The **Making Mission Possible** Series

Bioresources within a Net-Zero Emissions Economy:

Making a Sustainable Approach Possible

July 2021

Version 1.0

Executive Summary

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:
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Energy Transitions Commission

BIORESOURCES WITHIN A NET-ZERO EMISSIONS ECONOMY

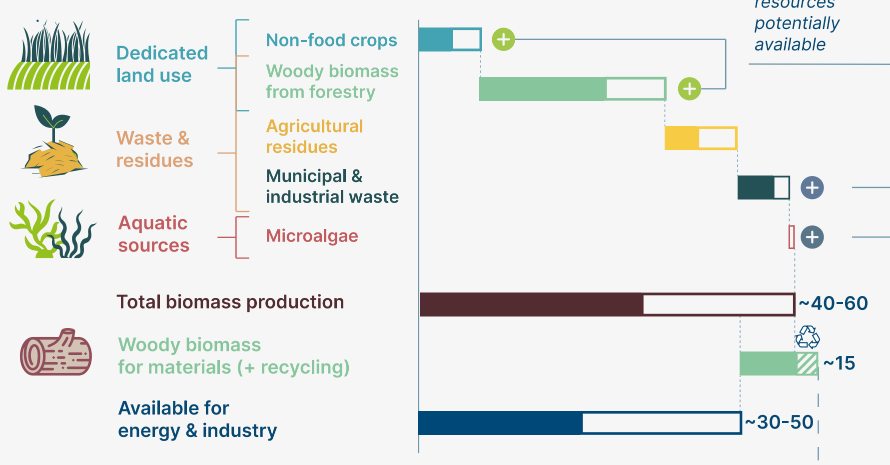
How much biomass can we use?

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

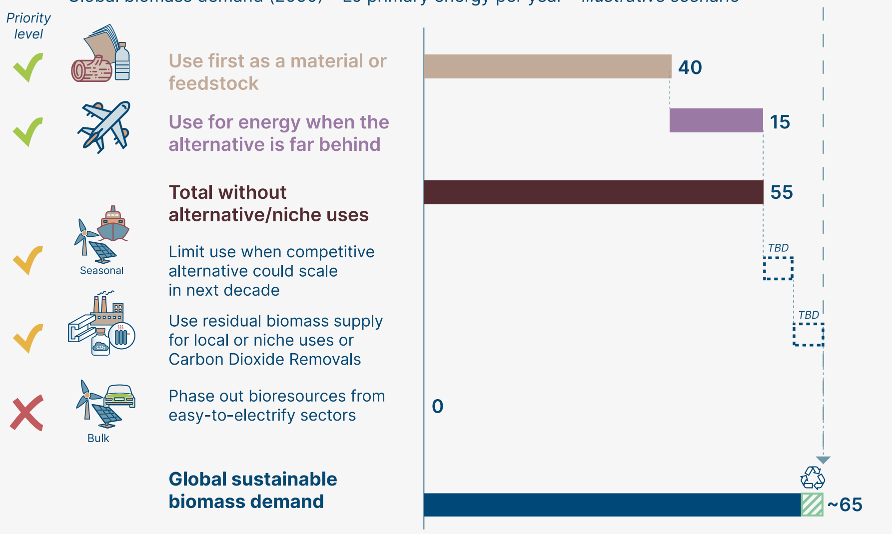
More land

New sources

Where should bioresources be used?

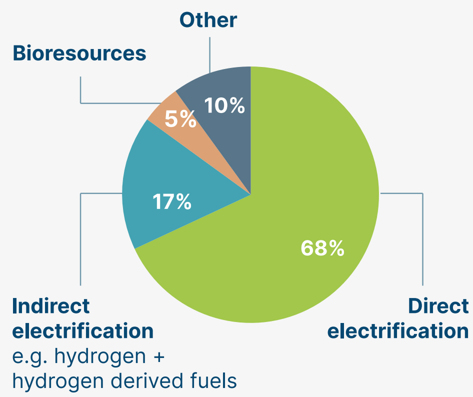
HOW TO PRIORITISE USES OF BIORESOURCES?

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*



Executive Summary

It is technically and economically feasible for the global economy to reach net-zero greenhouse gas (GHG) emissions by mid-century, and clean electricity will be at the centre of achieving that.[1] Rapidly falling costs of renewables and energy storage make it possible to achieve a massive expansion of clean power systems and electrification of end uses at low-cost, and, in turn, this will enable 'green hydrogen'[2] to be produced at scale, enabling further decarbonisation in heavy industry and bulk transportation. As described in two recent ETC reports on *Making Clean Electrification Possible* and the *Making the Hydrogen Economy Possible*, it is therefore feasible for non-fossil and non-bio-based energy resources to meet a large majority of energy needs by 2050 [Exhibit 1].

However, clean electrification combined with hydrogen cannot meet all decarbonisation needs. There are some sectors where direct electrification will likely remain impossible or uneconomic for many decades, and hydrogen will be significantly more expensive than hydrocarbon-based solutions in some applications. A completely decarbonised economy will therefore entail some remaining role for fossil fuels coupled with carbon capture and storage or use (CCS/U) together with the use of bioresources, potentially also combined with CCS. This report sets out the ETC's assessment of the role of bioresources in a net-zero emissions economy, and a forthcoming report will describe the appropriate role of the several different forms of CCS/U.

Bioresources could be used in many different applications, with the CO_2 absorbed in plant growth offsetting emissions during end use; and combined with CCS it could potentially deliver net carbon dioxide removals from the atmosphere (CDR, also known as 'negative emissions'). As a result, many analyses of the path to a net-zero carbon emissions economy have assumed a major role for biomass; demand for biomass is growing strongly, and public policy has supported bioenergy application in several sectors.[3]

But the total sustainable supply of biomass is severely limited. Plant photosynthesis is a very inefficient way to capture solar energy,[4] and using biomass to meet energy needs therefore creates a large demand for land, potentially competing with food production, biodiversity, or the use of natural forests or other ecosystems as carbon stores [Exhibit 2]. Adverse impacts on land use together with large conversion losses in bioenergy production can mean that some forms of bioenergy are far from net-zero carbon emissions over their lifecycle. And even low lifecycle emissions bioenergy may have adverse impacts on other environmental dimensions like biodiversity or local air pollution.

Strategies for biomass use must therefore start with a careful assessment of total sustainable supply. There are three core sources of biomass that can be used for energy and materials: biomass grown on dedicated land (e.g., energy crops, managed forests for materials production), biomass from waste and residues of other uses of land (e.g., forestry and agricultural residues, municipal and separately collected industrial wastes), and biomass from aquatic sources (e.g., seaweed).

