long-haul shipping industry in 2050.

High priority must therefore be placed on accelerating the development of green ammonia and other alternatives that do not create demand for bioresources. This requires both action by the shipping industry to continue developing engines, ship, and fuel handling facilities, and rapid development of low-cost green hydrogen production at scale.

172 Methanol can be produced from biomass; however, biomethanol production for use as a transport fuel should be limited as clear non-bio alternatives exist. Biomethanol can alternatively be used as a building block for plastics production.
173 IMO (2020), *Fourth Greenhouse Gas Study 2020.*
174 'Green' refers to production using renewable electricity rather than fossil sources. Green hydrogen shipping engines have a lower technology readiness level than green ammonia and methanol engines today.
175 Offshore Energy (2021), *Maersk to operate world's 1st carbon-neutral feeder by 2023.*
176 Global Maritime Forum (2021), *The First Wave – A blueprint for commercial scale zero emission shipping pilots.*
177 ETC (2021), *Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy.*

By 2050, 'green' ammonia is likely to be significantly cheaper than bio-diesel due to declining costs of hydrogen from renewable electricity



2050 assumptions

	Ammonia - global	Ammonia - EU	Ammonia - Singapore	Ammonia - China	Ammonia - Australia
Hydrogen capex, $/kW	200			80	200
LCOE, $/MWh	20	25	25	15	10

Exhibit 2.8

NOTE: See worked example for detail on calculation. [1] Biofuel assumes a cost reduction of 27.8% on non-feedstock opex/capex costs from current figures (15% reduction 2020 to 2035, 15% reduction 2035 to 2050) or a 40.5% reduction (-15% from 2020 to 2035, -30% from 2035 to 2050) in the low cost case. Global green ammonia costs based on a 2050 'green' hydrogen price of ~$1.4/kg.

SOURCES: 2020 IEA Renewable Transport Fuels - Production technologies and costs; 2020 IEA Advanced Biofuels – Potential for Cost Reduction; Techno-economic assessment of zero-carbon fuels – LR/UMAS (2020); ETC analysis.

Seasonal power generation

For both bulk power generation and daily balancing, variable renewables, batteries, and pumped hydro storage are likely to be lower-cost than biomass-based generation (see Section 2.2.2 above). Power system balancing over longer durations is a greater challenge, with systems needing to balance supply and demand both in response to predictable seasonal variations and less predictable week-by-week developments.

One option to meet these needs is to use flexible thermal plants burning biomass. But multiple alternative options are also possible including:

- **Long-distance interconnection** with other regions (both within and across countries) which have complementary renewable resources.
- **The 'overbuild' of variable renewable energy (VRE) assets** to meet predictable seasonal peaks even if that means curtailment in periods of low demand.
- **Industrial demand management**, with major energy users planning maintenance or other shutdowns for periods in which demand can be predicted to be high relative to supply, and thus electricity prices likely to be elevated.
- **Hydrogen produced from electrolysis** when renewable energy electricity is in abundant supply and burned in combined cycle gas turbines (CCGTs) when needed.
- **Pumped hydro storage,** where water is stored at altitude in lakes and used to produce electricity at times of peak demand.
- **Natural gas generation with CCS**.

The parallel power report describes how a combination of these options could make possible systems up to 80-90% dependent on variable renewables at total system costs no higher than today.[178]

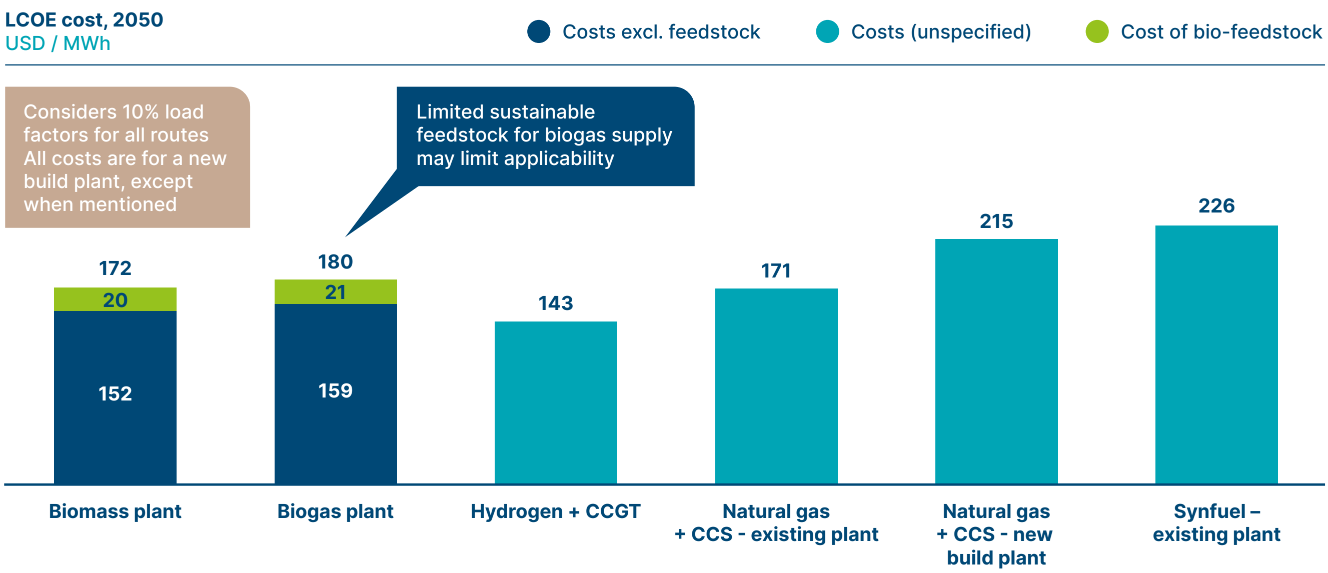
By 2050, cost estimates suggest that biomass generation for power balancing is unlikely to be cost-competitive with either [Exhibit 2.9]:

- **Natural gas plus CCS**, even if the assets (including CCS assets and infrastructure) are only operated for 10% of the year.
- **Green hydrogen burned in CCGTs**, which would potentially be c.15% cheaper than biomass generation, if hydrogen is available at $1.4 per kg.

Even if biomass were cost competitive with these options, the massive scale of energy needs for the power system makes it essential to focus primarily on non-bio alternatives, as if just 5% of predicted 2050 global electricity supply came from biomass-based generation, this would require 35 EJ of biomass per year, well over half our estimate of total prudent supply.

Exhibit 2.9

For seasonal flexibility, the hydrogen and CCS routes could be more cost-effective than bio-options by 2050



Key assumptions: Biomass plant: Capex: 2600 USD/kW, Opex: 3% of CAPEX. Hydrogen +CCGT: Capex: 1,000USD/kW for H2-ready turbine (BloombergBNEF), hydrogen cost: 1.4USD/kg including transport, Opex: 3% of Capex. Natural gas + CCS: CCS only Capex: 2590USD/kW, CCGT Capex: 783USD/kW. Opex: 20USD/kW/year.

SOURCES: IRENA (2018) *Power Generation Costs*; IRENA (2012)*Biomass for power generation*; Lazard (2018) *Levelized cost of energy analysis*; Strengers B., et al. (2018), *Negatieve emissies; Technisch potentieel, realistisch potentieel en kosten voor Nederland*; Guidehouse (2020) *Gas decarbonization pathways 2020-2050.*

Building heating

In heating for commercial and residential buildings, electricity is likely to be the dominant technology with a cost-competitive role for biomass restricted to some special circumstances. Heating demand is concentrated in mid- to high-latitude countries, and, in some geographies, electricity already plays a major role. In others, however, gas is the primary heating source, while northern China, for example, relies heavily on coal-based distributed heating systems.

The most cost-effective decarbonisation solution will be highly dependent on local conditions such as fuel prices, hours of sun, geothermal activity, and local resources and infrastructure. In most locations, heat-pumps will be the most cost-effective option, but Combined Heat and Power (CHP) with biowaste can be cost-effective for district heating.

- **Heat pump technologies** are improving rapidly at both small and large scales and for a growing range of temperatures. Their main advantage is their inherent energy efficiency which can reach over 300% (i.e., 3 kWh of heat delivered per kilowatt-hour of electricity input)[179] versus 100% for electric resistive heating, 90% from new gas boilers, and 60% for some old boilers still in operation. Significant further improvements in heat pump efficiency are also technically possible, with many studies suggesting 500-600% efficiency is feasible.[180]

178 ETC (2021), *Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy*.
179 This high efficiency is due to the ability of a heat pump to move heat already in the environment rather than create it.
180 Fraunhofer IEE (2020), *Hydrogen in the Energy System of the Future: Focus on Heat in Buildings.*

- **Resistive heating** provides another electricity-based option which may be more suitable for older housing stock with high retrofit costs where heat pumps are not feasible for climate or cost reasons.

- **Biowaste** can be used as a fuel in CHP plants that also generate electricity to improve efficiency levels. However, this solution will only be cost effective where district heating networks already exist and where supplies of biogenic waste are available, which limits its applicability. To achieve net zero-emissions operation, fossil fuel-derived waste (i.e., plastics) will need to be separated from the biogenic waste or the heating plant would have to be retrofitted with CCS (see Chapter 3), which are both complex and expensive processes.

Biomass for building heating will therefore only be cost-competitive where very low-cost, local bio-feedstock is available, where there are additional revenue streams (e.g., from waste disposal), or where there are significant sunk costs in infrastructure (i.e., district heating networks).

Electrification should therefore be favoured in most locations as the most competitive and resource-efficient solution for building heating. The impact of biomass combustion on air quality in cities constitutes an additional argument in favour of electrification. This will, however, require strong transitional policy support for existing buildings in order to overcome the significant upfront cost involved in replacing gas boilers with heat pumps and the investment in building insulation which will be needed in certain geographies. Electric heating and energy efficient building design should be mandated for all new buildings, supported by regulations, subsidies, or other incentives that drive accelerated retrofit.[181]

Traditional bioenergy use[182]

Traditional uses of bioenergy represent more than half the demand for primary biomass today (around 5% of the global primary energy demand). ‘Traditional bioenergy’ refers to inefficient and high-polluting use of solid biomass for direct combustion, particularly in developing countries. Fuels burned include wood, charcoal, manure, and other organic wastes and residues. A third of this volume is estimated to be trees from forests[183] and two-thirds are trees outside forests and other wastes.

The uses of traditional bioenergy are environmentally unsustainable:

- Solid biomass is often extracted from protected natural areas.
- Collection of forest biomass contributes to deforestation in some developing regions.
- Charcoal harvests currently exceed regeneration rates.

These uses provide cooking heat to around 3 billion people in the poorest areas of the world, but have a very negative impact on health:

- The combustion on open fires and traditional stoves are inefficient and poorly ventilated, leading to indoor air pollution and respiratory illness, causing almost 1.6 million deaths per year.
- The labour demands of collecting the biomass have negative socioeconomic impact, affecting mostly women and children.

It is therefore crucial that traditional uses of bioenergy are phased out in favour of improved access to modern cooking fuels and stoves. This requires strong efforts towards electrification (on and off-grid) or other clean cooking options, and socioeconomic development of remote poor and developing areas.

In this report we therefore exclude traditional biomass from our supply and demand estimates. We also do not assume that traditional biomass supplies can be diverted to new applications, since the collection of this distributed supply will often be prohibitively expensive and because most of this biomass is best left untouched in order to avoid deforestation or damage to protected areas.

Box G

181 ETC (2019), Mission Possible Sectoral Annex on Building Heating.
182 This section draws on the report from the UK Committee on Climate Change (2018), *Biomass in a low-carbon economy* (Box on ‘Traditional bioenergy’, page 28).
183 Collection of wood for traditional uses is unaccounted for in FAO forestry statistics. The sourcing, and thus sustainability attributes, of the biomass is also unknown.

Industrial heat supply

Low temperature industrial heat

For low-temperature heat, biofuels face strong competition from industrial heat pumps. Bio-based options would only be competitive when they can use cheap residues or waste that could not be economically used elsewhere, and in periods when electricity prices are high. By far the largest user of bioenergy for industrial low-temperature heating today is the pulp and paper industry, where heat is produced from low value biomass waste streams. This has enabled the sector to phase out most fossil fuel use.

As renewable electricity prices decline over time, these uses could be progressively phased out in favour of electrification. This is especially likely as competition for limited biomass supplies becomes tighter. In this scenario, collection and transportation mechanisms would need to be developed so that the freed up bioresources can be transferred to other uses (e.g., fibre uses, chemicals or biofuels production facilities). This trend could create extra biomass availability for other prioritised uses: three EJ of biomass could potentially be freed up by the full electrification of heat in the pulp and paper industry in 2050.[184]

High temperature heat and steelmaking

For industrial processes requiring high temperature heat, the long-term cost trade-off between bio-based decarbonisation routes and other options is unclear. The viability will depend on the technological progress of electricity-based routes, the local cost of bio-feedstocks, and the age and condition of existing industrial assets (since a switch to electricity or hydrogen-based solutions will often require building a greenfield asset, while the bio-based route may allow continued use of existing infrastructure).

In some cases, biomass may remain competitive against alternative options. A review of major alternatives (a range of direct electrification and hydrogen technologies) suggests that biofuels could be the lowest-cost option at prices as high as $5-8 per GJ in Europe,[185] depending on future electricity prices. But high-temperature processes often require highly refined fuels in gas or liquid form which are substantially higher cost than raw biomass. Meanwhile, electrical heating brings important advantages, both in precision and energy efficiency (e.g., where microwaves could be used), or in improved process efficiency (e.g., in avoiding materials losses in the reheating of steel). In principle, hydrogen can be used to produce very high temperatures, but some studies suggest that its flame is not well suited to cement production in particular, and the continued use of fossil fuels combined with CCS (which will, in any case, be required to capture cement process emissions) may be a cost-effective alternative. Other high-temperature heat processes (e.g., furnaces, boilers, and burners in refineries, glass, and ceramics industries) may be able to switch to hydrogen, but the precise balance between direct electrification and hydrogen in these sectors remains unclear, with technical innovation required in both routes.

Producing primary (ore-based) steel constitutes a special case as the fuel is used both as a source of heat and a reducing agent for the iron ore. In the form of charcoal, due to its carbon content, biomass can play both roles in a blast furnace. Biomass for steel also allows the continued use of existing production facilities, but current charcoal production is a major cause of deforestation and therefore often has a high land use and indirect CO_2 emissions footprint. Alternative decarbonisation routes such as hydrogen-based Direct Reduced Iron (DRI) – where some projects are already in development - and carbon capture and storage are likely to play a much larger role in decarbonising the steel sector. Furthermore, direct electrolysis may become technically and commercially feasible at some point in the future.

The use of bioresources is therefore likely to be limited to local uses in regions with abundant and low-cost biomass supply. However, given increasing demand for a limited supply of sustainable biomass, such cheap local resources (where proximate to port infrastructure) may increasingly be diverted to international trade to satisfy other, higher priority applications.

184 The pulp and paper industry will use c.5.5 EJ/year of final energy in 2050, out of which 55% will come from biomass. Source: IEA (2017), *Energy Technology Perspectives.*
185 Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*

2.2.4 Aviation - the only clear priority sector beyond materials

In many of the sectors described above, electricity or hydrogen (or ammonia derived from hydrogen) provide an increasingly cost-effective alternative route to decarbonisation than bioenergy. In aviation, this will also be true over short distances, but almost certainly not for long distance flights.[186] As a result, biofuels for aviation are likely to be a priority application of the limited supply of sustainable biomass, at least during a lengthy transition period.

Electricity, hydrogen, and hybrid planes are highly likely to play a major role for short and increasingly medium distances, potentially replacing jet fuel at distances up to 1000 km (currently accounting for about 25% of all aviation emissions).[187] But without a dramatic and currently unforeseeable improvement in battery energy density, or a fundamental redesign of aircrafts to accommodate far larger hydrogen volumes, these technologies will not be able to power long-haul aviation. The path to net-zero emissions in long distance aviation therefore relies on some combination of biofuels and synthetic or electro-fuels (synfuels or 'power-to-liquids'), collectively known as Sustainable Aviation Fuels (SAFs). While bio SAF routes are more technically ready than non-bio options, neither are deployed at scale today:[188]

- **Biofuels derived from waste oils and lipids** are commercially available today and production could be scaled up rapidly, but feedstock supply limits its potential to 5% of total jet fuel consumption globally.[189]

- **Biofuel production from lignocellulosic biomass** is not yet mature (c.5 years from large-scale commercial deployment). Production is likely to ramp-up from 2030 onwards.

- **Power-to-liquid fuels (synfuels)** are produced through the conversion of electricity and carbon dioxide into liquid hydrocarbons. This is achieved in a step-wise fashion via production of 'green' hydrogen from electrolysis, followed by reverse-water-gas-shift reaction with CO_2 to form syngas and ultimately catalytic Fischer-Tropsch synthesis for fuel production.[190] Power-to-liquid or 'synthetic' jet fuel implies higher energy losses than more direct uses of electricity due to the conversion steps involved. For this pathway to be sustainable in the long term, it requires not only zero-carbon hydrogen but also a renewable source of CO_2, from direct air carbon capture (DACC) or biogenic carbon. In the short term, however, CO_2 from industrial waste sources will be cheaper and more readily available to develop initial volumes, prove production at scale, and drive learning curve effects. This achieves a 'second use' of fossil carbon atoms but is not a net-zero emissions solution.

Analysis of likely future costs suggests that synthetic fuels may be cheaper in the long term, but that biofuels could be the most cost-competitive option for a lengthy transition period [Exhibit 2.10]:

- By 2050, synthetic fuels could be cheaper than biofuels if hydrogen were available at $1.4 per kg and if direct air capture of CO_2 were possible at around $100 per tonne. To compete against such costs, biomass would have to be available at less than $2 per GJ.

- But today, biofuel costs are less than 50% of those for synthetic fuels and likely to remain significantly lower well into the 2030s: biofuels will likely be cheaper than synthetic fuels in 2030 provided biomass is available at less than $10 per GJ.

- An alternative option, put forward by some, is that fossil fuel use in aviation could continue, and it would be cheaper to offset these emissions using direct air capture than to replace fossil fuels with biofuels or synthetic fuels.[191]

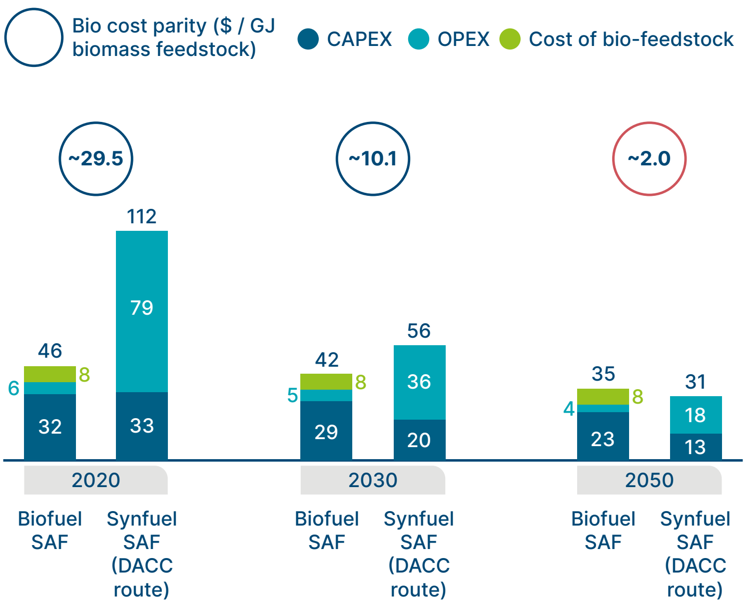
Long haul aviation thus faces the challenge of a possible double transition in future fuel supply (though not in terms of engine design): biofuels are needed in the coming two decades, but limits on sustainable feedstock supply mean that synfuels will also be needed to reach net-zero aviation by mid-century. In 2050, both options will likely play a major role with significant demand for sustainable biomass alongside a major role for DACC-based synfuels.