The 'prudent scenario' presented in this report estimates that sustainable supply at c.40-60 EJ produced per annum globally by 2050, of which c.10 EJ/year is currently used, and should continue to be used, as a material rather than an energy source, leaving c.30-50 EJ/year available to provide energy or to meet new material demands. In addition, about c.4

1 Energy Transitions Commission (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy.*
2 Produced in a zero-carbon fashion via electrolysis using zero-carbon electricity.
3 For example, largely due to policy, bioenergy use in the European Union has increased by 150% since 2000. Material Economics analysis (2021) based on EU Energy Balances from Eurostat.
4 Blankenship, et al. (2011) *Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement.*

EJ/year of demand for biomass used as material could be met by recycling of woody biomass.[5] In our 'maximum potential scenario' an additional c.60 EJ/year might become available over time, but c.45 EJ/year of this would only be available if changes in diet or food production technology enabled a dramatic reduction in land use for animal meat production, with the remaining c.15 EJ/year realised through further global advances in waste management (c.5 EJ/year) and development of a very large seaweed-for-energy industry (c.10 EJ/year).

Total potential demands for biomass in a net-zero emissions world greatly exceed the prudent scenario estimate of sustainable supply, and significantly exceed even the maximum potential.[6] It is therefore essential to prioritise the use of biomass on those sectors where it has a clear and sustained advantaged versus alternative decarbonisation routes. This implies using biomass primarily as a material (including in plastics feedstocks), in aviation, and in applications where it can be combined with CCS to deliver net carbon dioxide removals. Use in other applications – such as road transport, residential heat, shipping, or power generation without CCS – should be minimised and gradually phased out over time.

The optimal allocation of bioresources cannot be precisely defined in advance but should arise from the interaction between tightly defined and enforced sustainability standards, carbon prices to incentivise optimal use (including as a means to achieve carbon removals), and strategies to develop alternative decarbonisation routes while discouraging the use of bioenergy applications where it is highly likely to be uneconomic in the long term, or otherwise a low priority use.

The report addresses four objectives:

- Estimating the sustainable supply of bioresources.
- Identifying priority uses by sector.
- Assessing potential uses of biomass as a route to carbon dioxide removal.
- Highlighting policies and actions to ensure sustainable supply and highest-value use.

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

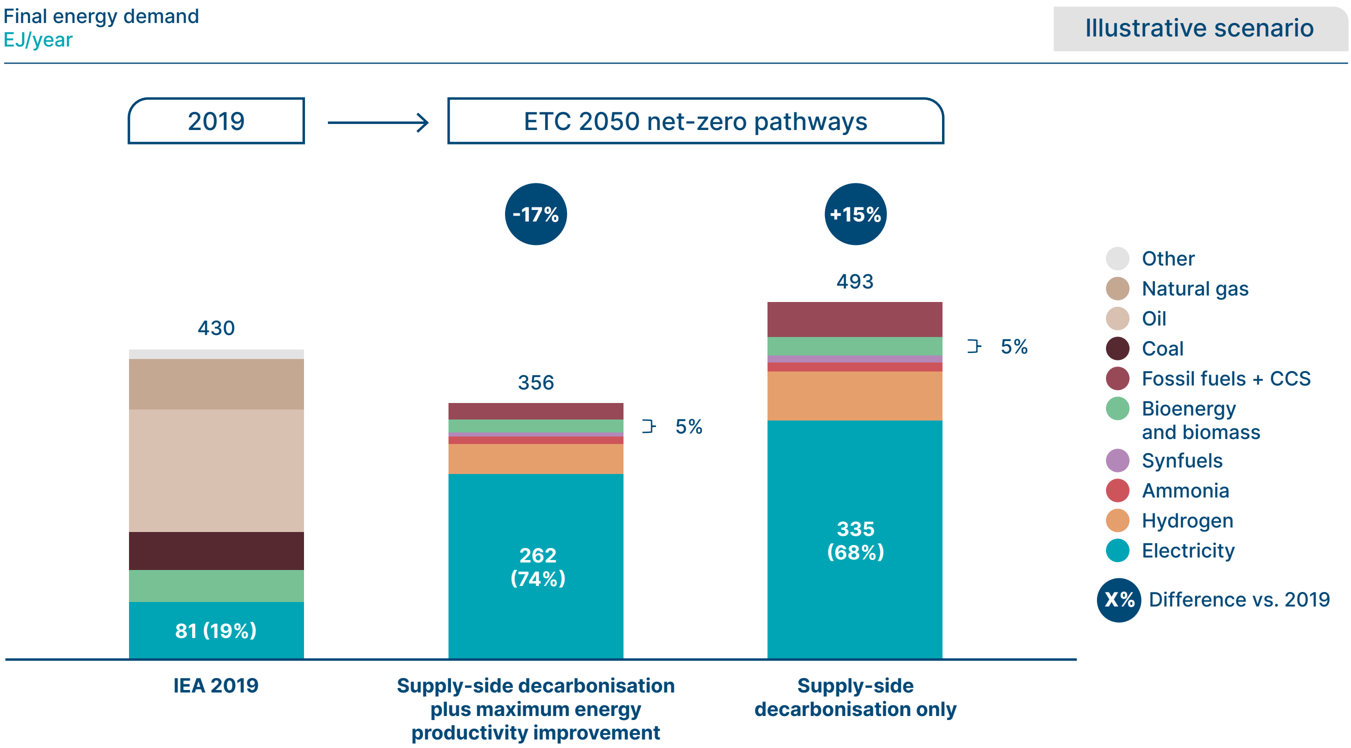


Exhibit 1

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

5 Based on IIASA analysis of 2018 FAO data and GLOBIOM results.
6 Biomass demand depends on the climate scenario. IPCC (2018), *Special Report on Global Warming of 1.5°C.* IRENA (2021), *World Energy Transitions Outlook: 1.5°C Pathway.*