If, in 2050, half of global energy demand for medium- and long-distance aviation were met with biofuels, this could require about 15 EJ/year of biomass feedstock.

186 Due to weight and volume limitations.
187 Waypoint 2050, (2020), *Report of the Air Transport Action Group (ATAG).*
188 World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.*
189 These feedstocks are often termed HEFA: hydrogenated esters and fatty acids. World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.*
190 World Economic Forum (2020), *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.*
191 See, for example, UK CCC (2018) *Biomass in a low-carbon economy.* Offsetting fossil use with Direct Air Carbon Capture (DACC) would present additional challenges in scaling up both DACC and renewable technologies. Additionally, this option doesn't address other forms of air pollution from fossil fuels that occur during combustion. This option isn't considered directly in this report but will be explored further in the ETC's upcoming report on Carbon Dioxide Removals.

Synfuels using renewable electricity and direct air carbon capture (DACC) are unaffordable today but may become competitive if 'green' hydrogen and DACC take off

Resource cost
$ / GJ SAF produced



Sensitivity analysis – Bio cost parity, global 2050
$ / GJ biomass feedstock

Bio cost-competitiveness

Hydrogen cost / Direct air capture cost	$2 / kg	$1.4 / kg	$1 / kg
$300 / tCO_2	13.5	10.2	7.9
$150 / tCO_2	7.4	4.1	1.8
$100 / tCO_2	5.3	2.0 *Scenario illustrated*	-0.2
$75 / tCO_2	4.3	1.0	-1.2

Exhibit 2.10

Biofuel SAF assumes a cost reduction by 2050 of 28% on non-feedstock OPEX/CAPEX costs from current figures (-15% 2020 to 2035, -15% 2035 to 2050) based on IEA projections for thermochemical conversion processes. Synfuel SAF assumes 2050 cost of hydrogen at $1.4/kg H_2, DACC at $100/t CO_2 captured, and even cost allocation amongst products (70% SAF yield from synfuel in 2050).

SOURCES: Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (2020); ETC analysis; Kraan et al., An Energy Transition That Relies Only on Technology Leads to a Bet on Solar Fuels, Joule (2019); 2020 IEA Renewable Transport Fuels - Production technologies and costs and 2020 IEA Advanced Biofuels – Potential for Cost Reduction.

2.2.5 Biomass gasification for hydrogen production

While clean electrification must be at the heart of all strategies to achieve a zero-carbon economy, other technologies will be required where direct electrification will likely remain impossible or uneconomic. Thanks to its energy density, storage, and transportability characteristics, hydrogen will play a major role in those sectors. In our recent report on the hydrogen economy, the ETC estimates that total global hydrogen use could grow 5-7 fold from today's 115 Mt per annum to reach 500 to 800 Mt by mid-century, with hydrogen accounting for 15-20% of final energy demand on top of 65% or more provided by direct electricity.[192]

All of this hydrogen must be produced in a low- or zero-carbon fashion, with two technology types almost certain to dominate:

- **'Green' hydrogen production** via the electrolysis of water which can be zero carbon if all the electricity used comes from zero-carbon sources.
- **'Blue' hydrogen production** which entails adding carbon capture and storage (CCS) to either Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR) or the use of POX (partial oxidation) of natural gas. These technologies differ in the carbon capture rates which they can achieve, with at least 90% considered the minimum for 'low carbon' hydrogen.

It is also possible to use biomass gasification to convert biomass to hydrogen and other products, without combustion. Once gasified, biomass can have a variety of use cases, including being used directly as hydrogen, burned directly as a fuel, or being upgraded to synthetic fuels (e.g., for use in aviation, or as ammonia in shipping). Gasification plants for biofuels are already being built and other biomass production routes are also being explored. These include biomass pyrolysis (application of heat without oxygen) to produce biochar, bio-oil, and gases including hydrogen, plus emerging biochemical routes and biomethane SMR or ATR (i.e., using biogas captured from waste).

192 Energy Transitions Commission (2021), *Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy.*

As the ETC's hydrogen report sets out, green hydrogen is likely to be lower cost than blue hydrogen in the long term and in most locations, and by mid-century could be lower cost than grey (fossil-based) hydrogen in many regions that have cheap renewable power resources. It will also likely be cheaper than bio-based hydrogen at any biomass price above $4 per GJ and it will be far more resource efficient. Hydrogen production via biomass gasification will require 10 times as much land devoted to biomass production than needed for renewable power generation for green hydrogen production.[193]

However, it is also possible to add CCS to bio-based hydrogen production, improving the economics if the carbon price minus the cost of CCS generates a significant 'CCS profit.' If biomass costs were low and carbon prices above $100 per tonne, biobased hydrogen might therefore compete with green hydrogen [Exhibit 2.11]. Some studies – including the Net-Zero America Princeton Study[194] - therefore see a major role for biobased hydrogen production as a means to achieve carbon removal. The potential implications of this for the optimal allocation of limited sustainable biomass supply are considered in Chapter 3.

Producing hydrogen from biomass is only cost-competitive under scenarios with a high price for concurrent carbon dioxide removals

Cost of hydrogen production
USD/kg hydrogen

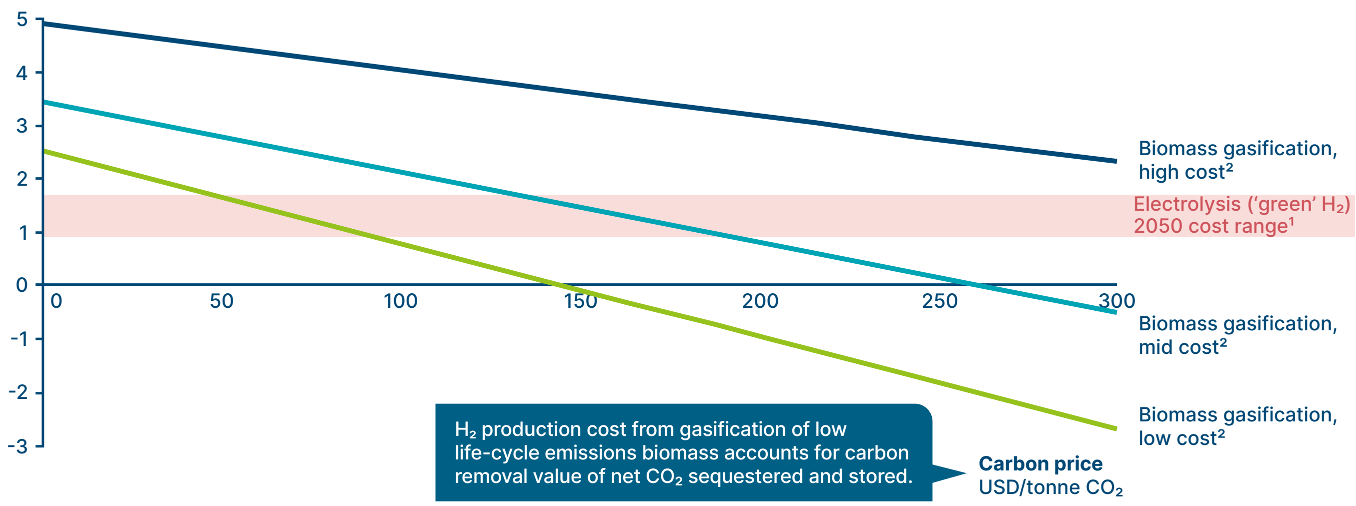


Exhibit 2.11

[1] Assumes 2050 LCOE of $10-29/MWh and CAPEX of $60-145/MW. [2] Hydrogen produced from biomass gasification assumes supply chain and process emissions losses of 50%, 25%, or 0% (in high, mid, and low cost scenarios, respectively) – these reduce the net carbon dioxide removal achievable. Biomass feedstock prices modelled are 11.7, 7.8, or 3.9 $/GJ (0.17, 0.11, or 0.06 $/kg). CAPEX for gasification and carbon capture is assumed to be 4,050, 2,700, or 2,160 $/kW H_2 (HHV). All scenarios assume an average energy content of biomass feedstock of 14 GJ/tonne, production yield of 0.095 kg H_2 / kg biomass feedstock, plant size of 300 MW, lifetime of 20 years, interest rate at 6%, utilisation of 95%, non-feedstock OPEX (operations & maintenance) of 6% of CAPEX, CO_2 capture rate of 90%, and a CO_2 transport & storage cost of $20/t$CO_2$.

SOURCES: ETC (2021), Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy; IEA (2018) Hydrogen from biomass gasification; Larson et al. (2020) Net-Zero America; IEA (2020), Advanced Biofuels – Potential for Cost Reduction; IEA (2021) Net-Zero by 2050.

2.3 Balancing supply versus demand

The four priority sectors for biomass use identified in this chapter are wood products, pulp and paper, plastics feedstock, and aviation. But, for illustration, if all the demand of just these four sectors were met with biomass, the total demand could reach c.90 EJ/year, exceeding our prudent estimate of 40-60 EJ/year of sustainable biomass supply (including biomass for materials). As Chapter 1 discussed, it is possible, though far from certain, to increase this supply sustainably. Changes in diets and food production technology might free up agricultural land (which could be used for bioenergy production) or other sources of biomass may be developed further (i.e., waste and macroalgae). This could result in up to an additional c.60 EJ/year of sustainable biomass supply becoming available by 2050.

Where possible, a portfolio of solutions should be developed. Demand for two of the priority sectors could be reduced by combining the use of bioresources with other decarbonisation options:

- In the case of plastics feedstocks, this would require a greater focus on circularity and recycling: in Material Economics' pathway, 60% of total demand for plastics could be covered by demand reduction and substitution in key supply chains (19% reduction of the demand for primary plastics) and chemical and mechanical recycling (respectively 26%

193 For assumptions, see ETC (2021), *Bioresources in a net-zero economy – Technical appendix* (to be published in 2021).
194 Larson et al. (2020), *Net-Zero America: Potential Pathways, Infrastructure, and Impacts - Interim Report.*

and 15% demand reduction), reducing the need for biomass from 41 EJ to 16.5 EJ per year in 2050.[195]

- In the case of aviation, if 50% of 2050 jet fuel consumption were provided by synthetic rather than biofuels, the required supply would fall from 30 EJ to 15 EJ.

With these adjustments, decarbonising the four sectors would result in 54 EJ of biomass demand – just within our prudent scenario for sustainable supply range [Exhibit 2.12].

In fact, the allocation of sustainable bioresources to different applications will vary by region and should reflect market prices, evolving technologies and costs, and the enforcement of strict regulations to require that only sustainable biomass is developed. But the likely imbalance between large-scale demands and constrained sustainable supply, which Exhibit 2.1 illustrates, implies that public policy must focus on:

- Not distorting the market by encouraging applications which do not constitute priority uses of bioresources.
- Discouraging the use of biofuels in sectors – such as road transport – where there are clear cost-competitive alternatives to decarbonise.
- Developing and deploying the alternative technologies (e.g., ammonia for shipping) which could reduce demand for biofuels in non-priority sectors.

Chapter 4 discusses the appropriate policy framework implied.

Meanwhile, meeting climate targets will require significant 'carbon removals', and bioenergy plus CCS (BECCS) is one route to achieve this. Chapter 3 therefore discusses how the need for carbon removal might change the relative economics and priorities considered in this chapter and the implications for optimal strategy if and when extra bioresources could be made available before mid-century.

Balance between supply and demand for biomass in a net-zero economy can be reached if use of biomass is prioritised and combined with other decarbonisation options

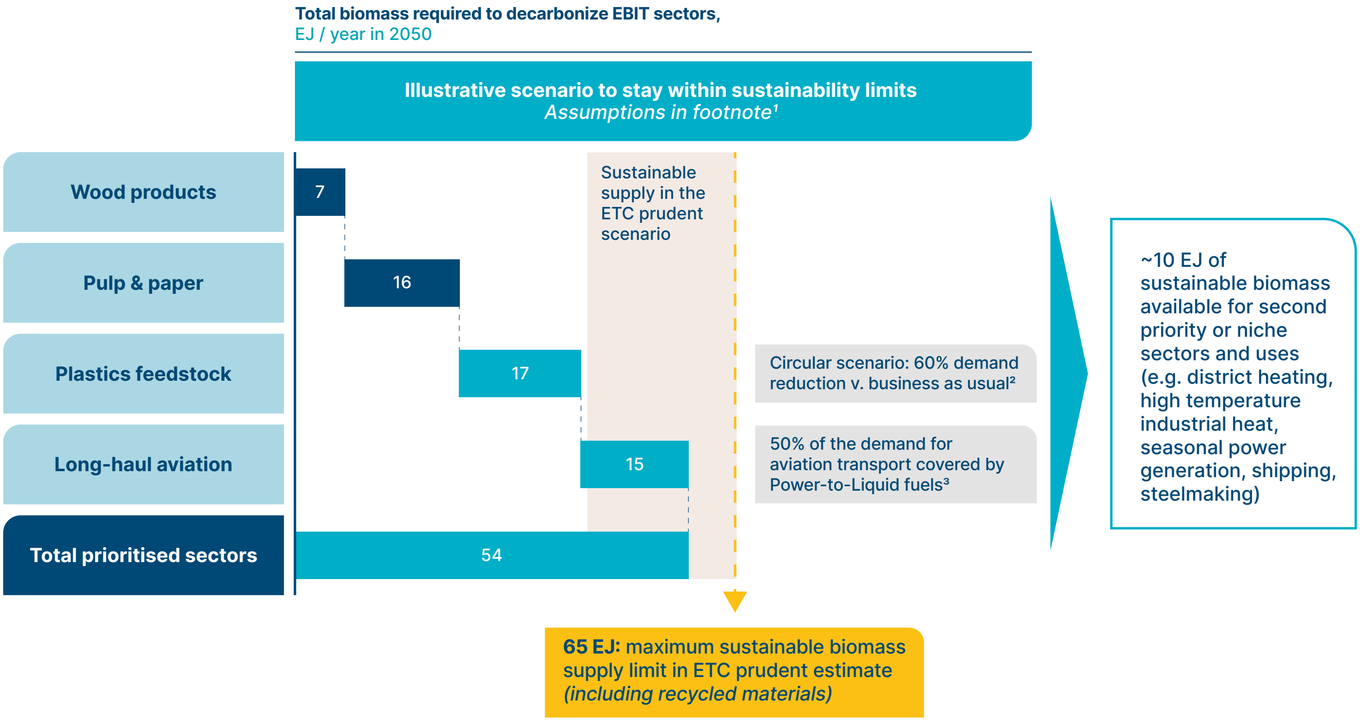
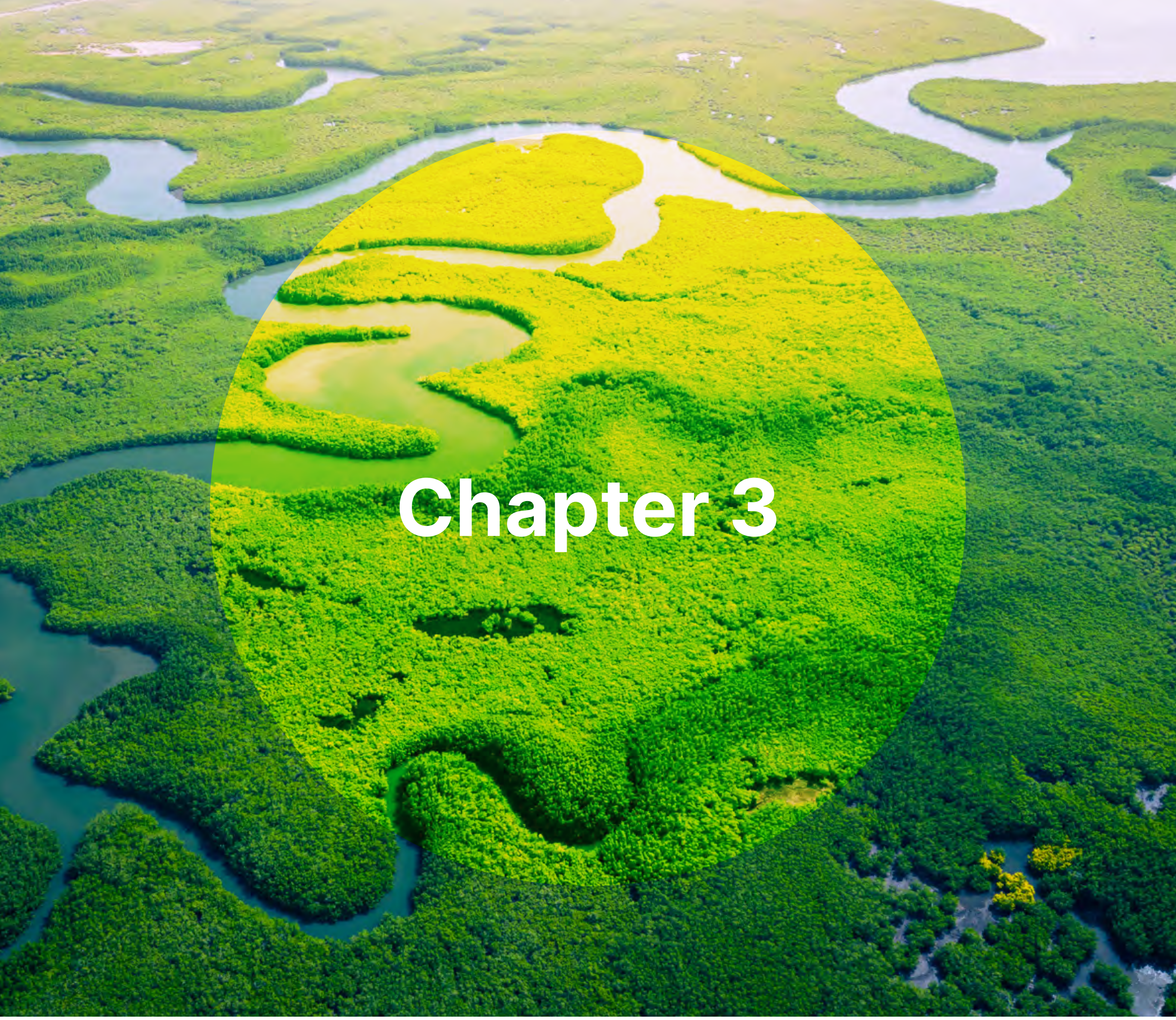


Exhibit 2.12

[1] **Wood products:** 824 Mm3 demand for wood product in 2050 (+21% vs 2006); 0.009 EJ/Mm3. **Source:** Material Economics (2021) *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
Pulp and paper: 550 Mt demand for pulp in 2050; 80% pulp yield per t feedstock; 0.19 EJ/Mm3. **Source:** Material Economics (2021).
Plastics feedstock: 818 Mt plastics demand in 2050; 51 GJ biomass per t plastics; 60% circularity and recycling in an average zero-carbon pathway v. business-as-usual (19% circularity, 15% mechanical recycling, 26% chemical recycling). **Source:** Material Economics (2021).
Aviation: 19 EJ final energy demand for aviation in 2050 (IEA RTS); 46% biomass to biojet fuels efficiency; 73% long-haul demand. **Source:** IEA (2017), *Energy Technology Perspectives.*
[2] Through increased materials efficiency, reuse and recycling. Corresponds to 56% demand reduction vs business-as-usual 2050 scenario.
[3] If in addition to the deployment of PtL, energy efficiency and modal shifts are optimised (based on the 2DS scenario of the IEA Energy Perspectives 2017), demand for biomass for aviation could go down to 10 EJ.