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

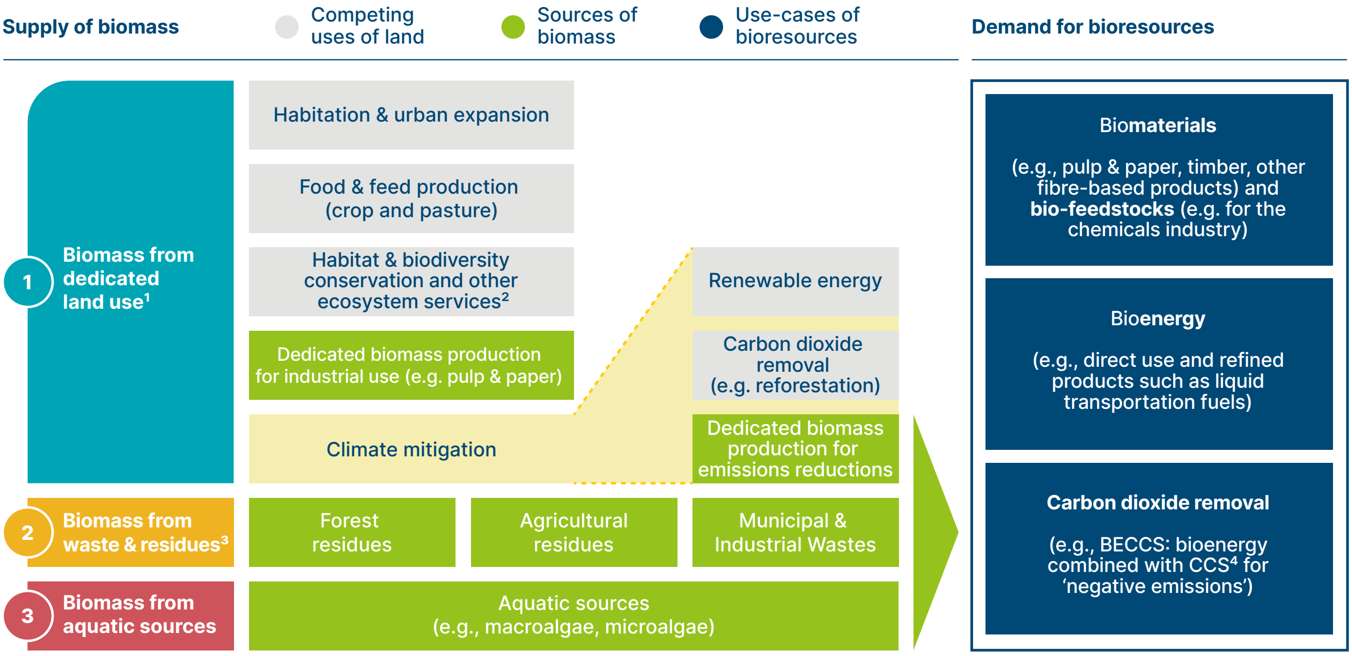


Exhibit 2

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.

Sustainable supply of bioresources

While biomass is in principle renewable, not all biomass is 'good' biomass from an environmental point of view. 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, and biomass production can still adversely affect biodiversity. In a net-zero emissions economy, biomass used for materials, for bio-feedstocks (e.g., for plastics), or for bioenergy must be sustainably sourced, with low lifecycle emissions. This implies the need to:

- **Avoid competition with other critical uses of land**, including for food production to feed the growing global population, for biodiversity protection, or for alternative forms of climate mitigation such as reforestation. 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.

- **Ensure a low lifecycle emissions footprint** by avoiding adverse land-use changes that release carbon stocks and by accounting for the 'opportunity cost' of the carbon that could be sequestered if biomass were not extracted (e.g., avoiding conversion of land already growing biomass and not harvesting prior to plant maturity when growth rates, and rate of carbon sequestration, decline).[7] New biomass production cannot provide an immediate offset because plants must capture carbon through grow before they can be harvested for use. Emissions from the cultivation, harvesting, transportation, and processing of biomass must also be minimised.

- **Account for other critical environmental and social considerations** including biodiversity conservation, and ecosystem and soil health (e.g., by retaining rather than harvesting a significant proportion of agricultural and forestry residues), alongside social considerations such as equity and cultural protection (e.g., indigenous peoples and land rights).

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

These criteria together imply that almost all bioresource used as an energy source should come from forest or agricultural residues or from various forms of waste, with minimal use of land dedicated for commercial bioenergy extraction. In particular they imply that there should be:

- No biomass production in areas already sequestering significant carbon above and below ground in growing biomass (e.g., tropical forests).
- No biomass production on land with rich soil carbon stocks (e.g., peatlands or intact forests).

Estimates of available biomass supply vary greatly according to the strictness of sustainability criteria, and even estimates which attempt to apply similar criteria vary significantly because of inherent uncertainties.[8] **Our prudent scenario** for the quantity of clearly sustainable biomass available by mid-century is **c.40-60 EJ/year** [Exhibit 3]. This compares to c.40 EJ/year of primary bioenergy used today[9] excluding materials (c.10 EJ/year) and traditional uses (c.25 EJ/year).[10] This sustainable biomass supply is comprised of:

- Approximately 5-10 EJ/year from non-food crops such as miscanthus or short rotation coppice (e.g., willow or poplar) grown on dedicated land (i.e., on marginal/degraded land or former crop- and pastureland).
- About 20-30 EJ/year derived from forestry, of which c.10 EJ/year is currently used for materials (e.g., timber), and of which c.10-20 EJ/year is in the form of forestry residues (produced when using the land primarily for stemwood production), subsequently available for other uses, including energy.
- Around 5-12 EJ/year of agricultural residues produced when using land primarily for food crop production while limiting residue extraction to protect soil and ecosystem health.
- An additional c.6-9 EJ/year from biogenic municipal and industrial wastes.
- A minimal amount from aquatic macroalgae sources of biomass (i.e., seaweed) which are currently being developed on a significant scale for high value uses rather than as an energy source.

Of this c.40-60 EJ/year of total production potential, c.10 EJ/year of woody biomass from forestry are already used as a material rather than energy,[11] and should continue to be so, leaving c.30-50 EJ/year potentially available either as source of energy or for new forms of material use.

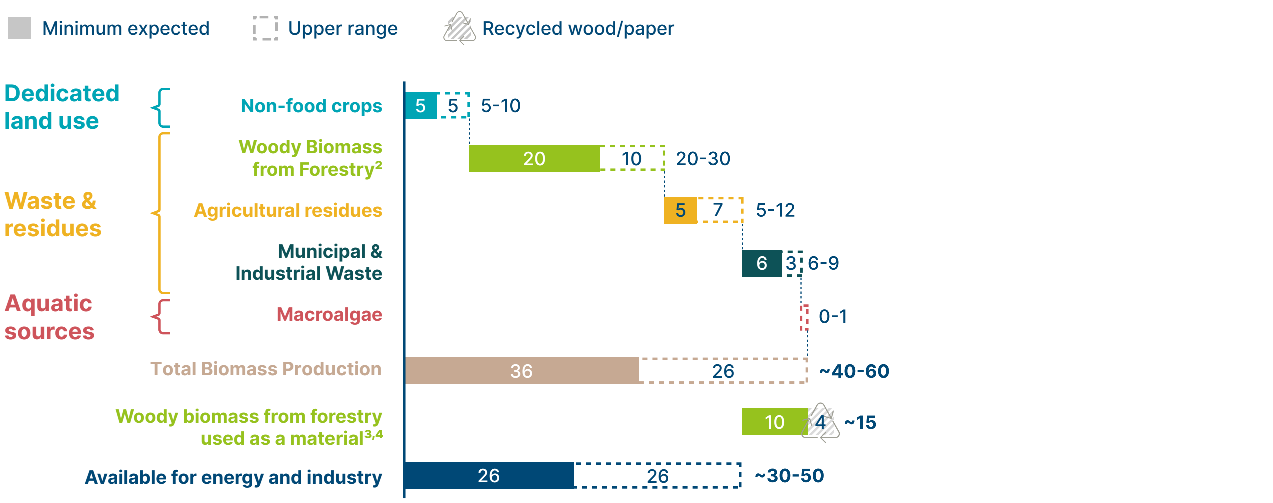
8 Slade et al. (2014), *Global bioenergy resources.*
9 IEA (2021), *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.*
10 Materials estimate based on IIASA analysis of 2018 FAO data and GLOBIOM results. Traditional uses of biomass include fuelwood, charcoal, and dung used in the residential sector, predominantly in developing countries; estimate from IIASA GLOBIOM (latest GLOBIOM FOLU-scenario model outputs shared Dec 2020).
11 In addition, about 4 EJ/year of recycled woody biomass are currently available to meet demand for materials, based on IIASA analysis of 2018 FAO data and GLOBIOM results.

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

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)



[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).

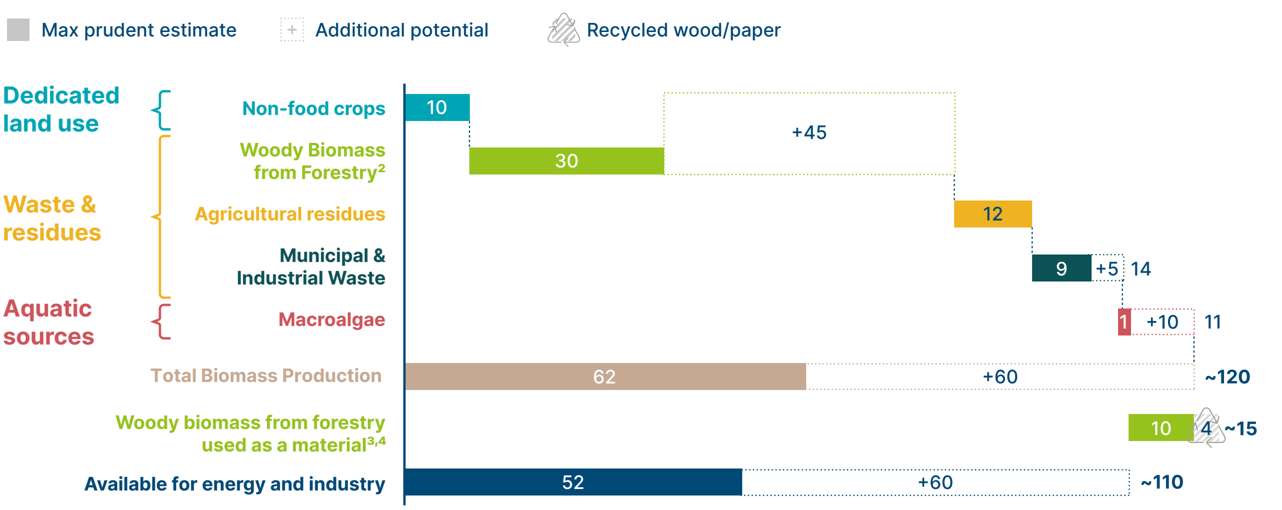
Exhibit 3

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)



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[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 4

Three possible, but highly uncertain, future developments could increase the sustainable supply [Exhibit 4]. Two could be driven by business model and cost developments with**:**

- Improved waste management and collection of organic wastes potentially providing an additional c.5 EJ/year of supply.[12]

- The development and scaling of a seaweed-for-energy industry of much larger scale than current macroalgae production (primarily for other, high value, uses, e.g., food additives). This could allow for a possible additional c.10 EJ/year, though with the caveat that it may always make sense to devote increased macroalgae (and microalgae) production to high value uses such as food and feed supply rather than to energy production.[13] This would deliver the indirect benefit of less pressure on land for food production.

The largest and most uncertain upside relates to the availability of land for dedicated biomass production. At present about 3,300 million hectares (3.3m km^2) of land is devoted to pasture or to cropland, with a significant share of the latter producing feed for livestock [Exhibit 5]. Analysis by the Food and Land Use (FOLU) coalition, suggests that a combination of major changes in diet and/or the development of new cultured and synthetic meat technology, alongside improved agricultural productivity and reduced food waste, could release as much as c.1,310 Mha from food production, of which about c.1,100 Mha might be suitable for either managed forests or energy crop cultivation.[14] While the optimal use of this land – both for biodiversity and climate mitigation purposes – may be to return much of it to permanent forest or other natural ecosystems, devoting 800 Mha or 250 Mha of it to managed forestry or energy crops, respectively, could deliver another c.45 EJ/year of sustainable biomass supply.[15]

Our **'*maximum potential scenario*'** therefore adds c.60 EJ/year of additional supply to the upper end of the c.40-60 EJ/year assumed in the 'prudent scenario'. It is important to note however that even if this additional supply eventually becomes available, it will only do so gradually, with changes in diet and synthetic meat production – levers which make additional land available – in particular likely to take time [Exhibit 6]. Even our maximum potential scenario is significantly less than some other estimates of total sustainable supply,[16] but it is broadly in line with the estimate presented in the International Energy Agency's recent Net-Zero report, though with a different specific mix.[17]

12 ETC Analysis; IEA; World Bank (2018); World Economic Forum – Clean Skies for Tomorrow Analysis (2020); The Pew Charitable Trusts and SYSTEMIQ (2020), *Breaking the Plastics Wave.*

13 Lehahn et al. (2016), *Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability;* Seaweed for Europe (2020), *Hidden champion of the ocean – seaweed as a growth engine for a sustainable European future.*

14 Adapted from IIASA GLOBIOM / Food and Land Use Coalition (2019), *Growing Better: 10 critical transitions to transform food and land use.*

15 Where land is used for managed forestry, approximately 17 EJ/year of the 45 EJ/year represents woody biomass for materials uses (e.g., timber).