195 Analysis by Material Economics (2021).



The role of bio-based carbon dioxide removal

Chapter 2 assessed priority uses of biomass as a source of materials, chemical feedstocks, or energy. But it is also possible for biomass production to be used to generate 'carbon dioxide removals' (or 'negative emissions') if the photosynthetically fixed CO_2 is followed by some form of long-term carbon storage without the re-release of CO_2. This chapter therefore considers how the prioritisation of use cases might change once the potential need for carbon removals is taken into account. It draws on the analysis presented in the ETC's recently published consultation paper '*Reaching climate objectives: the role of carbon dioxide removals*'.[196]

We consider in turn:

- How much carbon removals are needed to meet climate objectives.
- The portfolio of options for carbon removal.
- Their relative merits and trade-offs along several dimensions – technical readiness and cost, permanence of CO_2 storage, resource efficiency, and other benefits and disadvantages.
- The potential role of BECCS given either a prudent case or higher case estimate of sustainable biomass supply.

3.1 Carbon removals are needed to meet climate objectives

IPCC climate models assume that some level of 'carbon removals' will be needed if the world is to meet a climate objective of limiting global warming to well-below 2°C, with even more required to meet a 1.5°C objective. The required scale reflects not only the chosen climate objective, but also assumptions about the pace at which both long-lived (CO_2 and N_2O) and short-lived (methane – CH_4) greenhouse gases can be reduced. As a result, estimates of the required future carbon dioxide removals vary greatly; different IPCC scenarios suggest a range from 2.5-16 $GtCO_2$ per annum in the 2050s.[197]

The ETC's consultation paper on carbon dioxide removals sets out our initial estimates of the quantity of CO_2 removal required.[198] It draws on ETC analysis of the feasible pace at which emissions from the energy, building, industry, and transport (EBIT) sectors of the economy can be reduced, together with similar estimates for the agriculture, forestry, and other land use (AFOLU) sectors. Our illustrative scenario focuses on the climate objective of 1.5°C global warming above pre-industrial levels and assumes that methane emissions could be reduced by approximately 40-50% by 2050.

We will refine our estimates during the course of 2021, but Exhibit 3.1 summarises the initial conclusions. It suggests that:

- By mid-century, it would be possible to get CO_2 emissions from both the EBIT and AFOLU sectors close to 'net zero' – where 'net' here accounts for the use of carbon capture and storage (CCS) within industrial or power applications, but not as a separate 'carbon removal' technology. As a result, the long-term need for carbon removals to compensate for unavoidable residual emissions would be only 1-3 $GtCO_2$ per annum, which is considerably smaller than some other scenarios suggest.
- The feasible pace of emission reductions, however, will likely follow the convex curve shown on Exhibit 3.1, which is not nearly as fast as the pace required to meet IPCC's 1.5°C objective.
- As a result, there is a significant 'carbon overshoot gap' that will have to be closed by carbon dioxide removals. This could amount to around 200 $GtCO_2$ cumulatively over the next three decades, implying the need for average carbon removals of around 6 $GtCO_2$ per annum during that period.

196 ETC (2021), *Reaching climate objectives: the role of carbon dioxide removals.*
197 IPCC (2018), *Special Report on Global Warming of 1.5°C (SR1.5).*
198 ETC (2021), *Reaching climate objectives: the role of carbon dioxide removals.*

Further analysis may identify potential for faster and/or earlier reduction in both methane and CO_2 emissions, reducing the size of the overshoot gap and the need for carbon dioxide removal. Policy should focus strongly on achieving those reductions, but slower progress would of course increase the need for carbon removals. Moreover, if carbon removals do not develop as rapidly as needed to close the gap in the earlier decades, greater removals will be required in the future. As a result, the need for ongoing carbon removals beyond 2050 might turn out to be higher than Exhibit 3.1 suggests.

Despite uncertainties about precise figures, it is clear that carbon removals will have to play a significant role in meeting climate objectives and do so in addition to as-rapid-as-possible decarbonisation within the EBIT and AFOLU sectors.

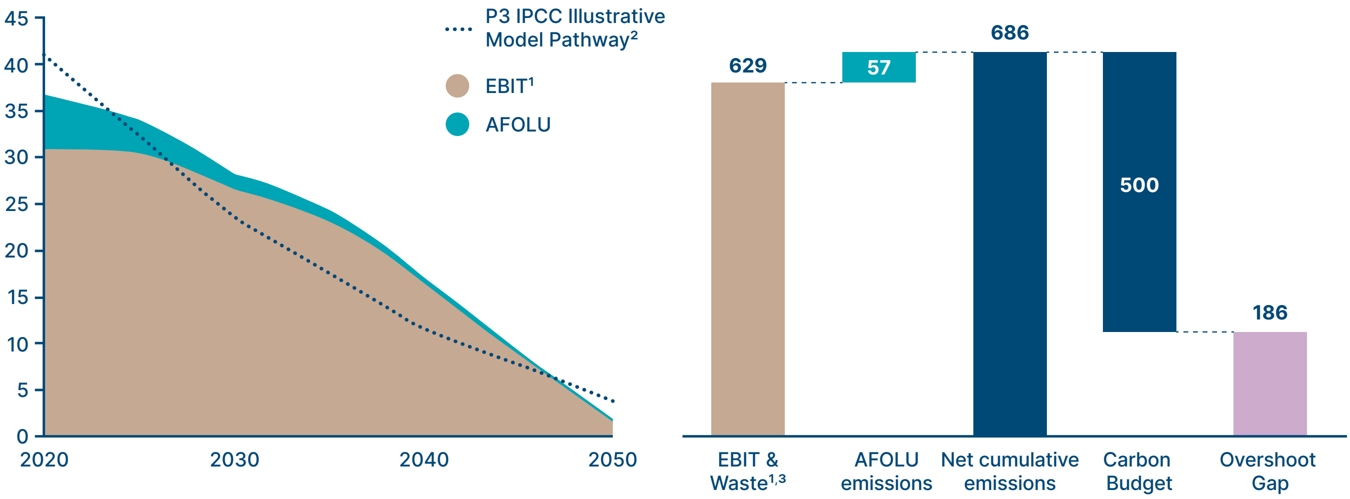
Exhibit 3.1

Carbon dioxide removals are needed to meet climate objectives: cumulative emissions expected to be ~200 $GtCO_2$ above the carbon budget by 2050

Preliminary

Total annual gross emissions across sectors,[1] shown in contrast with IPCC limited overshoot 1.5°C pathway for net emissions ($GtCO_2$/year)

Cumulative emissions across sectors and compared with the carbon budget ($GtCO_2$ 2020-2050)



NOTE: EBIT: Energy, building, industry, and transport sectors. AFOLU: Agriculture, forestry, and other land use.
[1] Point-source CCS assumed as part of within-sector decarbonization for EBIT sectors. [2] IPCC in 2018 published 42 modelling scenarios for >1.5°C, drawing on multiple data sources and projected trajectories from 2010 baseline data, meaning the illustrative pathways in 2020 represent a forecast from 2010 (not measured from today's baseline). Illustrative Model Pathway P3 is shown: a middle of the road scenario that assumes societal and technological development roughly follow historical patterns and drive net emissions reduction by changing the way energy and products are produced. [3] Waste CO_2 emissions negligible; ~1 $GtCO_2$.

SOURCES: SYSTEMIQ analysis for the ETC based on: IEA (2017), Energy Technology Perspectives; IEA (2020), Energy Technology Perspectives; Previous analyses of the Energy Transitions Commission; IPCC (2018) *Special Report for 1.5C.*

3.2 Options for carbon removal

Potential carbon removal technologies and mechanisms can be categorised into three types:[199]

- Natural climate solutions.
- Technological capture solutions combined with geological storage.
- Hybrid solutions.

The ETC consultation paper *Reaching climate objectives: the role of carbon dioxide removal* describes these options in detail; key points are summarised below.

199 Geo-engineering methods, which prevent warming by creating physical barriers (e.g., cloud seeding), are excluded from carbon removal methods as are carbon-neutral routes (e.g., direct air carbon capture (DACC) for synfuels) as they do not remove carbon in the long-term.

Natural Climate Solutions (NCS)

Natural Climate Solutions (NCS) use the natural process of photosynthesis to fix CO_2 from the air into plant biomass and use natural carbon stores of above-ground biomass (trees and other plants), below-ground biomass (e.g., roots), and carbon sequestration in the soil to lock up carbon over varying periods of time.[200] Some forms of NCS include:

- Better management of peatlands and other ecosystems with significant carbon stores.
- Re/afforestation which produces a gradually increasing store of carbon during the period of forest growth (which varies significantly between different types of forests).
- Soil carbon sequestration through improved agricultural practices, such as leaving a proportion of agricultural residues on the soil.

Because these options utilise natural photosynthetic processes and involve decisions about land use, their implementation overlaps with other agriculture, food, and land use related issues. This creates both (i) opportunities for co-benefits in terms of biodiversity or local employment creation, and (ii) risks related to competition for land use.

Technological capture solutions combined with geological storage[201]

At the other end of the spectrum, direct air carbon capture and storage of CO_2 (DACCS) does not rely on plants, roots, or soils for either carbon capture or carbon storage. Instead:

- Direct air carbon capture (DACC) uses energy inputs to sequester CO_2 from ambient air in an energy-intensive process.
- CO_2 is then stored via compression and injection into geological formations such as those of depleted oil and gas fields or saline aquifers.

This solution does not entail complex overlaps with agriculture, food, and other land use related issues, and therefore creates neither the potential co-benefits nor the risks associated with NCS and BECCS options.[202]

Hybrid options

Bioenergy with carbon capture and storage (BECCS) represents a hybrid solution: carbon is fixed through natural photosynthetic processes but storage is achieved through technological and geological means. In this process:

- CO_2 capture is achieved by plant photosynthesis into biomass, whether via trees (which might be collected as forestry residues) or various forms of fast-growing energy crops.
- The biomass is then converted into useable energy. One route is combustion for thermal energy generation (for instance in steel or cement plants, or in electricity generation).[203] Alternative conversion options are gasification followed by Fischer-Tropsch synthesis or enzymatic fermentation, both for biofuel production. During these processes, CO_2 can be captured from the waste gas streams.
- The energy co-products of BECCS add a revenue stream to this carbon removal option. However, whilst 100% of the biomass carbon is released during combustion when used for power or heat production (of which c.90% could be captured), only c.15-55% of carbon can be captured from biofuel production processes with the rest either emitted at the process stage or released back into the air at point of use.[204]
- The capture process requires energy inputs as per DACC, but due to the significantly higher concentration of CO_2 in the flue gases compared to dilute, atmospheric CO_2, the energy required, and therefore costs, are much lower.[205]
- Finally, CO_2 is transported and stored in a manner identical to that for DACCS.[206]

200 Nature-based Solutions (NBS) are activities that harness the power of nature to reduce the accumulation of greenhouse gases (GHGs) in the atmosphere and provide benefits for adaptation, biodiversity, and human well-being. Natural Climate Solutions (NCS) can be considered as a subset of NBS with a specific focus on addressing climate change. NCS has been defined as 'conservation, restoration, and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands' (Griscom et al. (2017), *Natural Climate Solutions)*.

201 Note that this definition does not explore 'geo-engineering' solutions, which do not aim to increase carbon dioxide removal, but instead target changing earth system elements such as the earth's albedo.

202 DACCS has a minimal land use footprint, as discussed in the following section.

203 In some cases, biomass can also be used as chemical feedstock for iron ore reduction in primary steel production.

204 Fajardy et al. (2019), *BECCS deployment: a reality check.*

205 In the case of specific biofuel production processes, there are very high CO_2 streams available, e.g., in ethanol production (85-100% CO_2 concentration) or biogas upgrading (30-50% CO_2 concentration). These are very low-cost options of carbon capture (<$50/ton). IEA (2019), *Putting CO_2 to Use – Creating value from emissions; Global CCS Institute (2021), Technology Readiness and Cost of CCS.*

206 Transport costs for BECCS, however, can be higher because DACCS can be deliberately located near sequestration sites and near low-cost forms of renewable power. BECCS may have less flexibility depending on the location of the biomass source.

The biomass production or extraction for use in BECCS raises the same issues relating to sustainability discussed in Chapter 1, as carbon dioxide is captured via photosynthesis in plants. However, from a downstream perspective, there would be limited land use issues associated with CCS, except those related to CO_2 transport pipelines.

Other hybrid solutions include the use of biochar, in which biomass is produced via photosynthesis and then pyrolyzed to yield a form of pure carbon which, if added to soil, both ensures long-term carbon storage and provides soil improvement benefits.[207]

Recently, it has been suggested that 'BECCS' as a term is limited and overly emphasises energy use.[208] Not all bio-based carbon dioxide removal processes generate bioenergy, and in many cases the carbon removal benefit of BECCS may be more valuable than the production of energy itself. Thus, biomass carbon removal and storage – BiCRS – may be a more appropriate term to describe processes where the primary aim is to use biomass to remove CO_2 from the atmosphere and store carbon underground or in long-lived products.[209]

While not discussed in detail here, other types of carbon dioxide removal technologies include various 'mineral absorption' solutions such as ocean alkalinisation and enhanced weathering. These can achieve enhanced CO_2 capture by means other than photosynthesis but are at much earlier stages of technology development compared to NCS, DACCS, and BECCS/BiCRS options.

207 National Academies of Sciences, Engineering, and Medicine (2019), *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.*
208 Sandalow et al. (2021), *Biomass carbon removal and storage (BiCRS) roadmap.*
209 Sandalow et al. (2021), *Biomass carbon removal and storage (BiCRS) roadmap.*

South American tropical rainforest.

3.3 Relative merits of different removal options and trade-offs

The relative merits of different CDR options reflect a complex set of trade-offs along various dimensions – including technological readiness and cost, the temporal profile of carbon removals, CO_2 sequestration permanence and storage, resource efficiency, and potential co-benefits. The balance of these factors will change over time in the light of technological and other developments, and the optimal mix cannot therefore be determined in advance. Appropriate policy (discussed in Chapter 4) must therefore focus on the market incentives and regulations that will help achieve an optimal balance. Exhibit 3.2 sets out a current assessment of the most well-known options along the different dimensions.

Exhibit 3.2

Overview of the most well-known future carbon dioxide removal options

	Description	Estimated carbon removal potential in 2050	Estimated costs in 2050	Resource Considerations and Other Co-benefits				
					Key Co-benefits[1]	Resource Constraints	Land Required (Mha/ Gt CO_2/ Yr)	Permanence (years)
Natural climate solutions (NCS)	**Technological readiness level (TRL) = HIGH** CO_2 is sequestered via photosynthesis and stored in biomass and soils through natural processes.	Afforestation/ Reforestation: **1-10** Gt CO_2/Yr Soil Carbon Sequestration: **1-9** Gt CO_2/Yr All other NCS: **0-10** Gt CO_2/Yr	Afforestation / Reforestation: **\$5-50** / tCO_2 Soil Carbon Sequestration: **\$0-100** / tCO_2	**Forest and wetland restoration**	Ecosystem restoration	Land Water Fertiliser	~70[2]	10-1,000+ (above and below land)
				Commercial forestry for materials	Displaces steel & concrete	Land Water	~130[3]	~50-200
Biochar	**TRL = MEDIUM** Biomass is pyrolyzed and used to stabilise organic matter.	Biochar: **0.5–2** Gt CO_2/Yr	Biochar: **\$30-\$120** / tCO_2	**Biochar**	Soil health	Biomass	n/a	1,000+
BECCS	**TRL (capture) = MED-HIGH TRL (storage) = MED-HIGH** CO_2 is sequestered via photosynthesis, the biomass used for bioenergy, and most of the CO_2 is then captured and geologically stored (CCS).	BECCS from residues: **2-5**[4] Gt CO_2/Yr BECCS from energy crops: **0.5-5**[7] Gt CO_2/Yr	**\$100-\$200** / tCO_2	**BECCS from residues[4]**	Energy	Land Water Fertiliser	~280[4]	100-1,000+
				BECCS from energy crops[7]	Energy	Land Water Fertiliser	~50[5]	100-1,000+
DACCS	**TRL (capture) = MEDIUM TRL (storage) = MED-HIGH** CO_2 is captured from ambient air and stored via CCS.	**0.5-5** Gt CO_2/Yr	**\$100-\$250** / tCO_2	**DACCS from renewables[6]**	-	Power Water	~5	100-1,000+
Mineral Absorption	**TRL at scale = LOW** Adding mineral materials to accelerate biogeochemical processes on land and in oceans that sequester CO_2 through rock weathering and ocean geochemical processes.	Ocean alkalinisation: **~ 1** Gt CO_2/Yr Enhanced Weathering: **2-4** Gt CO_2/Yr	Ocean alkalinisation: **\$14-\$500** / tCO_2 Enhanced Weathering: **\$50-\$200** / tCO_2	**Ocean alkalinisation**	Habitat creation	Power Minerals	n/a	1,000+
				Enhanced weathering	Soil health	Power Minerals	n/a	1,000+

NOTES: NCS: Natural climate solutions. DACCS: Direct air carbon capture and storage. BECCS: Bioenergy with carbon capture and storage. TRL = Technological readiness level. CCS: Carbon capture and storage.
[1] List of co-benefits not exhaustive.
[2] Not all NCS options have a land use requirement. Figure assumes average of sequestration rates in temperate (3.5 tC/ha/yr) or tropical (4.1 tC/ha/yr) climates for afforested former pasture/crop land.
[3] Assumes biomass growth of 5.15 tC/ha/yr and that 36% of total roundwood under bark harvested from commercial forestry is used for materials, of which at least 75% is used to produce medium- to long-life products (i.e., from 'sawn-wood', 'wood-based panels', and 'other industrial roundwood', as defined by the FAO).
[4] BECCS from residues does not require dedicated land but uses existing land used for other purposes. Represents global availability of biomass residues in 2050. Assumes average of available biomass from forest and agricultural residues as reported by Smith et al. (2016) and a 90% carbon capture efficiency in BECCS.
[5] Assumes average of available biomass from energy crops as reported by Smith et al. (2016) and a 90% carbon capture efficiency in BECCS.
[6] Liquid sorbent DAC.
[7] Range represents food and agricultural systems shift enabling energy crops grown on freed up land to increase above current supply (~0.5-1 Gt CO_2/yr). If 250Mha of additional crop/pastureland made available via food systems transition, ~5 Gt CO_2/yr additional carbon capture and storage theoretically possible via BECCS.

SOURCES: SYSTEMIQ analysis for the ETC based on: Vivid Economics based on Fuss et al. (2018); Bui et al. (2018) Carbon capture and storage (CCS): the way forward.; National Academies (2019), Negative Emissions Technologies and Reliable Sequestration A Research Agenda; Smith et al. (2016); WRI Carbon Benefits Index Calculator; Renforth et al. (2017); Roe et al. (2019); Fuss et al. (2018); BloombergNEF (2021), Material Tech Highlight – Direct Air Capture.

Technological readiness

Natural climate solutions such as re/afforestation can clearly be implemented today. BECCS/BiCRS carbon removal solutions are also technically possible and close to commercial application: biomass is already used in several end use applications and carbon capture and storage are proven technologies, albeit only deployed on a small scale today. UK power generator DRAX is currently capturing 1 t/day in a pilot facility and plans to be capturing and storing 8 Mt/year CO_2 from its biomass burning power plants by 2030.[210] DACC is also technically possible and close to commercial application, but currently only demonstrated at small scale and with commensurately high costs. Companies such as Carbon Engineering have been capturing atmospheric CO_2 since 2015 and will begin construction of their first commercial plant in 2022. They are targeting capture of 1 Mt CO_2 by 2024.[211]

Costs

Exhibit 3.3 sets out estimates of the potential costs of different types of carbon removal in 2050. Key features are that:

- Natural climate solutions such as afforestation are likely to be the lowest cost options with an estimated range of \$5-\$50 per tonne of CO_2 captured and stored.[212] This reflects the fact that the physical capture and storage process is performed 'for free' by nature. Costs therefore primarily reflect the price of the relevant land, which in turn reflects its value in alternative uses such as food production. However, costs for NCS solutions vary greatly by specific location and circumstance and could either increase or decrease over time.
  - Costs could increase as the quantity of NCS carbon removals rises and as competition with alternative land uses therefore intensifies.
  - Costs could potentially fall if, as discussed in Chapter 1, changes in the agricultural system allow for a significant release of land from food production.
- Costs for both BECCS/BiCRS and DACCS will tend to be higher than those for NCS because the carbon capture, transport, and storage processes require energy and other inputs. Estimated carbon capture costs for bioenergy applications are expected to be lower than those for DACC due to the much higher concentration of CO_2 in waste streams than in air.[213] But the cost for DACC – currently around \$300 and \$400 per tonne of CO_2 captured[214] – could fall to or below \$100 per tonne over time, reducing the importance of this difference.[215,216] A full comparison of BECCS/BiCRS versus DACCS must, however, reflect the inherently different nature of these options:
  - DACCS is pure carbon removal technology that neither generates useful by-product (such as energy), nor creates complex sustainability concerns in comparison with BECCS/BiCRS.[217] The total cost of capture, transportation, and storage thus provides essentially all of the information required to assess the desirability of DACCS.
  - BECCS/BiCRS operations, by contrast, combine the use of energy in an end application with CCS applied to the waste streams from that operation while depending on a constrained supply of sustainable biomass. As a result, (i) the economics of BECCS/BiCRS could in several cases be more favourable than the straight comparison of carbon capture costs suggests due to the generation of co-products such as heat, power, and biofuels; but, conversely, (ii) acceptable volumes of BECCS/BiCRS are constrained by sustainability issues that are not relevant for DACCS. For BECCS/BiCRS, as with all bioenergy use, the actual CO_2 savings depend on whether the production and extraction of the biomass itself leads to CO_2 emissions that counteract some of the benefit. Some studies have suggested this can have a large impact, eroding between 38-54% of the emissions reductions.[218] In addition, the application BECCS/BiCRS to specific industrial sites can entail bespoke engineering costs (e.g., to retrofit plants to both use biomass and enable carbon capture) that will not be faced in greenfield DACCS developments.

210 Drax (2021), *Drax and Mitsubishi - Heavy Industries sign pioneering deal to deliver the world's largest carbon capture power project*; Drax (2019) *Carbon dioxide now being captured in first of its kind BECCS pilot.*

211 BloombergNEF (2021), *Material Tech Highlight: Direct Air Capture.*

212 National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration*; Vivid Economics (2018) based on Fuss et al. (2018), *Negative emissions—Part 2 - Costs, potentials and side effects.*

213 Lowest cost estimates for power generation BECCS/BiCRS are via oxy-fuel combustion (using pure oxygen rather than air in the combustion process) yielding a concentrated CO_2 stream.

214 Solid sorbents are at higher costs today. Current costs for technology from Carbon Engineering are closer to \$250/tCO_2.

215 Fuss et al. (2018), *Negative emissions—Part 2 - Costs, potentials and side effects;* World Resources Institute (2020), *CarbonShot: Federal Policy Options for Carbon Removal in the United States; National Academies (2019), Negative Emissions Technologies and Reliable Sequestration; Vivid Economics (2020), An investor guide to negative emission technologies and the importance of land use.*

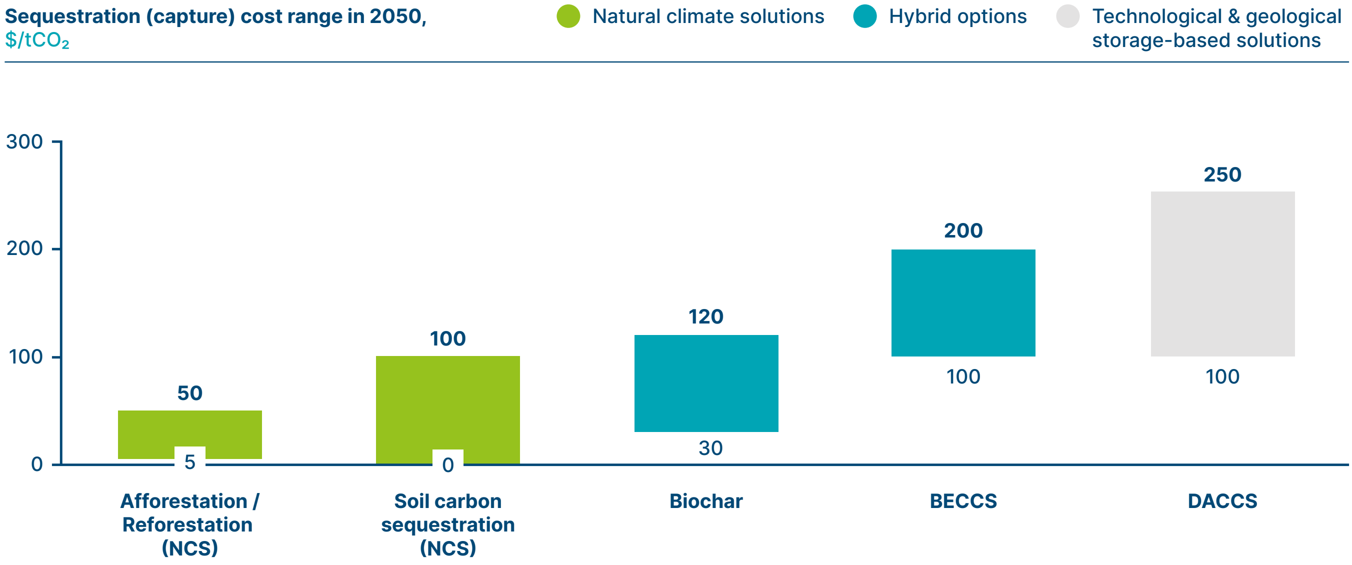
216 Carbon Engineering report projected costs of ~\$250-270 per tonne of CO2 captured at their Texas Permian Basin project, DAC 1. This project is currently in the Front-End Engineering and Design Phase, with the stated aim of beginning the engineering, procurement, and construction phase in 2022. 1PointFive (2020), Oxy Low Carbon Ventures and Rusheen Capital Management Launch 1PointFive.

217 DACCS does require land, water, and other resource inputs, but the scale of the land area required is just a tenth, or less, of that of the requirement for BECCS. BloombergNEF (2021), *Material Tech Highlight: Direct Air Capture.*

218 Once approximately 50% of the carbon efficiency is eroded, the solution is no longer carbon negative (although it can be carbon neutral). Fajardy et al. (2017), *Can BECCS deliver sustainable and resource efficient negative emissions?*

Bio-based carbon dioxide removal is likely to remain cheaper than DACCS in the long term; but Natural Climate Solutions (NCS) are the lowest cost carbon removal option

Exhibit 3.3



NCS: Natural climate solutions. DACCS: Direct air carbon capture and storage. BECCS: Bioenergy with carbon capture and storage.

NOTE: CO_2 Capture and Storage Costs are both included for NCS but considered separately for biochar, BECCS and DACCS.

SOURCES: National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration*; Vivid Economics based on Fuss et al. (2018); BloombergNEF (2021), *Material Tech Highlight – Direct Air Capture.*

Storage and permanence

CO_2 removed from the atmosphere could be stored in one of four ways – in land-based nature, geological storage, the oceans, or in long-life products and buildings ('storage in use') [Exhibit 3.4]. The first two are the most relevant for this discussion. Each entail different resource demands and management challenges, and for each it is important to assess the permanence/duration of storage, although no standardised approach to assessing that duration is yet in place.

- Storage in land/the biosphere – both in natural and managed forests – involves direct sequestration of carbon into plant biomass and soils and is, in principle, possible on a large scale. However, there are risks to the long-term storage potential, due to wildfire, pests, and disease accentuated by both the impacts of climate change and anthropogenic deforestation; these factors are highly location and context specific. The duration of storage in the land/biosphere could range anywhere from 10 years (in the case of exogenous events such as extreme weather destroying trees) to 10,000+ years, in the case of ancient peatlands.[219] Active management of storage (e.g., 'climate smart technologies' which use technology and human activity to increase the permeance of storage in the biosphere) to increase effective duration is necessary to maximise the potential of storage in the biosphere.

- Geological storage[220] makes CCS possible and is also at a high level of technological readiness due to its current use within the oil and gas sector. It secures carbon in sedimentary formations, basalt, and peridotite, and has the theoretical potential to store vast quantities of carbon, though availability of storage capacity varies greatly by country/region. It is relatively secure in terms of permanence. Depending on the integrity of geological formations chosen, leakage rates are likely to be less than 1% over 100 years and the effective duration of storage is likely 1000+ years.[221] Earthquakes brought about by the injection of CO_2 into geological formations are improbable and would likely only have moderate local magnitudes if they occur.[222] Using CCS on large scale will, however, require extensive transportation infrastructure and therefore investment.

219 Treat et al. (2019), *Widespread global peatland establishment and persistence over last 130,000 years.*
220 Underground storage in saline aquifers or depleted oil and gas reservoirs.
221 Carbon retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1000 years. Note: 'likely' is 66-100% probability. IPCC (2005), *Carbon Capture and Storage.*
222 IPCC (2005), *Carbon Capture and Storage.*

- There could be significant potential for storing additional carbon in the oceans, however, the technologies to achieve this are the least proven and the possible feedback effects on the ocean are the least clear.

- Storage-in-use – the storage of carbon in bioproducts such as timber or concrete – has a relatively small capacity compared with the volume of CO_2 that must be sequestered for a 1.5°C global warming pathway. It also has a relatively low permanence, with typical storage durations estimated between c.10-200 years. Even if the storage is not permanent, however, it can still play a valuable role as the use of biomaterials typically substitutes for high-carbon alternatives (such as steel or conventional concrete in construction).

Land (biosphere) storage has proven feasibility but a greater uncertainty range for permanence; while geological storage is likely high permanence

Type	Variants	TRL (1-11)[1]	Range of Carbon Storage Potential (Gt CO_2/Yr)[2]	Permanence of Storage (years)
Land Storage	Above land	11	2.2-30	10-1000[4]
	Below land	10-11		100-1000+
Ocean Storage	Deep ocean	9	0.3-2	1000+
	Alkalinity Enhancement	2-5	1-40	1000+
Geological Storage	Sequestration via mineralisation in reactive rock formations (e.g. Basalt & Peridotite)	3-5	1-32	100-1000+[3]
	Sequestration in depleted oil & gas fields and saline aquifers	7-11	5-10	100-1000+[3]
Storage with usage	Concrete	7-9	TBD	100+
	Materials from commercial forestry	10-11	TBD	50-200
	Long-life fibre product	9-10	TBD	10-100

NOTES: List of storage options not exhaustive.
[1] TRLs combined from multiple sources. Scales adjusted from a scale of 1-9 to 1-11 for easier comparison with other assessments such as the IEA. TRLs range from basic principles (1) to active large scale operations (11).
[2] Literature review of a variety of sources giving a maximum range of sequestration potential.
[3] Leakage risk very likely below 1% over 100 years; IPCC: Carbon Capture and Storage, 2005.
[4] Some natural forests can maintain carbon stocks for hundreds or thousands of years.

SOURCES: Hoegh-Guldberg et al. 2019; The Royal Society, 2018; Fuss et al. 2018; Bui et al 2018; Roe et al. 2019; IEA (2020), ETP Clean Energy Technology Guide.

Exhibit 3.4

Resource efficiency, biodiversity, and other impacts

While photosynthesis is a natural and – in some sense – 'free' process, it is also quite inefficient. Even in the most favourable environments and using the most efficient plants, less than 1% of total solar energy is converted into usable energy within the biomass. By contrast, solar farms can achieve conversion efficiencies of 15% or more.[223] This difference in energy conversion efficiency in turn has implications for the amount of land required to capture one tonne of CO_2. Thus:

- Dedicated land use for energy crops would require about 500,000 km^2 (i.e., an area about 700 km x 700 km or 50 Mha, equivalent to the size of Spain) to sequester 1 $GtCO_2$ each year via BECCS/BiCRS.[224] If the source of biomass for BECC/BiCRS was instead forest residues, which makes up the bulk of the supply in our prudent case, then a forest managed for stemwood production (i.e., focused on materials) of five times this size might be required to produce enough residues to sequester 1 $GtCO_2$ each year. Some countries are undertaking pilots aiming to increase the quantity of carbon sequestered per hectare of land each year, assessing the optimum plants to use and optimum locations to plant them.[225]

- DACCS is at least 10 times[226] more land efficient with the required land footprint for solar PV panels to provide the electricity for DACC being about 50,000 km^2 per $GtCO_2$ per year.[227] This land does not need to be suitable for biomass production.

- While NCS solutions are similarly land-intensive as BECCS/BiCRS (using biomass from residues or, to a lesser extent, dedicated land), in comparing NCS to DACCS it is wrong to think about the higher land-use as a necessarily negative factor since devoting land to afforestation, for example, will deliver other benefits. NCS options can provide additional value for ecosystems and people such as habitat and biodiversity conservation, nutrient cycling, maintenance of soil quality, climate change resilience benefits including water regulation and flood protection, water and air purification, limiting of erosion, as well as livelihoods, employment, and recreation for local populations.[228]

The relative land efficiency of NCS versus BECCS/BiCRS in terms of CO_2 removal depends on the timescale considered and the particular BECCS/BiCRS option deployed. To compare the potential of various bio-based options for carbon removal, we therefore looked at the hypothetical use over time of 100 hectares of land for afforestation or reforestation (i.e., return to natural forests), for energy crops for BECCS/BiCRS, and for managed forests enabling use of wood in materials and of forestry residues in BECCS/BiCRS. The co-benefits to carbon removal depend on the method used [Exhibit 3.5]. The analysis suggests that:

- Over the 100-year period, BECCS/BiCRS from energy crops produces the greatest carbon sequestration, with afforestation ranking second and managed forests options being less effective when judged on their ability to remove atmospheric carbon dioxide [Exhibit 3.6].

- But, over a 30-year period, managed forests sequester more carbon than afforestation, and can be almost as effective at sequestering carbon as energy crops [Exhibit 3.7].

- Energy crops are the worst option in terms of biodiversity and wider ecosystem services, while afforestation is by far the best.

Choices between NCS and BECCS/BiCRS therefore involve trade-offs between carbon capture volumes, the timing of sequestration, and wider biodiversity and ecosystem benefits.

223 Blankenship, et al. (2011) *Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement.* Note: Energy efficiency of photosynthesis is defined as energy content of biomass that can be harvested divided by solar irradiance over the area with a theoretical maximum efficiency of c.12%. Photosynthesis in crop plants is ≤1% overall but during the growing season, C3 and C4 plants can reach as high as 3.5% and 4.3% efficiency, respectively.

224 Assumes 90% of CO_2 from BECCS can be captured. Smith, et al. (2016), *Biophysical and economic limits to negative CO_2 emissions*; National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration*; Zhao D. et al. (2016), *Maximum response of loblolly pine plantations to silvicultural management in the southern United States*; P. Lauri et al. (2014). *Woody biomass energy potential in 2050.*

225 Global Citizen (2021), *Britain to Start 'World Leading' Trials to Suck Carbon Dioxide Out of the Air with Trees and Rocks.*

226 BNEF and Carbon Engineering estimate DACC could be as much as 100-fold more land-efficient than BECCS depending on the type of renewable generation used (e.g., wind). Source: BloombergNEF (2021), *Material Tech Highlight: Direct Air Capture.*

227 ETC analysis based on National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration*; Kraan et al. (2019), *An Energy Transition That Relies Only on Technology Leads to a Bet on Solar Fuels*; PlanEnergi (2018), *Solar cell and solar heating systems on arable land*.

228 Bui et al. (2018), *Carbon capture and storage (CCS): the way forward*; National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration A Research Agenda*; Smith et al. (2016), *Biophysical and economic limits to negative CO_2 emissions*; WRI Carbon Benefits Index Calculator; Renforth et al. (2017), *Assessing ocean alkalinity for carbon sequestration.*

Summary conclusions on relative merits of different carbon removal options

The analysis above suggests that:

- A portfolio of carbon removal technologies will be required, with no one solution providing a silver bullet which can deliver adequately rapid growth in removals without significant offsetting disadvantages. Policy therefore needs to encourage the development of a suite of solutions.[229]

- Returning land to nature is valuable independent of carbon removals. Choosing to sacrifice biodiversity and ecosystem health in order to mitigate climate change is unlikely to result in a world resilient to future catastrophe. At the same time, climate change left unchecked will drive unprecedented biodiversity loss. Both issues must be tackled together.[230] Natural climate solutions provide benefits for nature and climate simultaneously and therefore have unique value. There are also models of energy crop production (such as agroforestry) and forest management (such as climate-smart forestry) that enable multiple benefits to be realised simultaneously; these should be pursued.[231]

- But in some locations – in particular where land is of poor quality and physically removed from biodiversity rich areas – energy crop production could enable maximum carbon removal, while allowing other land, which is less degraded and with higher potential for biodiversity recovery (e.g., the edge of a forest) to return to nature.