16 IEA (2017), *Energy Technology Perspectives* (and sources within).

17 The IEA estimates 102 EJ/year for energy uses, including 40 EJ from dedicated land (closer to our maximum potential estimate from this source, c.55 EJ, than to our prudent estimate, c.5-10 EJ) and 43 EJ from agricultural residues and municipal and industrial wastes (more optimistic than our maximum potential for these combined organic waste sources of c.26 EJ). IEA (2021), *Net-Zero by 2050 - A Roadmap for the Global Energy Sector.*

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

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

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

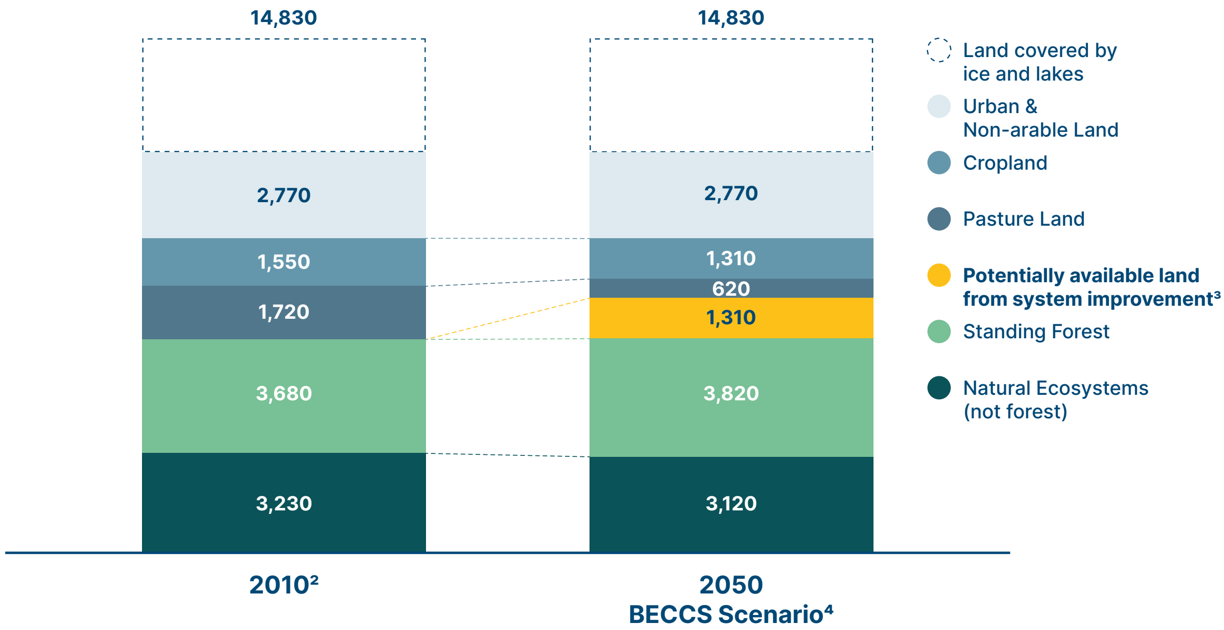


Exhibit 5

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*.

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

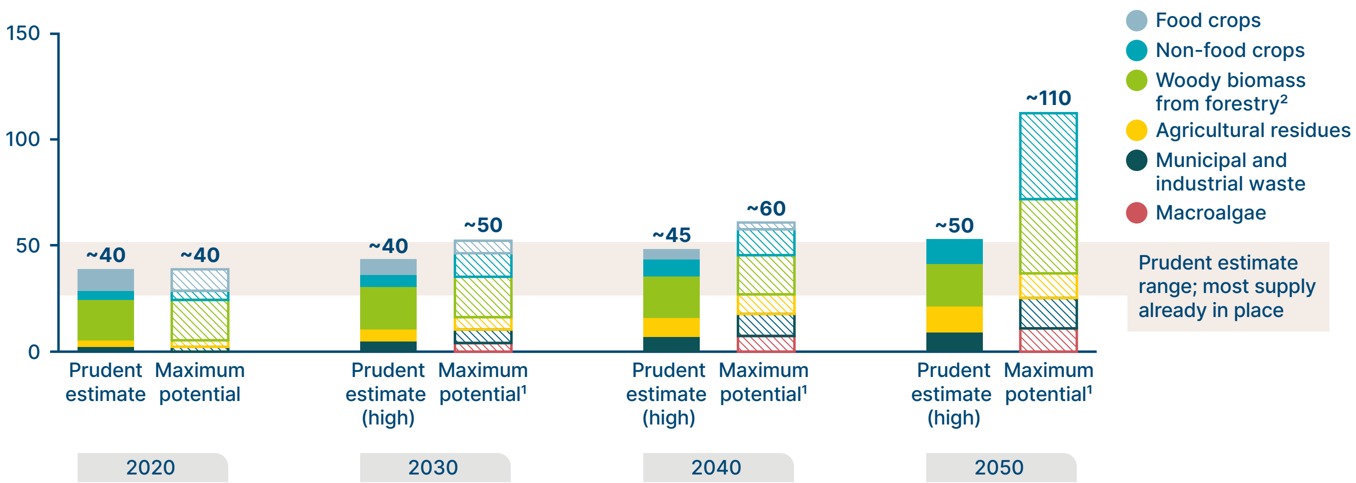


Exhibit 6

[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*.

During the next three decades, given likely rising demands for bioenergy, constrained supply is therefore likely to produce upward pricing pressure, which might support increased sustainable supply (e.g., by making waste and residue collection more economic), but could also create pressures for unsustainable biomass production which must be constrained by tight sustainability standards.

Within the overall global picture, however, it is also important to recognise specific regional conditions, opportunities, and risks. In particular:

- The USA is among the most favourably endowed countries in terms of bioresources relative to population and has prioritised land use for both forestry and bioenergy crop production,[18] implying its optimal decarbonisation pathway may involve a larger proportionate role for bioresources than elsewhere.[19]

- Like the USA, Europe has significant areas of managed forests which make up the bulk of sustainable biomass production in the region.[20] While land constrained, leading waste management practices allow a greater share of organic biomass from waste to be captured than in other areas.

- Many estimates of biomass potential in Asia fail to take sufficient account of sustainability criteria and estimates vary greatly.[21] Asia's large land mass provides significant opportunity for sustainable biomass to be supplied from waste and residues of agricultural production, in particular, if residue extraction limits to protect soil health are respected.

- Equatorial countries are the most favourable locations for rapid biomass growth and could be a source for some sustainable biomass production. However, these are also the locations where there is greatest danger that unsustainable biomass production at the expense of natural ecosystems with high-carbon stocks will have harmful effects on the climate as well as biodiversity.

18 USDA Forest Service, 2016 data; US Energy Information Administration (2021), *Biofuel explained: Ethanol.*
19 Princeton's Net-Zero America Study (2020), *Potential pathways, Infrastructure and impacts.*
20 Material Economics (2021), *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
21 Zhao (2018), *Assessment of potential biomass energy production in China towards 2030 and 2050.*

Priority uses of bioresources by sector

Biomass could in theory meet energy or material demands in almost all sectors of the economy. As a result, potential demands for bioresources hugely exceed sustainable supply. For the purposes of illustration, if one were to assume all of today's sectoral demands for energy or materials were met with bioresources, demand would be around 640 EJ/year versus c.40-60 EJ/year of sustainably-produced supply in our prudent scenario (Exhibit 7). But with required electricity supply likely to grow c.4-5 times by 2050 (as described in the ETC's report on *Making Clean Electrification Possible*) the imbalance will become still more extreme. Even if all sustainable biomass were devoted to electricity production, with none available for other sectors, it could only meet about 5% of future electricity demand. Furthermore, use of biomass for energy, unless accompanied by CCS, creates local air pollution even if such bioresources truly have net-zero emissions over their lifecycle.

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

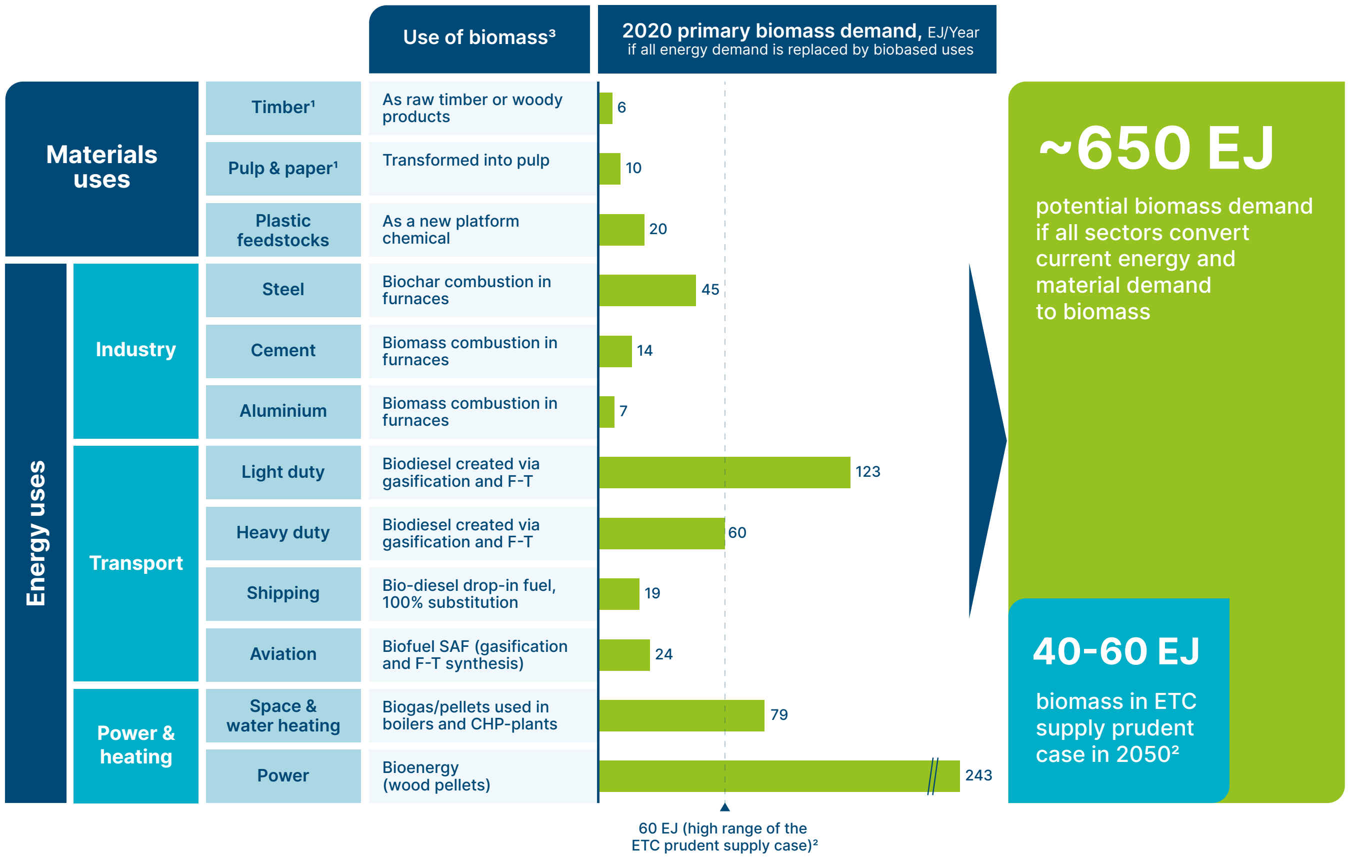


Exhibit 7

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

Strategies for the role of biomass in a mid-century zero-carbon economy must therefore enable optimal allocation of limited sustainable supply to priority uses, and in particular to those where alternative decarbonisation options are either unavailable or likely to be prohibitively expensive in the long-term. Three criteria should drive this optimal allocation:

- **Resource efficiency**, and in particular how much land is needed for bio-based or alternative decarbonisation options. This strongly favours electrification and non-bio-based sources of energy wherever feasible.
- **Future decarbonisation costs**, which, for instance, favour the use of bioresources as a material, while making its use in light duty transport severely uneconomic [Exhibit 8].
- **Technical readiness**, which in some cases could favour using biomass as a transitional option, but with the danger that this might slow progress towards full decarbonisation and create future stranded assets.

Applying these criteria and taking a long-term, mid-century view leads us to the following conclusions:

- **The highest priority use of sustainable biomass supply should be where it is used as a material (e.g., timber, pulp and paper, wood products) or feedstock** (e.g., bio-feedstock in the plastics industry), not an energy source, taking advantage of the inherent characteristics of bioresources. Use as materials also lessens local air pollution effects compared to most bioenergy uses.

- **Most current applications of bioenergy – in particular in road transport and bulk power generation – will be uneconomic** versus renewable electricity or hydrogen.

- **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, use of biomass in these sectors should still be tightly limited** and initially higher-cost electricity-based options should be favoured in order to keep total demand within sustainable supply constraints and accelerate cost reduction of the electricity-based options. In the long term, biomass use in these sectors will tend to be limited to specific niches where the bio route is highly advantaged, or locations where bioresources are locally abundant.

- **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.

- **Aviation is one sector where biofuels should play a major transitional role** and may be a significant technology even in the long term, since the alternative option (power-to-liquid or 'synthetic' jet fuel) implies higher energy losses than more direct uses of electricity and may not reach cost-competitiveness and scale fast enough to achieve necessary emission reductions.