Plants remove carbon from the atmosphere as they grow; co-benefits depend on how land is managed and where carbon is stored in the long term

Annual net removals of carbon from the atmosphere per unit area,
t Ceq./ha/yr

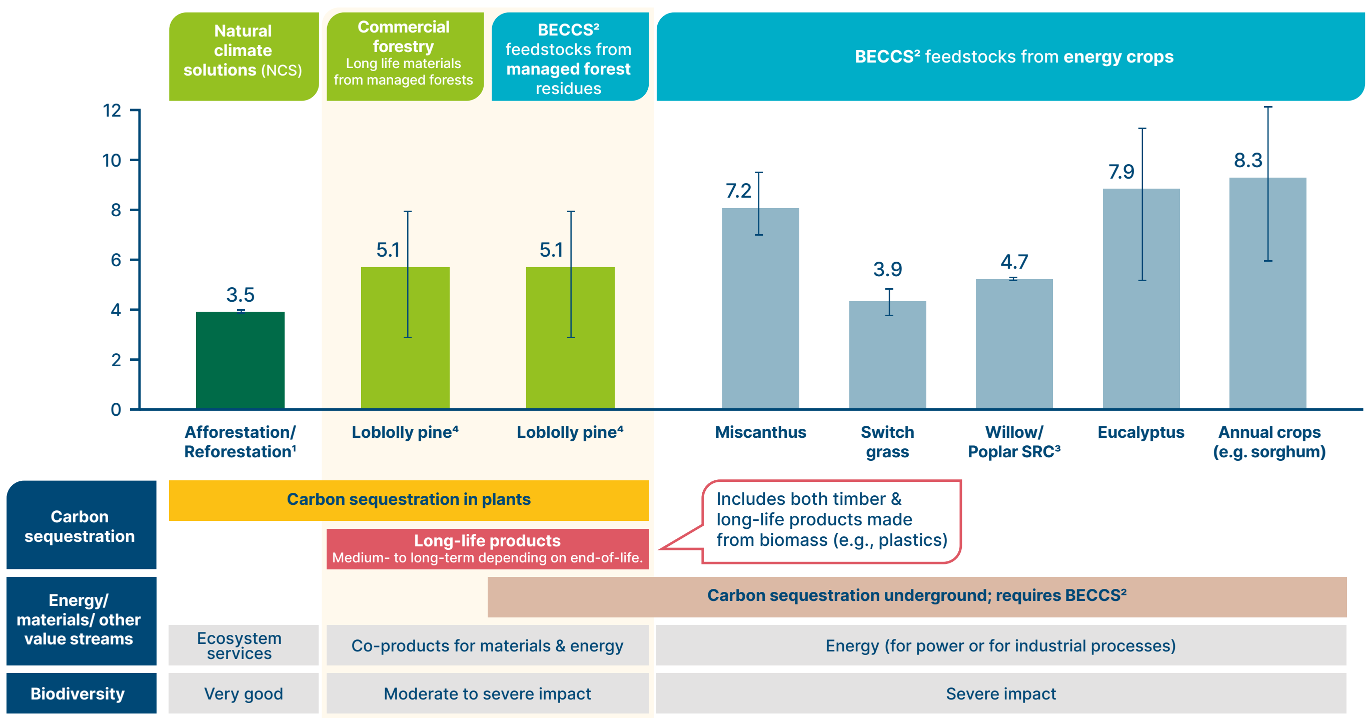


Exhibit 3.5

NOTES: [1] Afforestation/Reforestation assumes 500 tCO_2/ha = 136 tC/ha from forest regrowth over 40 years to maturity (assumes linear uptake), so mean annual accrual rate is 3.4 tC/ha/yr; WRI figure of crop/pastureland to forest of 3.6 tC/ha/yr. [2] BECCS: Bioenergy with carbon capture and storage; [3] SRC: Short rotation coppice; [4] Loblolly pine plantations in the southern US - mean annual biomass increment ranged from 5 to 16 Mg/ha/yr, depending on site quality, planting density, and cultural intensity. Assumes carbon content of ~49% wt. on dry basis.

SOURCES: Smith et al. (2018), *Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target*; Smith et al. (2016), *Biophysical and economic limits to negative CO2 emissions*; Zhao et al., (2016) *Maximum response of loblolly pine plantations to silvicultural management in the southern United States*. WRI (2018), *Carbon Benefits Index*.

229 There is additional value to prioritising emissions reductions and removals immediately because even if we remove carbon decades from now, we cannot undo near term glacial melt, permafrost thawing, ocean acidification, and other damages. Raven et al. (2021), *Scientist Letter to Biden, Von der Leyen, Michel, Suga & Moon Regarding Forest Bioenergy.*

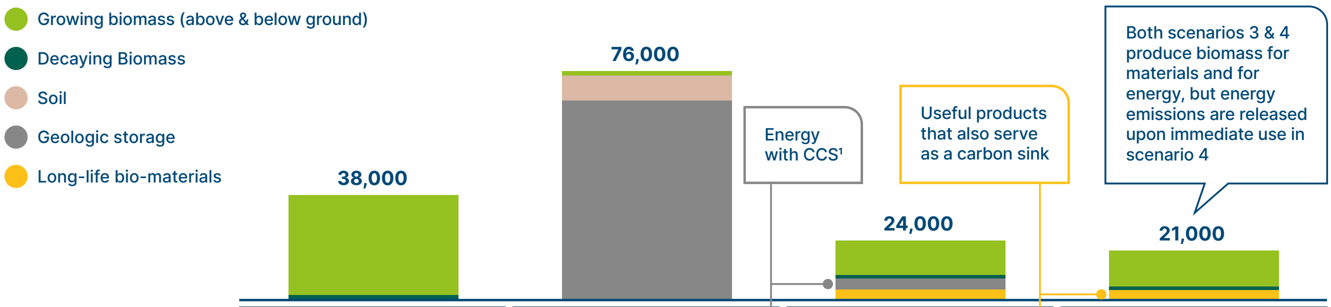
230 United Nations - Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2021), *Tackling Biodiversity & Climate Crises Together and Their Combined Social Impacts.*

231 Calvin et al. (2021), *Bioenergy for climate change mitigation: scale and sustainability*; Verkerk et al. (2020) *Climate-Smart Forestry – the missing link.*

After 100 years, energy crops for BECCS result in most CO_2 stored, but afforested land and managed forests still hold significant storage

Tonnes carbon (stock after 100 years)

Illustrative



Total additional outputs:	1. Afforestation	2. Energy crops for BECCS	3. Managed forest for materials + BECCS	4. Managed forests for materials + biofuels
Long-life bio-materials (t dry biomass)	n/a	n/a	5,500	5,500
Energy (t dry biomass) or converted	n/a	148,000 = 281,000 MWh	7,000 = 13,000 MWh	7,000 = 5M litres biodiesel
Biodiversity	Very positive if location suitable for restoration of nature	Negative if location suitable for restoration of nature	Management dependent but tends towards low	Management dependent but tends towards low

Scenario modelling: Evaluating the abatement potential and outputs of different uses of land

	1. Afforestation	2. Energy crops for BECCS	3. Managed forest for materials + BECCS	4. Managed forests for materials + biofuels
Climate	Temperate			
Starting Conditions	100 ha former crop/pasture land; all hectares planted in year 0			
Mean biomass growth above & below ground (tC/ha/yr)	3.6	8.3	5.1 for trees aged 0-40 years, 0.5 after age 40	
Growth period before harvest (years)	n/a	1	30	
Harvest regime	n/a	100 ha harvested & regrown each year	1 ha harvested and replanted each year (after year 30)*	
Amount of decomposing biomass (% of growing)	4.6%	n/a	4.6%	
Residence time before 90% has decomposed (years)	35	n/a	35	
Fraction of total biomass in harvested forest stand used for materials	n/a	n/a	21%	
Fraction of total biomass in harvested forest stand used for energy	n/a	n/a	26%	
Fraction of slash (branches and tops) removed	n/a	n/a	40%	
Lifetime of bio-based materials (years)	n/a	n/a	100	
Carbon content of woody biomass (tC / t dry biomass)	48.8%			
Power generation from biomass combustion (MWh/t dry biomass)	n/a	1.9		n/a
Efficiency of carbon capture	n/a	95%		n/a; biofuel carbon returned to atmosphere immediately

Exclusions from illustrative modelling²:

- Albedo effects (e.g., negative climate forcing from new, dark biomass on land)
- Land use change emissions
- Avoided emissions from power generation
- Avoided emissions from biofuels use
- Avoided emissions from materials use
- Biomass thinnings yielding woody material prior to harvest period in managed forest
- Biomass thinnings in afforestation scenario

*Additional harvests (e.g., from replanted stands following a second or third rotation period) not included; only 1 stand harvested each year even if multiple stands have reached maturity.

Exhibit 3.6

NOTES: In the managed forest scenarios, only 1% of the forest stands are harvested each year (1 ha of 100 ha total); in the energy crop scenario, all 100 ha are harvested each year.
¹ CCS: carbon capture and storage. ² Not exhaustive.

SOURCES: SYSTEMIQ analysis for the ETC (2021).

Energy crops for BECCS provide the greatest sequestration potential

Carbon removed from the atmosphere via use of 100 ha of land
(tC, cumulative)

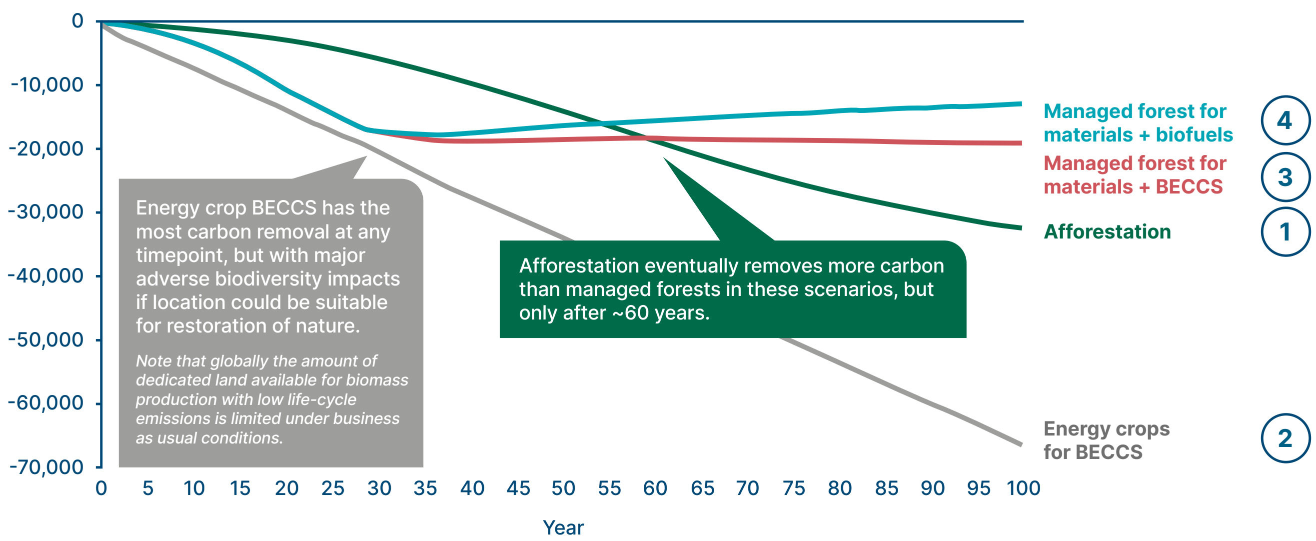


Exhibit 3.7

NOTES: NCS: Natural climate solutions. DACCS: Direct air carbon capture and storage. BECCS: Bioenergy with carbon capture and storage.
In the managed forest scenarios, only 1% of the forest stands are harvested each year (1 ha of 100 ha total); in the energy crop scenario, all 100 ha are harvested each year.

SOURCE: SYSTEMIQ analysis for the ETC (2021).

3.4 Implications for prioritised use of biomass

The requirement for large scale carbon removal in the next three decades affects the prioritisation outlined in Chapter 2. While materials uses will likely remain highest priority given the absence of alternatives, uses of biomass that can be combined with carbon capture and storage will become more attractive relative to uses where CCS is not feasible (such as aviation).

Some CCS potential in priority sectors

The extent to which the priority uses of bioresources identified in Chapter 2 [Exhibit 2.12] can be combined with BECCS, and thus deliver both carbon dioxide removal (BiCRS) and within-sector decarbonisation, differs:

- Materials use in wood products, but not in pulp and paper,[232] achieves a form of carbon storage, but duration is likely shorter term.

- Plastics production from bio-feedstocks effectively 'stores' carbon within the global stock of plastics, but without 100% effective collection and recycling, some of this carbon will be released at end-of-life (via plastics incineration or degradation). Carbon emissions produced in waste-to-energy incinerators could be captured if CCS is applied, but it will be impossible to ensure that all plastics are either recycled or only incinerated if CCS is in place. However, regardless of their lifecycle, it may be possible to capture and store process emissions from the production of plastics from bio-feedstocks.

- In distributed mobility sectors such as aviation and long-distance transport, it is very unlikely that CCS will ever become practical or cost-effective, with CO_2 therefore released at point of biofuel use. It is, however, possible to apply CCS to some biofuel production processes, with different processes enabling different levels of carbon capture. The need for CDR favours gasification routes, which allow the capture of up to 55% of total biomass carbon, while maximum capture from fermentation routes is 15%.[233] In the near term, using biofuels produced with CCS would mainly displace fossil fuel use, increasing the carbon benefit. In the longer term, opportunities to shift vehicles to electrification and shift aviation to synthetic fuels limit the carbon reduction benefit to the maximum of 55% of biomass carbon that can be captured in biofuel production.

232 As discussed in section 2.2.3, wood residues are currently used for low temperature heat in the pulp and paper industry (nearly 80% of the CO_2 emitted by pulp and paper mills is biogenic). These residues could be reallocated to higher value uses if heat provision is electrified. Alternatively, CCS could be fitted at pulp and paper facilities to generate CDR from continued use of residual biomass onsite. This would minimise biomass collection and relocation costs and provide the pulp and paper industry with an additional revenue stream. Sagues et al. (2020), *Prospects for bioenergy with carbon capture & storage (BECCS) in the United States pulp and paper industry.*

233 Fajardy et al. (2019), *BECCS deployment: a reality check.*

- CCS could be installed in distributed heating or combined heat and power (CHP) systems; however, this is unlikely to be very economic as CCS benefits from economies of scale. Furthermore, electricity and hydrogen could be used as alternatives to bioenergy in many heating applications.

If the four priority sectors used the 54 EJ of biomass resource as illustrated in Exhibit 2.12, application of carbon dioxide removals technologies could potentially generate removals of a maximum, theoretically, of c.3.2 $GtCO_2$/year in 2050. Of this:

- Approximately 2.3 $GtCO_2$/year could be from the application of CCS to emissions from the production of plastics from bio-feedstocks and the production of bio-jet fuels if a gasification process enabling the maximum 55% of biomass carbon to be captured is used for each.[234]

- As much as 0.9 $GtCO_2$/year could be from long-life timber products.[235]

Greater CCS potential in power generation and hydrogen production

By contrast, much larger quantities of carbon removal could be achieved if biomass were devoted to applications where higher carbon capture rates are feasible. In both power generation and hydrogen production via biomass gasification, capture rates of 90% or greater could, in principle, be achieved. As a result, if c.40 EJ of biomass supply were devoted to such applications (rather than to plastics, aviation, or niche and second priority uses),[236] as much as c.6 $GtCO_2$/year of carbon dioxide removal could be achieved in total, including c.5 $GtCO_2$/year from sequestration of carbon captured through CCS processes and 0.9 $GtCO_2$/year from long-life timber products.[237,238] Allocating biomass supply this way would make it essential to develop alternative decarbonisation solutions for other sectors – for instance synthetic fuel for aviation – with implications for the total zero carbon electricity requirement.

Carbon capture dominates the overall cost of CCS/U

Combined capture, transport and storage costs (2019)[1]
$/tonne CO_2

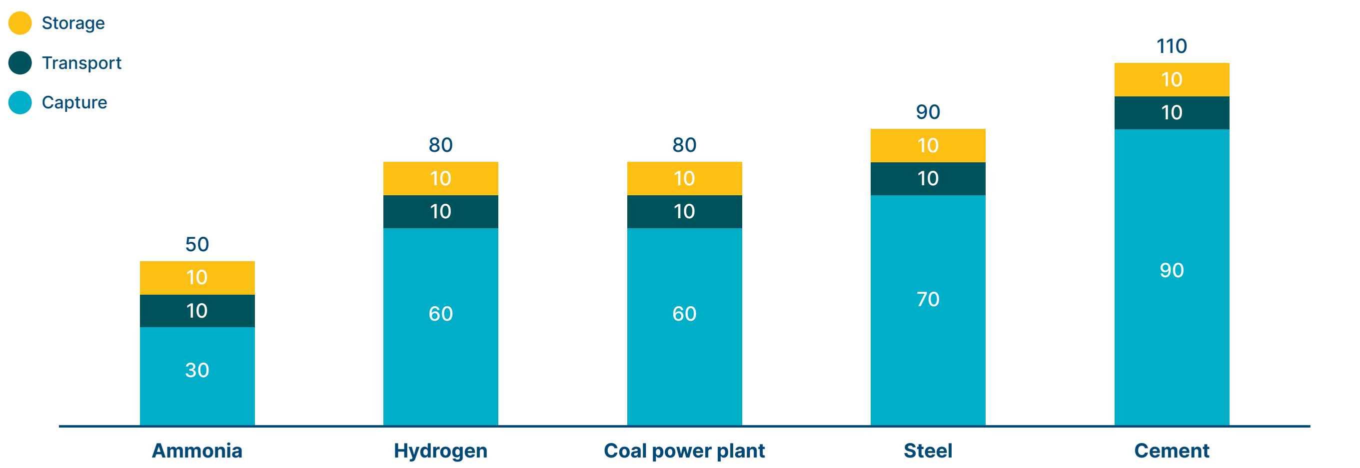


Exhibit 3.8

NOTES: [1] Capture costs based on the range mid-point suggested by IEA are illustrated. Cost estimates are based on the United States. All capture costs include cost of compression. Values for hydrogen stem from ETC report. Storage costs are indicative and vary significantly depending on the characteristics of the storage reservoir and the location of the CO2 storage site (onshore/offshore). Similarly, transportation costs vary with distance, mode of transport and capacity but typically range between 3-20$/ton. Sources: IEA (2019), Energy Technology Perspectives – CCUS in clean energy transitions; ETC (2021), Making the Hydrogen Economy Possible – Accelerating clean hydrogen in an Electrified Economy.

234 Fajardy et al. (2019), *BECCS deployment: a reality check.*
235 Assumes 100% of wood products that are not pulp & paper (i.e., timber) are long life, and represent an additional carbon sink. However, in the long-term the carbon 'stored' in timber would balance as the amount of wood disposed post-use is balanced by the amount of wood added.
236 But maintaining allocation of c.7 EJ biomass to wood products and c.16 EJ to pulp and paper.
237 Assumes c.9 EJ biomass per $GtCO_2$ captured based on a 90% carbon capture efficiency in BECCS (e.g., for power generation) process, that biomass is 50% carbon on a mass basis, and an energy content of biomass of c.14 GJ / tonne. The carbon removal from BECCS here is a theoretical maximum assuming zero lifecycle CO_2 emissions of biomass if adverse land use change is avoided and the supply chain fully decarbonised. Depending on the reality of supply chain emissions from growing, processing, and transporting the biomass, the net emissions sink, and thus efficiency of the biomass for use in climate mitigation, would decrease.
238 If we do not make progress in halting deforestation and other perverse land use changes, the ability of bio-based carbon dioxide removals to meaningfully contribute to closing the carbon overshoot gap will dwindle.

Carbon prices and capture costs – the potential for 'CCS profit'

The actual allocation of limited sustainable biomass supply will and should be determined by the relative economics of different applications allowing for the value of carbon sequestration, potentially set by a carbon price. If the relevant carbon price is above the costs of carbon capture, transport, and storage, BECCS/BiCRS can deliver a 'CCS profit'. The costs are dominated by the capture element, which varies by application and can be improved through use of oxy-fuel combustion,[239] where applicable. Current cost estimates vary from \$50/tCO2 for ammonia to \$110/tCO_2 for cement [Exhibit 3.8]. CCS costs for biomass power production and biomass gasification are anticipated to be at least \$60 per tonne, implying that carbon prices above this level would be needed to deliver a 'CCS profit'.