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?"

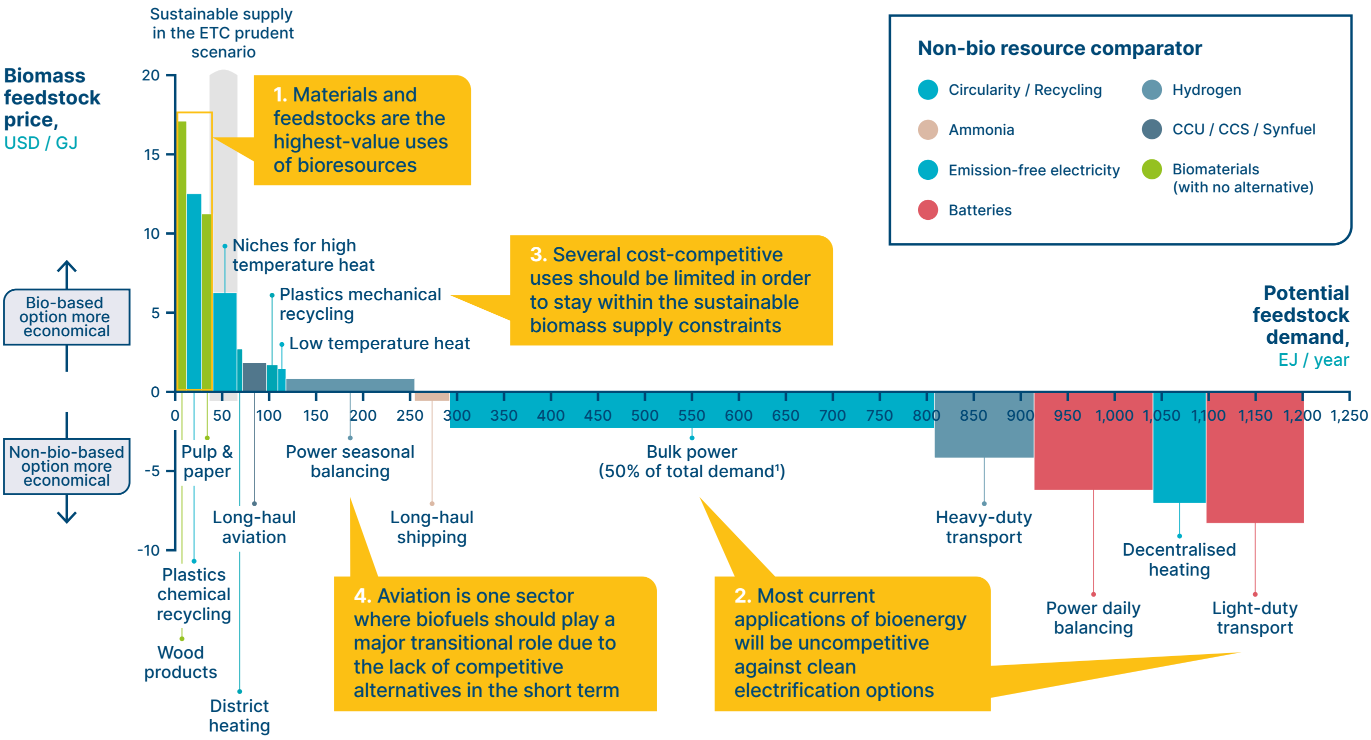


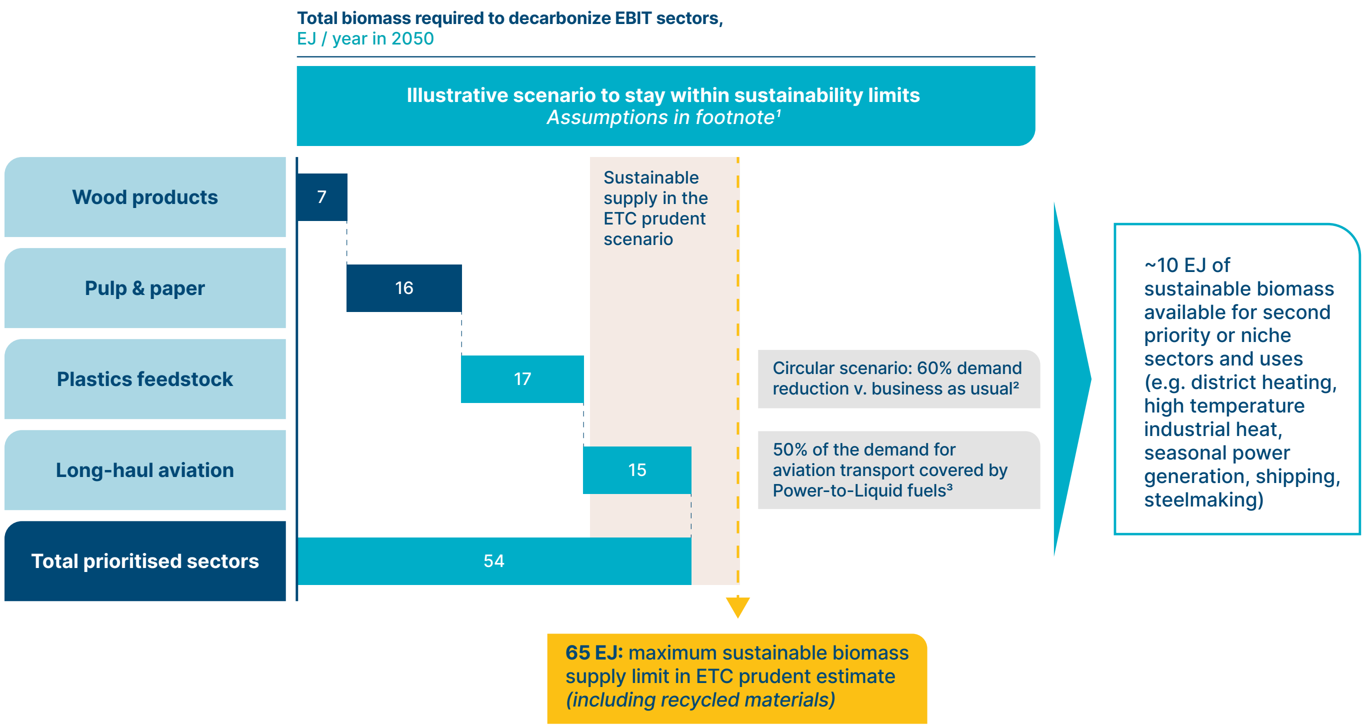
Exhibit 8

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).