Where a carbon profit can be achieved, this will change the relative cost competitiveness of different possible uses of biomass, improving the relative economics of power and heat-related applications [Exhibit 3.9]. Whether, in total, each of these applications is economic will depend not only on the price of carbon but also on the value of the energy (or other co-products) produced, as well as the costs of production. This complex combination of prices and costs will also determine the relative economic attractiveness of different BECCS/BiCRS options. Thus, as Exhibit 3.10 illustrates, the relative economics of biobased power generation versus hydrogen production will depend on:

- For power generation, the price of electricity at various times of day and year, the costs of generation (which will reflect biomass input costs), and the 'CCS profit' arising from the carbon price less the CCS cost.
- For hydrogen, the hydrogen price, the cost of biomass-based hydrogen production, and the 'CSS profit'.

Given this complexity, it is not possible to predict in advance what forms of BECCS/BiCRS will be most profitable, with the answer likely to vary significantly by region and specific circumstance.

Global biomass cost-parity curve for 2050: impact of potential revenues from CO_2 capture and storage

Cost-parity curve – Breakeven biomass cost vs. alternative leading non-biogenic solution; global (2050 outlook)
"At what biomass feedstock price is the bio option cost effective?"

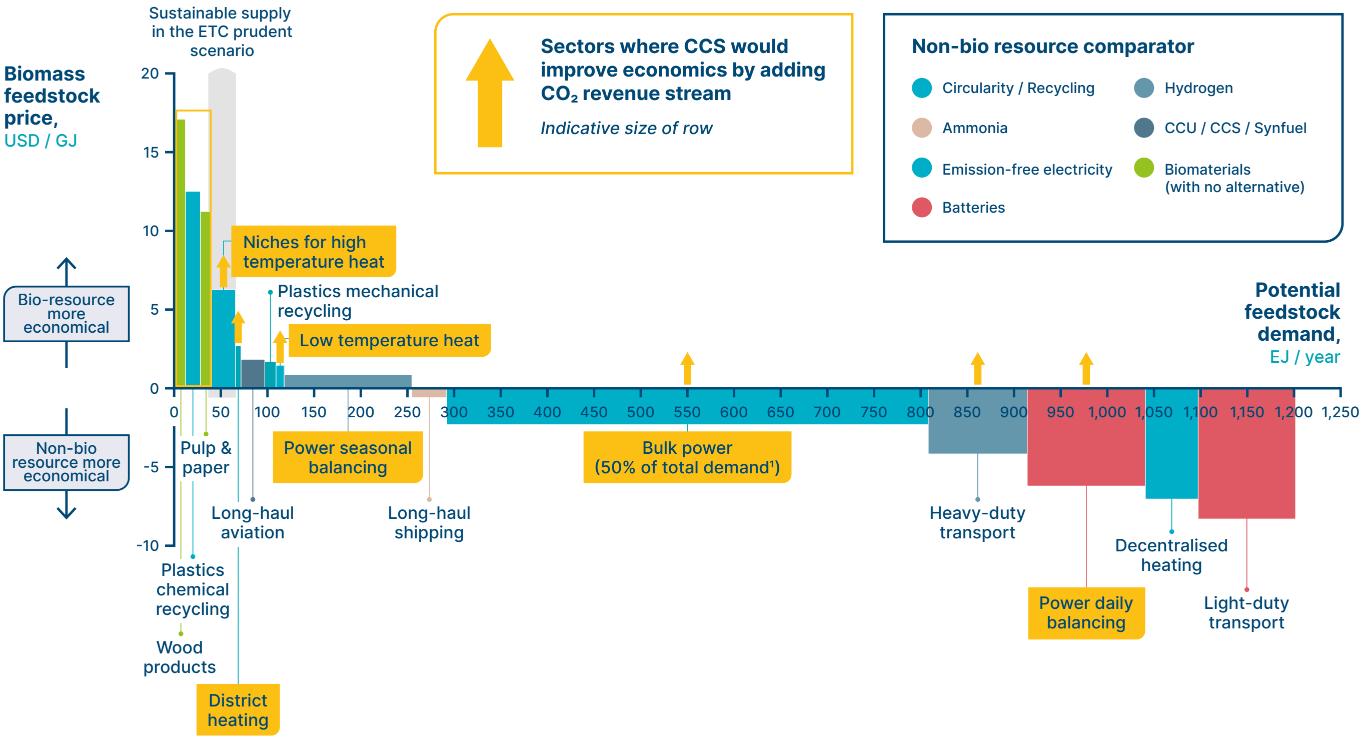


Exhibit 3.9

NOTE: [1] We limit the potential demand for biomass for bulk power to 50% of the demand of the segment in order to make the graph readable.
SOURCE: Material Economics and ETC analysis (2021).

239 Using pure oxygen rather than air in the combustion process, yielding a concentrated CO_2 stream.

Competitiveness of CDR from biopower against CDR from biohydrogen depends mostly on coproduct sales price

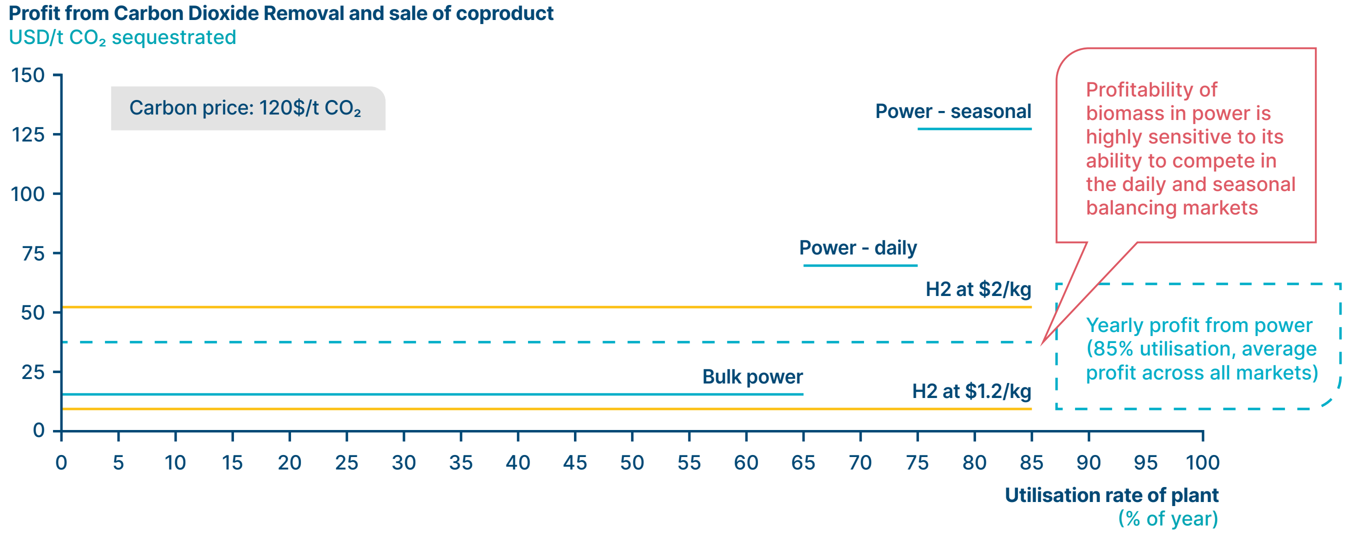


Exhibit 3.10

Power assumptions: Bulk power: 20$/MWh sales price; Daily flexibility: 80$/MWh sales price; Seasonal flexibility: 150$/MWh sales price.
CCS assumptions: Capture cost of $40/t$CO_2$ for both biogasification and combustion of biomass for power. T&S cost of $20/t$CO_2$. In reality, capture costs may differ for these processes.

SOURCE: ETC analysis (2021). Hydrogen breakeven price = $1/kg.

Implications of additional supply in the maximum potential scenario

Even if the value of carbon removal (expressed in a carbon price) does make the use of biomass in power generation cost competitive, it will still be possible to meet only a very small proportion of total power demand with biomass generation while staying within sustainable supply limits. If *all* of the 50 EJ[240] of sustainable supply indicated by the top end of our prudent scenario were devoted to biomass power generation, after conversion losses this would produce around 20 EJ of electricity supply which is less than 6% of ETC estimates for total required electricity supply in 2050 of around 100,000 TWh or 360 EJ.[241] Furthermore, that would be at the expense of other high priority uses such as aviation and plastics feedstocks.

The potential for uses of biomass that achieve carbon removals (BECCS/BiCRS) would, however, grow if diet change, technological innovations, organic waste collection, or seaweed-for-energy development were to make possible any of the additional c.60 EJ of sustainable supply in our 'maximum potential scenario'. Whether or not these additional resources become available will only emerge gradually over time, with major additional supply unlikely to become available before the late 2030s and 2040s.

Any estimate of either the precise level of demand that can be sustainably met with biomass, or of the optimal allocation by sector, can therefore be illustrative only. But a comparison of the ETC estimates presented in this report with those included in the IEA's Net-Zero report helps to illustrate areas of clear agreement and key open issues [Exhibit 3.11].[242]

- In both cases, the allocation to liquid biofuels is around 15 EJ/year, and both we and the IEA assume that this supply should increasingly be shifted from road transport to shipping and aviation applications.

- Our analysis includes a specific focus on materials uses, not only in the form of wood products and input to the pulp and paper industry, which are not explicitly covered in the IEA's analysis, but which we believe should be an important focus for policymakers given the natural advantages of using biomass as a source of material rather than of energy.

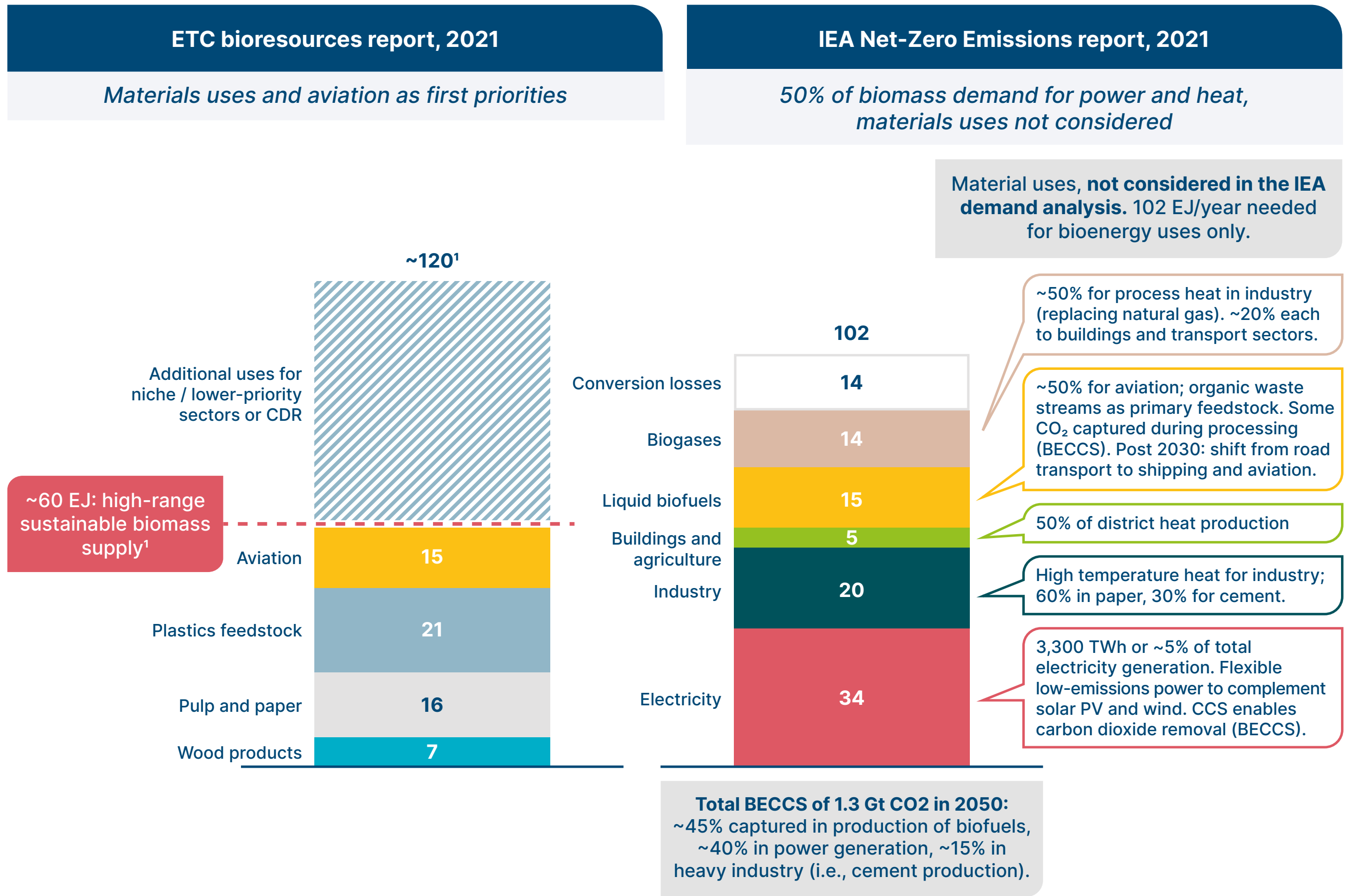
- The IEA assumes a significant 34 EJ/year allocation to biomass power generation. This reflects, in part, the IEA's strong focus on achieving near-total global power decarbonisation by 2040 and their belief that this may require a role for biomass to replace coal or gas in existing power plants. But, as illustrated above, these 34 EJs, which would produce about 14 EJ of final electricity supply, will still only provide a trivial proportion of future global electricity generation.

240 Excluding annual production of stem wood for materials (c.10 EJ/year).
241 Energy Transitions Commission (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy.*
242 IEA (2021), *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.*

Exhibit 3.11

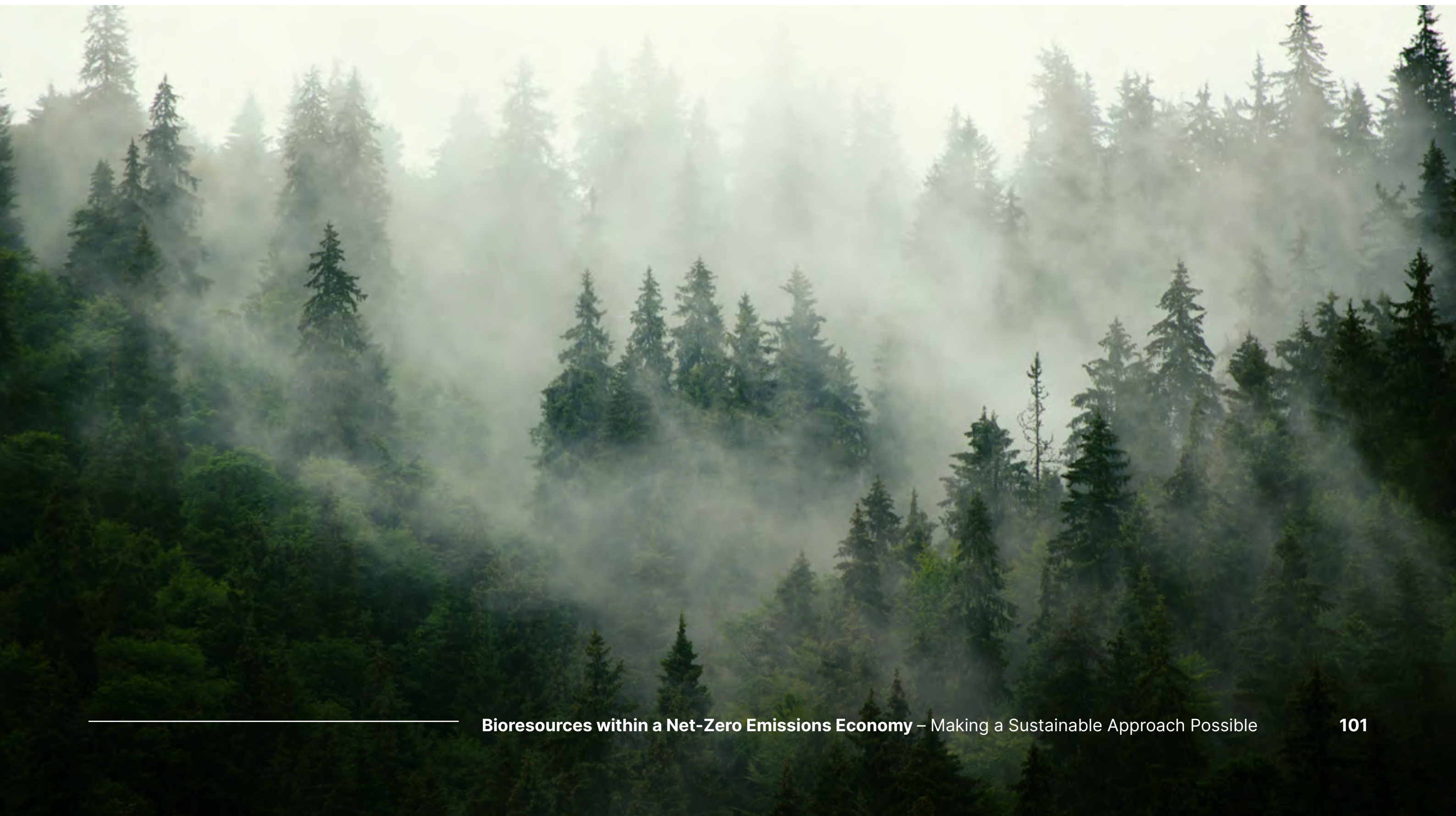
The IEA dedicates 50% of bio supply to power generation and high temperature heat for industry, applying significant CCS

Uses of biomass in 2050, EJ primary biomass



NOTES: [1] Includes high-quality stemwood from forestry suitable for the timber and pulp & paper sectors (~10 EJ/year today, FAO Industrial Roundwood less by-products used for energy). Additional high-quality stemwood could be made available if freed up land were dedicated to forestry.

SOURCES: IEA (2021) Net-Zero by 2050 - *A Roadmap for the Global Energy Sector*.



Industry and policy actions required to ensure optimal use of bioresources

As Chapters 1 to 3 have described, competing demands for biomass resources could easily exceed sustainable supply. One crucial policy priority is therefore to drive, as rapidly as possible, the development of other decarbonisation routes – in particular renewable-based electricity generation and clean hydrogen production – which are not subject to such inherent supply constraints. Forceful policies in those areas will ensure sufficient future supply and drive down costs.

Biomass will nevertheless play a small, but still vital, role in the future energy system. However, sustainable supply cannot be precisely estimated and the optimal allocation of constrained supply between alternative uses will depend on uncertain future developments along many dimensions. The optimal scale of bioresource use and allocation between sectors must therefore arise in part from the interaction between tightly defined and enforced sustainability standards and carbon pricing to guide optimal allocation. This should be supplemented by policy action to spur the development of alternative non-bio-based decarbonisation options and to discourage the use of bioenergy applications where it is highly likely to be uneconomic in the long-term.[243]

The chapter sets out the detailed actions required in three sections:

1. Ensure that biomass is sustainably sourced while pursuing opportunities to increase sustainable supply.
2. Create the conditions for prioritised use of bioresources.
3. Support key technologies to enable efficient, sustainable supply and use of bioresources.

4.1 Ensure that biomass is sustainably sourced while pursuing opportunities to increase sustainable supply

It is vital that any biomass used for climate mitigation purposes is sustainably sourced with low lifecycle emissions and minimal adverse impacts (e.g., on biodiversity). This requires:

- Defining and enforcing clear sustainability standards for biomass supply.
- Safeguarding alternative uses of land.
- Pursuing opportunities to grow sustainable biomass supply.

Define and enforce clear sustainability standards for biomass supply

Policymakers should agree on clear standards that ensure biomass supply has truly low lifecycle carbon emissions and is sustainably sourced. These must cover the full supply chain, be specific to each type of biomass, and be concrete enough to enable effective implementation and enforcement. Box H sets out the key principles which should be reflected in precise standards.

Given the risks associated with use of unsustainable biomass, the importance of clear standards is uncontroversial – the challenge lies in their precise definition and implementation. Vague and broad-brush sustainability standards may be too weak to be effective. Detailed implementation of some standards will need to reflect specific local circumstances – for instance guidelines for the fraction of agricultural residues left unharvested should ideally vary by crop and by soil type. However precise, standards to govern all possibilities cannot be defined at national or international level, but decentralised rule-making may result in uneven and inconsistent implementation.

As a general rule, bioenergy criteria used by governments do not correspond to our recommended criteria. Today's standards tend to allow nearly unlimited use of existing agricultural lands and exclude only small shares of natural lands either through direct restrictions or greenhouse gas criteria. They often fail to recognise the critical opportunity costs of land either to store carbon or to meet rising demands for food. Lifecycle analyses in greenhouse gas criteria may also improperly credit plant growth as offsetting emissions by burning biomass regardless of whether that plant growth is additional to what would occur without dedicated biomass production. As a rule, more restrictive criteria are necessary to ensure biomass achieves both true and significant greenhouse gas reductions and avoidance of harm to food security and biodiversity.

243 ETC (2020), *Making Mission Possible.*

Alongside the adoption of criteria that limit biomass resources to those specified in Box H, this implies the need for policymakers to (i) take immediate actions to prevent the highest risk activities and (ii) focus on transparency and traceability, data analysis, monitoring techniques, and governance approaches that can make standards more effective.

Take immediate actions to prevent the highest risk activities related to biomass sourcing. These include:

- An immediate and comprehensive ban an any conversion of either preserved natural ecosystems (e.g., tropical forests) or high carbon-storing soils (e.g., peatlands) for commercial biomass exploitation.
- Use of innovate transparency tools to monitor for land use change and illegal logging.
- Accelerating and enforcing the adoption of 'deforestation-free' supply chain commitments.

In addition, mechanisms must be created to allow transparency and traceability of all biomass supply chains across national and international boundaries to guarantee sourcing of sustainable biomass with low lifecycle emissions. Critical information should be visible through the supply chain, including:

- The location and type of land from which biomass is harvested (see point on data below).
- The harvesting / collection techniques and any sustainability standards applied during this process (e.g., sustainable forest management techniques such as leaving tree roots and stumps to decay in order to support soil health and biodiversity).[244]
- The methods used to collect, process, and transport the biomass being harvested, aiming to decarbonise these processes as rapidly as possible.

244 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*

Data analysis and monitoring to ensure optimal land use include:

- Applying sustainability criteria, including carbon stocks within the land, to generate maps and a clearer understanding of where lands with low environmental opportunity costs are located – i.e., those suitable for cultivating biomass with low lifecycle carbon emissions such as marginal or abandoned land.
- Using spatial planning to identify the optimal allocation of land for agriculture (based on yield, natural capital, and soil health), the allocation of natural ecosystems for legal protection and large-scale restoration, and geographical boundaries of urban growth and infrastructure.
- Identifying cleared or abandoned agricultural lands where biophysical or human factors / market forces are blocking natural regeneration.
- Monitoring and evaluating the impact of specific uses of land in terms of carbon stocks and other benefits (biodiversity, water quality, etc.).
- Improving the definition, analysis, and verification of the net-carbon content of biofuels.

Required governance and legal safeguards include:

- Ensuring that any incentives for biofuel use are tied to an accurate assessment of the net-carbon content of the fuel.
- Agreeing on clear definitions, practices, and standards (e.g., establish clear Climate-Smart Forestry guidance).[245]
- Establishing independent certification and implementing monitoring systems (through technology and on-the-ground verification) to verify carbon calculations and demonstrate carbon savings following international norms. Monitoring systems should consider the land-use system as a whole, rather than focus on particular uses such as bioenergy, to ensure the full impact of the energy feedstock expansion is assessed, including any knock-on impacts on other land uses, such as agriculture.
- Engaging a wide range of stakeholders (industry, NGOs, etc.) to develop trust in the system. Strengthen community engagement processes to ensure on-the-ground practices match rhetoric and to facilitate monitoring.
- Developing publicly available reporting.
- Engaging in regular revision processes.

These standards can and should be adopted and used at multiple levels including:

- **Voluntary certification schemes** (e.g., the Sustainable Biomass Program, the ISEAL Alliance, the Forest Stewardship Council)[246] can play a useful role if they incorporate the low lifecycle carbon emissions sustainability criteria outlined in Box H, but multiple different standards can enable 'greenwashing' through the adoption of the least ambitious standard available.[247]
- **National regulations** consistent with these sustainability criteria are therefore required to govern both biomass produced in the country and biomass sourced from other countries.
- **International standards**: robust, reliable biomass supply chains can be best supported by sustainable biomass standards and policies that are consistent across markets and, ideally, agreed at international level.

245 Climate-Smart Forestry strategies are aimed at (i) 'increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services, (ii) enhancing the health and resilience through adaptive forest management, and (iii) using wood resources sustainably to substitute non-renewable, carbon-intensive materials.' Verkerk et al. (2020), *Climate-Smart Forestry – the missing link.*

246 The Sustainable Biomass Program (SBP), founded in 2013, is applied in 31 countries with the objective of promoting and maintaining sustainable woody biomass supply chains via an independent third-party certification scheme. It has five Certification Bodies that have been accredited independently by Accreditation Services International (ASI) and has a 5-yearly standard revision process with stakeholder involvement. Compliance with the SBP standard must be demonstrated by regulated companies themselves; regulatory requirements are set by national governments. The ISEAL Alliance is a Code of Good Practice providing a framework for defining effective and credible sustainability systems. Credibility Principles were developed after a year-long consultation with contributions from >400 stakeholders around the globe. Sources: *Sustainable Biomass Program* (2019); *ISEALAlliance.org*, accessed June 2021.

247 UK Committee on Climate Change (2018), *Best practice in international biomass governance.*

Principles for sustainable biomass supply

Each source of biomass has specific sustainability criteria which ensure low lifecycle emissions and that production does not compete with alternative uses of land. Guiding principles for sustainable supply by source are outlined here.

Biomass grown on dedicated land

Ensure biomass from dedicated land use avoids land-use conflicts and contributes positively to climate mitigation:

- Because of rising demand for food, and the value of natural lands for carbon storage and biodiversity, dedicated energy crops should only be grown on a highly limited supply of marginal lands, that are generating minimal food supplies and are not good candidates for alternative restoration.
- If a combination of dietary changes and increases in agricultural productivity can generate surplus agricultural land on a global, net basis, this land could be devoted to dedicated energy crops, if i) the expected yields and energy uses of those crops result in substantially greater greenhouse gas reductions than restoring this land to nature, and ii) if this land is not of, or adjacent to land, with significant ecological value (e.g. abundant biodiversity, protected land), where there is high potential for biodiversity to re-establish itself.

Focus on biomass from waste and residual sources to reduce pressure on land:

Woody biomass from forestry

- For bioenergy purposes, only forest residues should be used, and their quantity and manner of collection should limit biodiversity effects and avoids adverse effects on soil carbon.

  For uses of forest biomass for materials purposes (which will also generate the residues for energy uses):
  - Adopt sustainable, adaptive forest management practices (e.g., climate-smart forestry)[1] to protect carbon stocks and ameliorate biodiversity impact.
  - Allow for appropriate growth/rotation times to avoid carbon opportunity costs from premature harvests.
  - Pursue opportunities to minimise biodiversity impacts:
    - Preserve intact forest landscapes.
    - Maintain a fraction of intact land between managed areas (e.g., >25%)[2].
    - Plant non-invasive and diverse (ideally native) species.
    - Measure biodiversity impacts of intervention (e.g., surveys or genetic sampling).

Agricultural residues

- Limit biomass extraction to protect soil and ecosystem health, e.g. leaving sufficient residues on the land.

Municipal and industrial waste

- Encourage circular economy efforts both to reduce amount of waste created and increase effective waste collection and separation[3]:
  - Establish and expand waste collection rates in the middle-/low-income countries.
  - Collect organic waste as a separate waste stream wherever possible.
  - Separate the organic fraction from mixed waste.
- Ensure that carbon accounting recognises the share of biogenic and non-biogenic (fossil-derived) materials in energy recovery systems. Controlled disposal (e.g., incineration) should be the last resort, with CCS employed to ensure use disposal of mixed waste does not contribute to carbon dioxide emissions.

Biomass from aquatic sources

- Evaluate the impact of scaling macroalgal cultivation and extraction (in coastal shallows and deep sea) on ocean ecosystems.
- Focus on resource-efficient microalgal production technologies, which minimise competition for water and other resources.

Supply chain and process emissions

For all of these biomass sources, it is also essential to reduce supply chain and process emissions from transformation of biomass into bioresources to improve the effectiveness of bioresources for climate mitigation. Important levers to achieve this include:

- Electrification of cultivation, collection, transport and processing of biomass, alongside decarbonisation of the power grid.
- CCS infrastructure to capture process emissions where biomass is covered to bioresources.

Box H

NOTES: [1] Verkerk et al. (2020) *Climate-Smart Forestry – the missing link.*
[2] Current law in South Africa, for example, requires that forest plantations leave about 25% of the landscape intact for water conservation, erosion control, and biodiversity.
[3] SYSTEMIQ (2020), *Breaking the Plastic Wave.*

Safeguard alternative uses of land

Although our report has focused on uses of biomass for climate mitigation purposes, other factors have important implications for land use planning such as biodiversity conversation, food security, and the livelihoods and land rights of indigenous peoples groups and local communities. These topics are not covered in depth in this report but are considered by other forums, including the Food and Land Use Coalition. However, we do note that legal protection and enforcement of carbon-rich ecosystems must be underpinned by policies, investment, and incentives that support alternative livelihoods for indigenous peoples groups and local communities. These include:[248]

- **Payments for carbon mitigation services** (carbon removal and storage within 'Natural Climate Solutions'), which should benefit local and indigenous communities (who play critical roles in forest stewardship) and both enforce and incentivise forest protection and restoration.

- **Payments or subsidies for ecosystem services to** support biodiversity, water system management, and provide other important benefits.

- **Social safety nets and/or transition finance** to de-risk transition for forest communities and smallholder farmers.

- **Grant indigenous peoples' groups** legal title to their traditional lands and the means to defend them.

Complementary to this, research is required to understand agricultural techniques, technological innovations, and project management and governance structures which can maximise the level of carbon sequestration within the landscape and ensure its permanence. Actions to do this, as well as mechanisms and policies to channel financing at scale towards these natural climate solutions, are addressed in the ETC's ongoing work on carbon dioxide removals.[249]

Pursue opportunities to grow sustainable biomass supply

Access to larger quantities of sustainable biomass will make it much easier for the world to meet a 1.5°C climate objective. Policies and investments should therefore seek to realise the three additional sources of sustainable biomass which our maximum potential scenario suggests might deliver up to an additional 60 EJ/year of sustainable supply by 2050.

This should include action to directly increase organic waste and macroalgae resources:

- **Maximise the potential for use of organic waste** through investment in waste collection infrastructure (particularly in emerging economies) to expand the proportion of waste that is collected and processed. This includes collection of organic waste separately from non-biogenic waste, to enable valorisation and efficient use,[250] and investment in biogas recovery for wastes from livestock (i.e., manure), crop residues, and other agricultural wastes. Increasing statutory targets (e.g., for collection, recycling, and sorting) can drive circular economy and waste management advances.[251]

- **Realise the potential for ocean biomass production** by developing and scaling macroalgae (seaweed) cultivation for energy applications, establishing cost and resource-efficient processing and conversion technologies, and evaluating the impacts of large, offshore seaweed farms on marine biodiversity.

248 Food and Land Use Coalition (2021 *in press*), *Accelerating the 10 Critical Transitions: Positive Tipping Points for Food and Land Use Systems Transformation.*
249 ETC (2021), *Reaching climate objectives: the role of carbon dioxide removals.*
250 SYSTEMIQ (2020), *Breaking the Plastic Wave.*
251 SYSTEMIQ (2020), *Breaking the Plastic Wave.*

In addition, policy and private investment should seek to maximise the potential to release land from food production, some of which might then be devoted to biomass production for materials and energy.[252] This will require:

- **Improving agricultural productivity** through better information and technology sharing between countries and via precision genetic engineering.
- **Expanding the production of macro- and microalgae** as sources of food and animal feed.
- **Developing biotechnologies** to enable the production of synthetic meat and dairy and alternative proteins.
- **Reducing food loss** – e.g., by 25% by enforcing appropriate standards[253] to improve food supply chain efficiencies and through education.
- **Encouraging the adoption of more plant-based diets** (e.g., to achieve a 65% reduction in meat and dairy consumption in Europe).[254]

Across all sources of biomass there are additional opportunities to increase potential supply by improving and expanding the radii of collection and transport systems.[255]

4.2 Create the conditions for prioritised use of bioresources

Past policies to support bioenergy development have, in some cases, encouraged uses that have soon proved uncompetitive with other decarbonisation options (e.g., the use of biofuels in road transport). This reflects the unpredictability of technological developments. For instance, the unanticipated pace of improvement in electric vehicle technology and costs made electrification the cheapest route to emissions reductions in the transport sector far earlier than many analyses initially assumed. Optimal policies therefore need to combine:

- **Use of carbon prices to guide sector allocation**, including in relation to carbon removal opportunities.
- **Deliberate policies to discourage suboptimal use**, encourage priority use, and develop alternative decarbonisation options.
- **National and local strategies** which take into account the details of local land use and sustainable biomass supply.

Carbon pricing and carbon removals

Carbon pricing is not a policy panacea. In many sectors of the economy, other policy instruments – whether direct subsidies or regulation – have proved more effective drivers of decarbonisation.[256] But carbon pricing, underpinned by clear measurement of the full lifecycle carbon emissions of the biomass deployed,[257] needs to play a key role in allocating scarce sustainable biomass supply towards uses with the highest value.

This will be particularly important in applications where biomass can be used to achieve carbon removals (BECCS/BiCRS) since the economics depend on the 'CCS profit' (the revenue stream received from carbon removal, minus the cost of CCS). Such revenue streams can sometimes be generated by including BECCS/BiCRS operations within emissions trading schemes, with companies that still have positive gross emissions effectively paying BECCS/BiCRS operators for carbon removals. In these cases, the total number of credits available within the scheme (declining rapidly over time) should be set to be compatible with the required reduction of net emissions (i.e., the dashed line on Exhibit 3.1) with higher gross emissions offset by carbon removals.

252 If actions can free up crop- or pastureland from food needs, use of land should be considered holistically at a regional or national level. First consideration should be additional food production needs (e.g., as climate change disrupts current production), and alternative uses should also be evaluated (e.g., returning to nature for biodiversity, carbon sequestration in standing forest). In certain locations, where freed-up land is depleted and far removed from biodiversity-rich areas, the most efficient use of land could be to dedicate a portion of land to high-yield, efficient biomass production (e.g., to energy crop plantations) to enable other land closer to biodiversity hotspots to be returned to nature.

253 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*

254 Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use*; The Lancet (2019), *Food in the Anthropocene: The EAT Lancet Commission on Healthy Diets from Sustainable Food Systems.*

255 This is likely to include development of 'hub and spoke' models where biomass processing is concentrated in bio-hubs supplied by local 'spoke' bio-processing facilities which partially transform biomass into more easily transportable formats (e.g., through pyrolysis or pelletisation).

256 To date, most biofuel policies have not been based on carbon pricing as, where they exist, current carbon prices are insufficient to support biotechnology use.

257 It is critical that carbon pricing schemes do not start from the assumption that all biomass is carbon neutral as with early iterations of the Renewable Energy Directive.

But many countries without comprehensive emissions trading schemes and carbon removals may be required not only to offset remaining gross emissions in the energy, building, industry, and transport (EBIT) sectors, but also emissions from agriculture, forestry, and other land use (AFOLU) which usually fall outside emissions trading systems. Alternative revenue streams to drive removals may therefore be required, for instance from direct publics payments for carbon removal (potentially funded via carbon taxes). Alternatively, emissions trading schemes could be extended to cover these AFOLU sectors and natural climate solutions.[258]

Carbon removal strategies therefore need to be underpinned by decisions on 'who should pay'. Options are discussed in the ETC's consultation paper on carbon removals and will be assessed in an ETC report on the role and financing of carbon removals which will be published later this year.[259]

Discouraging suboptimal use, supporting priorities, and developing alternatives

In many regions, including Europe and the USA, current policy frameworks directly support the use of biomass in specific sectors where biomass is already, or is very close to being, uncompetitive compared with alternative decarbonisation routes (e.g., bioethanol or biodiesel for light duty road transport). Encouraging biomass use in sectors where it will become uneconomic creates a 'double transition' risk, increasing the cost of the net-zero transition by creating stranded assets and slowing down the deployment and cost-competitiveness of long-term zero-carbon solutions. It also results in less bioresource being available for priority sectors.

Carbon pricing alone cannot produce an optimal solution, and in some conditions could encourage transitional solutions (e.g., moving to liquified natural gas (LNG) in shipping) which further exacerbates risks of stranded assets. Policies should therefore reflect reasonable expectations of future technological and cost developments, as discussed in Chapter 2, by:

- **Ensuring that any incentives for biofuel use are tied to an accurate assessment of the net-carbon content of the fuel**, meeting the standards discussed in Section 4.1.[260]

- **Gradually phasing out mandates and subsidies for biofuel use in the road transport sector**, with any remaining support ideally focused on those subsectors where internal combustion engines are likely to play a dominant role for longer (e.g., certain heavy duty trucks).

- **Prioritising biofuel use in the aviation sector** with existing biofuel production assets shifting their output, where possible, to primarily provide jet fuel rather than fuels for road transport (respecting existing policy mandates) or shipping. Fuel blending mandates should be introduced that require the aviation sector to use a gradually rising proportion of Sustainable Aviation Fuel (SAF), whether bio-based or synthetic, alongside support for pilot scale projects and commercial scale-up.[261]

- **Encouraging the use of bioresources as feedstocks for the chemicals industry**, for instance by requiring a growing percentage of plastics feedstock to come either from recycled or bio-based material and by supporting R&D and pilot demonstration projects for use of bio-feedstocks for plastics.

- **Strongly supporting the development of alternative, non-bio-based decarbonisation options** in sectors such as shipping (i.e., 'green' ammonia or methanol) and residential heat (i.e., heat pumps) where these are highly likely to be the long-term economic solution.

258 For example, New Zealand's emissions trading scheme includes forestry. Vivid Economics (2019), *The Future of Carbon Pricing in the UK.*

259 ETC (2021) *Reaching climate objectives: the role of carbon dioxide removals.*

260 The Low Carbon Fuel Standard in California assesses carbon intensity of fuels based on a life cycle assessment. Carbon intensity scores are examined against an annually declining carbon intensity benchmark. California Air Resources Board (2021).

261 Not all SAFs will be bio-based; over time, an increasingly large proportion of SAFs will need to be sourced from synfuels. Energy Transitions Commission and the World Economic Forum (2020), *Clean Skies for Tomorrow - Joint Policy Proposal to Accelerate the Deployment of Sustainable Aviation Fuels in Europe.*

National and regional strategies to reflect local land use and bioresources

Seventy per cent of global emissions are now covered by some form of net-zero emissions target,[262] and countries which have adopted such targets will now need to develop comprehensive strategies to achieve them. These should include detailed considerations of the role which bioresources will play reflecting the specific circumstances of local land use, bioresource availability, and sectoral demands. Such strategies should cover:

- **The definition of tight sustainability standards**, aligned with the criteria set out above. This should apply both to any bioresources produced within the country and to any imports from other countries, prohibiting imports from countries that do not apply adequately tight local standards.

- **An assessment of available local and imported biomass**, considering these tight sustainability standards.

- **The appropriate role of bioresources in all sectors**, given the available supply, the availability of other decarbonisation options, and including the role of nature-based carbon removals, BECCS/BiCRS, and materials in addition to energy. On the basis of these strategic assessments, countries may choose to take steps to reduce double transition risks, e.g., through the withdrawal of incentives and/or use of bans (or phase-out targets) to disadvantage the use of biotechnologies in non-priority sectors that are competitive or close to competitive today (e.g., shipping and bulk power generation without CCS).

- **Regulations to preserve and prevent the conversion of any remaining ecosystems** which have high biodiversity or are large carbon stores (e.g., intact forests and peatland).

4.3 Support key technologies to enable efficient, sustainable supply and use of bioresources

Technological innovation is a fundamental enabler to the optimal use of bioresources to aid decarbonisation. Support for key technologies requires three types of action:

- **Focused, public and private R&D efforts** to achieve both incremental improvements in existing technologies and fundamental breakthroughs.

- **De-risking of pilot projects** within the value chain to scale up, reduce costs, and commercialise new technologies.

- **Supporting the roll out of existing technologies globally**, especially to developing countries.

Key technological developments have been described throughout this chapter and are summarised in Exhibit 4.1. Priority areas for technological development are:

- **Safeguarding sustainable supply** of biomass by identifying land with low environmental opportunity costs, enhancing measurement and monitoring, and improving governance structures for natural climate solutions.

- **Increasing sustainable biomass supply** through better waste collection systems and infrastructure, investing into new, potentially large-scale sources of biomass such as seaweed, and improving the efficiency of existing uses of land (e.g., through improved crop yields, food waste reduction, or development of alternatives to animal products enabled by biotechnologies).

- **Improving the use of bioresources** by bringing advanced biomass conversion technologies to commercialisation, demonstrating BECCS/BiCRS, and developing innovative biomaterials (e.g., bio-based plastics).

- **Reducing overall demand for biomass** by scaling alternatives (such as hydrogen or electrification) where they are available.

262 IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector.*

Support key technologies enabling efficient, sustainable supply and use of bioresources

- Breakthrough R&D
- Commercial scale up
- Incremental R&D
- Roll out existing technologies comprehensively

Safeguard sustainable supply

- **Develop maps / datasets** (e.g. with satellite data) to identify lands with low environmental opportunities costs
- **Improve supply chain monitoring** (at site / feedstock level, and cross-land use sector) and **data gathering / transfer**
- **Measure biodiversity and lifecycle carbon impacts** of biomass production (e.g. via surveys, genetic monitoring)
- Improve **measurement & monitoring of Natural Climate Solutions** (e.g. satellite/drone monitoring)

Improve use of bioresources

- Improve efficiency and decrease costs of **biorefinery transformation** (e.g., gasification/pyrolysis and enzymatic hydrolysis)
- Increase efficiency and decrease cost of adding **carbon capture to all bioenergy technologies**
- Develop **innovative biomaterials** (e.g., new fibres, bioplastics, structural materials)
- **Improve carbon sequestration rates and permeance** in NCS (e.g. agricultural techniques, technological innovations, and governance structures)

Increase sustainable biomass supply

Increase waste biomass supply

- Investment in comprehensive **municipal waste collection infrastructure** at scale
- Improve **sorting technologies** (e.g., to separate organic from mixed wastes)
- Establish **separate collection of organic waste** (e.g., enabled through valorisation)
- Expand **biogas collection and processing** (e.g., in intensive livestock systems)

Develop new sources – scale ocean seaweed cultivation for energy uses

- Reduce costs of **seaweed-for-energy processing & conversion technologies** (e.g., dewatering)
- Scale **near-shore seaweed production**
- Develop **open ocean seaweed** cultivation and collection technologies
- Research **impacts of large, offshore seaweed** farms on marine biodiversity

Free up current crop and pasture land

Enable dietary shifts

- Develop **cultured meat**
- Develop **alternative proteins** (e.g., insect- and plant-based)
- Create and scale **dairy alternatives** (e.g., via precision fermentation)

Improve agricultural efficiency

- **Information & tech. sharing** to improve global crop yields
- Use **precision genetic engineering** to develop high yield, climate resilient crops with reduced input requirements
- Scale & reduce costs of resource efficient **microalgae** cultivation
- **Reduce food waste** through better demand management using data/analytics
- Expand **regenerative agricultural** practices (e.g. no-till agriculture, cover crops, agroforestry)
- Increase **livestock productivity** (e.g., through improved food quality, breeding, and health care)

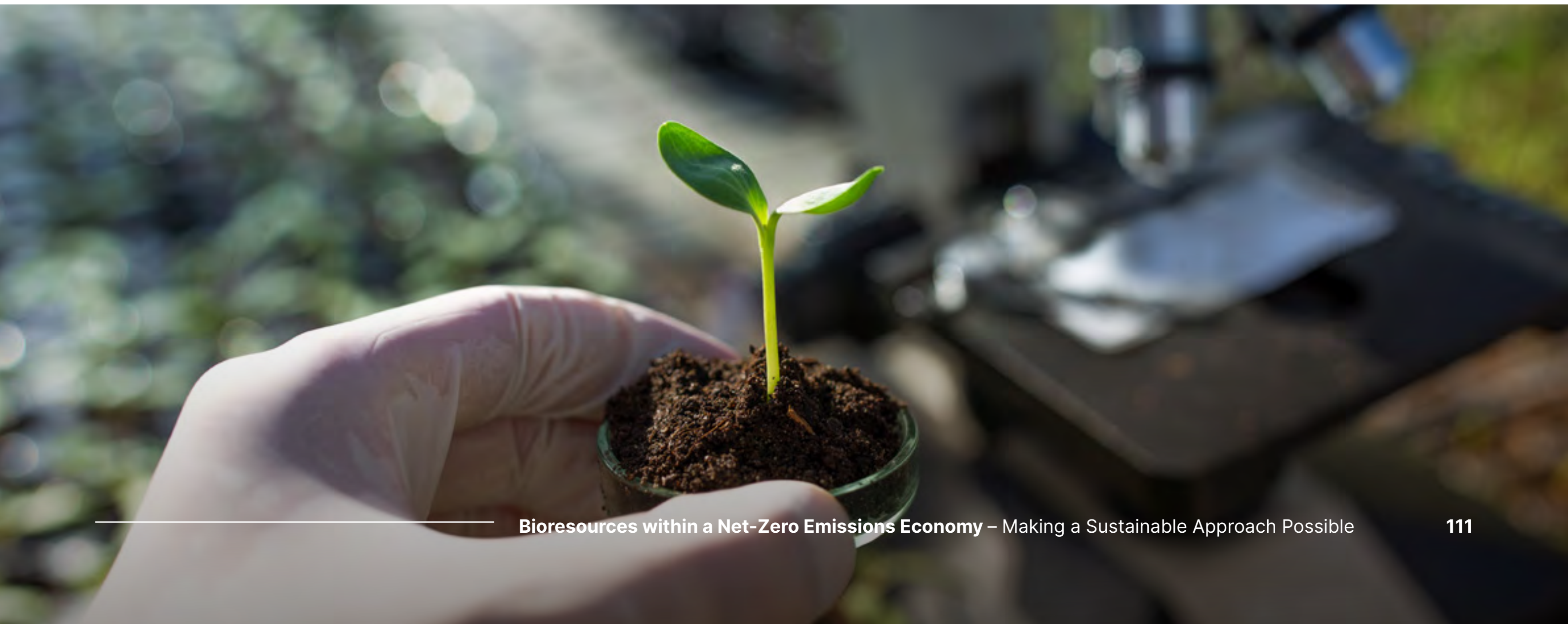
Extend feasible collection radii of biomass

- Establish **'hub & spoke' infrastructure** to reduce biomass collection / transportation costs

Reduce demand for bioresources by scaling alternatives and improving efficiency

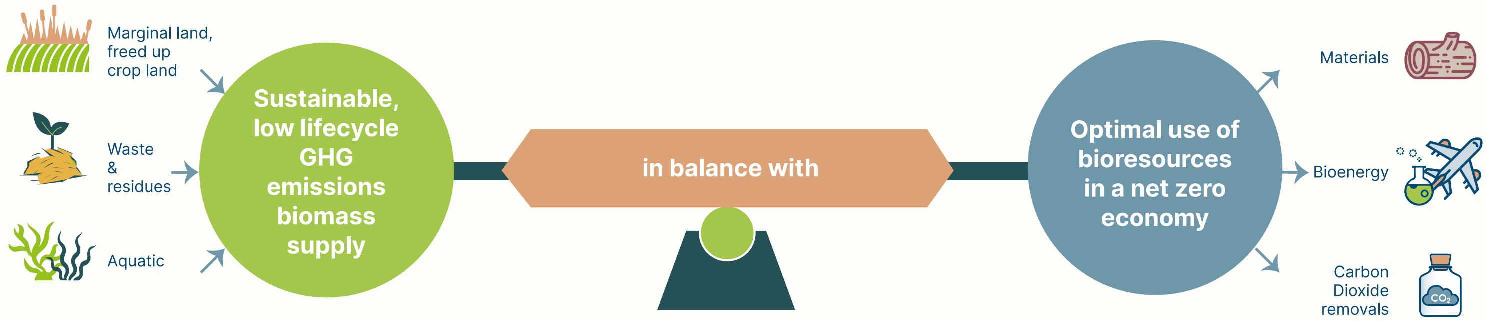
- Accelerate **non-bio resource development** (e.g. wind, solar, hydrogen)
- Scale **carbon dioxide removal** (CDR) **alternatives** (e.g., DACCS)
- Evaluate **emerging alternative CDR options** (e.g., CO_2 mineralisation, ocean alkalinity enhancement)
- Improve **energy and materials efficiency** (e.g., lightweighting)
- Move to a more **circular economy** (e.g., design materials for recycling)

Exhibit 4.1



Energy Transitions Commission

ENSURING A SUSTAINABLE APPROACH TO BIORESOURCES



TOP INDUSTRY AND POLICY ACTIONS ACROSS THE VALUE CHAIN

SAFEGUARD SUSTAINABLE SUPPLY

1. Set clear standards for sourcing truly sustainable, low-emission biomass
2. Use supply chain transparency, data analysis & governance to enforce standards
3. Protect tropical forests, peatlands
4. Incentivise alternative uses of land (e.g. payments for ecosystem services and CO2 removals)

GROW SUSTAINABLE SUPPLY

1. Increase organic waste collection globally
2. Scale seaweed-for-energy production
3. Release land from food production:
   - Improve global agricultural productivity;
   - Produce micro- & macro-algae for food/feed;
   - Reduce food waste
   - Global shift to plant-based diets
   - Develop and scale synthetic meat and dairy alternatives

CREATE CONDITIONS FOR OPTIMAL BIORESOURCE USE

1. Establish meaningful carbon taxes / prices
2. All policy support for biofuel use based on lifecycle carbon content
3. Drive deliberate policies to discourage suboptimal use of bioresources (e.g. light duty road transport) and to encourage priority use (e.g. aviation and plastics feedstocks)
4. Develop national and regional bioresource strategies reflecting local supply and demand

SUPPORT KEY TECHNOLOGIES TO ENABLE EFFICIENT, SUSTAINABLE SUPPLY & USE OF BIORESOURCES

Safeguard sustainable supply:

5. Use data analysis to improve land use choices; develop technologies to improve supply chain visibility and monitoring of Natural Climate Solutions

Grow sustainable supply:

4. Make land-use more efficient through innovation in precision biotechnologies, regenerative agriculture, synthetic meat / dairy and micro/macro-algae

Create conditions for optimal bioresource use:

5. De-risk pilot projects in biogasification for jet fuels and for plastics biofeedstocks

SCALE NON-BIO-BASED DECARBONISATION OPTIONS WHICH ARE LESS SUBJECT TO SUPPLY CONSTRAINTS

Clean energy

Clean hydrogen

Fossil fuels + CCS/U

Concluding remarks

The Energy Transitions Commission believes it is possible to reach net-zero carbon emissions by mid-century, significantly increasing the chance of limiting global warming to 1.5°C. Actions taken in the coming decade are critical to put the global economy on the right track to achieve this objective. Succeeding in that historic endeavour would not only limit the harmful impact of climate change, but also drive prosperity and better living standards, while delivering important local environment benefits. A net-zero GHG economy will be built on abundant, affordable zero-carbon electricity, complemented by clean hydrogen. Sustainably sourced biomass can also play a role, and its value is likely to be highest if used in materials (including in plastics feedstocks), in aviation, and in applications where it can be combined with CCS to deliver net carbon dioxide removals. Policymakers, investors, innovators, producers, buyers, and more generally both public and private sectors have a major responsibility to collaborate and act now at the local, national, regional and global scales to ensure all bioresources are truly sustainable and low lifecycle emission, grow truly sustainable supply and develop technologies and infrastructure that ensure use of biomass is prioritised to where it offers the greatest benefits to decarbonisation.

Acknowledgements

The team that developed this report comprised:
Lord Adair Turner (Chair), Faustine Delasalle (Director), Ita Kettleborough (Deputy-Director), Meera Atreya (Lead Author), Laetitia de Villepin, Tassilo Bismarck, Sanna O'Connor-Morberg, Mike Hemsley, Lloyd Pinnell, Ryan Reinaldy, with the support of Per Klevnäs, Karl Murray, Johan Haeger, and Mark Conrad (Material Economics) as well as Scarlett Benson, Maximilian Bucher, Rob Campbell-Davis, Alexandre Kremer, Phillip Lake, Tommaso Mazzanti, Mark Meldrum, Fellipe Mendes, Hettie Morrison, Aparajit Pandey, Francisco Pereira, Elena Pravettoni, Caroline Randle, Adrien Vincent, Andreas Wagner (SYSTEMIQ).

This report builds on analyses developed by our knowledge partners, whom we would like to thank again for the quality of their inputs:
Albert Cheung, Amy Grace, Logan Goldie-Scot, Seb Henbest, Benjamin Kafri, (BloombergNEF); Charlie Bloch, Elizabeth Hartman, Rudy Kahsar, Thomas Koch Blank, Amory Lovins, James Newcomb, Madeline Tyson (Rocky Mountain Institute); Shruti Dayal, Sunil Dhingra Will Hall, G Renjith, A K Saxena, Thomas Spencer (The Energy and Resources Institute).

The team would also like to thank the ETC members and experts for their active participation:
Rajit Nanda (ACWA Power); Christoph Beckmann, Elke Pfeiffer (Allianz); Javier Bonaplata, Nicola Davidson, Alan Knight (ArcelorMittal); Abyd Karmali (Bank of America); Rod Davies, Doris Fuji, Nicholas Lawson, Ian Luciani, Fabio Montemurro, Chris Phillips, Kirsty Salmon, William Zimmern (BP); Jeanne Ng (CLP); Cameron Butler, Rob Kelly, Ro Maxwell, Wei Sue (Climateworks Australia); Sandrine Dixson-Declève (Co-President, Club of Rome and Ambassador for Europe, Energy Transitions Commission); Dana Barsky (Credit Suisse); Ashwani Pahuja, Anupam Badola (Dalmia Cement); Bin Lyu (Development Research Center of the State Council); Tanisha Beebee, Chloe Drew, Rebecca Heaton, Ross McKenzie (DRAX); Cristian Carraretto, Adil Hanif, Dimitri Koufos, Frederic Lucenet, Eric Rasmussen (EBRD); Dries Acke, Rebecca Collyer, Pete Harrison, Thomas Legge, Phillip Niessen, Trees Robijns (European Climate Foundation); Patrick Curran (Grantham Institute, London School of Economics); Matt Gorman (Heathrow Airport); Andrea Griffin (HSBC); Isabel Gomez, Francisco Laverón, Samuel Perez (Iberdrola); Chris Dodwell (Impax Asset Management); Ben Murphy, Andrew Symes (IP Group), Christopher Kaminker (Lombard Odier); James Smith-Dingler, Elizabeth Watson (Modern Energy); Matt Hinde, Terry McCormick, Joseph Northwood, Nick Saunders, Nicholas Young (National Grid); Peter Aagaard, Jakob Askou Bøss, Anders Holst Nymark, Peter Kristensen (Ørsted); Aditi Garg (ReNew Power); Jonathan Grant, David Leigh (Rio Tinto); Charlotte Brookes, Mallika Ishwara, Martin Haigh (Royal Dutch Shell); Emmanuel Normant (Saint Gobain); Sandrine de Guio, Emmanuel Laguarrigue, Vincent Minier, Vincent Petit (Schneider Electric); Brian Dean (SE4All); Camilla Palladino (SNAM); Jesper Kansbod, Martin Pei (SSAB); Alistair McGirr (SSE) Jan Braten, Kristian Marstrand Pladsen (Statnett); Brian Dean (Sustainable Energy For All); Abhishek Goyal (Tata Group); Madhulika Sharma (Tata Steel); Reid Detchon (United Nations Foundation); Mikael Nordlander (Vattenfall); Johan Engebratt, Niklas Gustafsson, Monica Johansson (Volvo Group); Luke Pritchard, Rasmus Valanko (We Mean Business); David Nelson (Willis Towers Watson); Asger Garnak, Karl Hausker, Jennifer Layke, Tim Searchinger, (World Resources Institute), Paul Ebert, Phil O'Neill, Geeta Thakoral, Frank Wouters (Worley).

The team would also like to thank the ETC's broader network of experts for their input:
Fulvio Di Fulvio, Nicklas Forsell, Michael Obersteiner, Hugo Valin, (IIASA); Marc Von Keitz, Krishna Doraiswamy (ARPA-E); Chris Chuck (Bath University); Cooper Rinzler, Eric Toone, Eric Trusiewicz (Breakthrough Energy Ventures); Gareth Hughes, Amy Ruddock (Carbon Engineering); Phil Cruver (Catalina Sea Ranch); Sir David King (Centre for Climate Repair); Marian Schoen (Climate KIC); Tim Jacobs (Copernicus Land Service); Lauri Hetemäki, Marc Palahi, Hans Verkerk, Jo Van Brusselen (European Forest Institute); Chelsea Baldino, Stephanie Searle (ICCT); Timothy Goodson, Thomas Spencer (IEA); Göran Berndes, Ioannis Dimitriou, Ir. Luc Pelkmans (IEA Bioenergy TCP); Roger Aines (Lawrence Livermore National Laboratory); Brian Wilcox (Marine BioEnergy); Anders Åhlén (Material Economics); Julien Claes, Alastair Hamilton, Agata Mucha, (McKinsey); Mike Allen (Plymouth Marine Laboratory); Keith Coleman (SuSeWi); Ben Dixon, Liesbeth Huisman, Morten Rosse, Eveline Speelman, Trishla Shah (SYSTEMIQ); Daniel L. Sanchez (UC Berkeley); Bob Scholes (University of the Witwatersrand, Johannesburg); Scott Lindell (Woods Hole Oceanographic Institution).

The **Making Mission Possible** Series

Bioresources within a Net-Zero Emissions Economy:

Making a Sustainable Approach Possible

July 2021

Version 1.0

Energy Transitions Commission