These conclusions suggest that the key priority sectors for bioresource use are those where it can be used as a material – in wood products, pulp and paper, as a plastics feedstock, and as aviation biofuel. Even demand for these sectors only, if met entirely from bioresources, would well exceed our 'prudent scenario'. However, demand from these sectors could lie just within the prudent range [Exhibit 9] if bioresource use were combined with other decarbonisation options – in particular recycling of plastics and use of synthetic fuels in aviation alongside biofuels. Thus, a portfolio of decarbonisation solutions is required.

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



[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.

Exhibit 9

Bioenergy as a route to carbon dioxide removal

In addition to being used to meet energy and material requirements, biomass production and use, if combined with carbon capture and storage, could be a means to achieve 'carbon dioxide removals' (CDR, also known as 'negative emissions'). This process is known as either Bioenergy with Carbon Capture and Storage (BECCS) or Biomass Carbon Removal and Storage (BiCRS), with some proponents favouring the latter term since it highlights that carbon removal may be a more important rational and economic driver of the activity than energy production and use.[22] Biomass based 'carbon removal' can also be delivered through storage of carbon above and below ground in natural ecosystems (e.g., re/afforestation or peatland restoration), in projects known collectively as Natural Climate Solutions (NCS).

The key priority to achieve a zero-carbon economy and limit climate change is to reduce gross emissions across all sectors of the economy, and the ETC believes that it is possible to reduce emissions from the Energy, Building, Industry and Transport sectors (EBIT) to around 1-3 Gt CO_2 per annum in 2050 (after the application of CCS to industrial processes but before any role for 'carbon removals').[23] However, as discussed in the recent ETC consultation paper on 'The Role of Carbon Dioxide Removals', the indicative feasible pace of emissions reduction suggests that there is likely a significant 'carbon overshoot gap' compared to the maximum cumulative emissions that would give the world a 50% chance of limiting temperature rise below 1.5°C above preindustrial levels.[24] This gap must be met by carbon removals if we are to limit global warming to safe levels [Exhibit 10]. BECCS/BiCRS is one technology category that could help achieve this, alongside Natural Climate Solutions and Direct air Carbon Capture and Storage (DACCS).

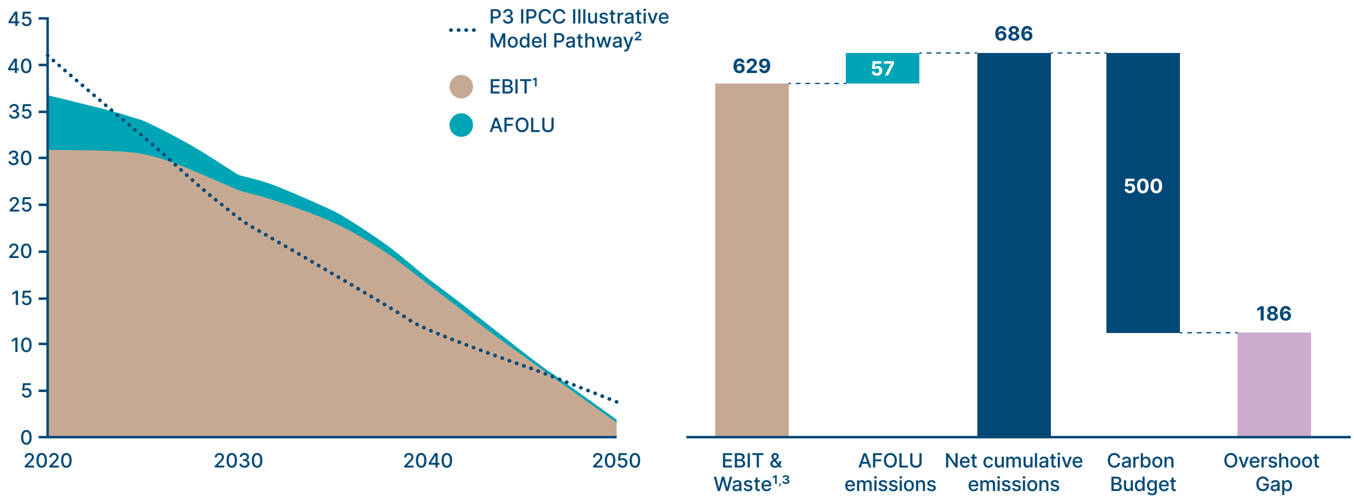
Both BECCS/BiCRS and NCS rely on photosynthesis to fix atmospheric CO_2 into biomass. However, while BECCS/BiCRS relies on technology and geological storage to achieve long-lasting sequestration primarily in underground storage,

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.*

Exhibit 10

22 Sandalow et al. (2021), *Biomass carbon removal and storage (BiCRS) roadmap.*
23 ETC (2021), *Reaching climate objectives: the role of carbon dioxide removals.*
24 The IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report* estimates that to provide a 50% chance of staying below 1.5°C of warming the carbon budget from 2020 is ~500 $GtCO_2$, adjusted to account for emissions 2018-2020. This would give an ~90% chance of staying below 2°C of warming, estimated by approximating the probability distribution for a carbon budget which would limit warming to below 2ºC using a normal distribution. ETC (2021), *Reaching climate objectives: the role of carbon dioxide removals.*

and often producing energy as a co-product, NCS projects generally store carbon within living natural systems. BECCS/BiCRS offers high confidence both of the amount of carbon captured and the permanence of geological storage. However, today BECCS/BiCRS solutions are more expensive and more difficult to scale than many NCS alternatives.[25] NCS solutions also offer significant ecosystem and biodiversity co-benefits alongside carbon sequestration and storage for climate mitigation – issues which can naturally be tackled together.[26] The relative benefits of carbon removal options are explored in the ETC's ongoing work on carbon dioxide removals.[27]

Carbon dioxide removal technologies will be economically viable if the price paid for carbon removals exceeds the cost of carbon capture, transport, and storage, thus generating a 'CCS profit'. If such profit can be earned, the relative cost-competitiveness of different alternative uses of bioresources as materials or for energy will change, with applications where CCS is feasible – such as power generation and some direct heat applications – becoming more attractive [Exhibit 11].

This will increase further the potential imbalance between demand and sustainable supply, and therefore both the price of biomass and the danger of an unsustainable supply response. It may also imply that some uses which would be priorities in the absence of the carbon removal option – in particular aviation biofuels – may be squeezed out over time, increasing the importance of developing other decarbonisation options.

Over time, the growth of the possible (but far from certain) additional supply considered in our maximum potential scenario may somewhat reduce this CDR-related biomass supply and demand imbalance; however, it is highly likely that demands for biomass for all uses will remain significantly greater than sustainable supply.

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?"

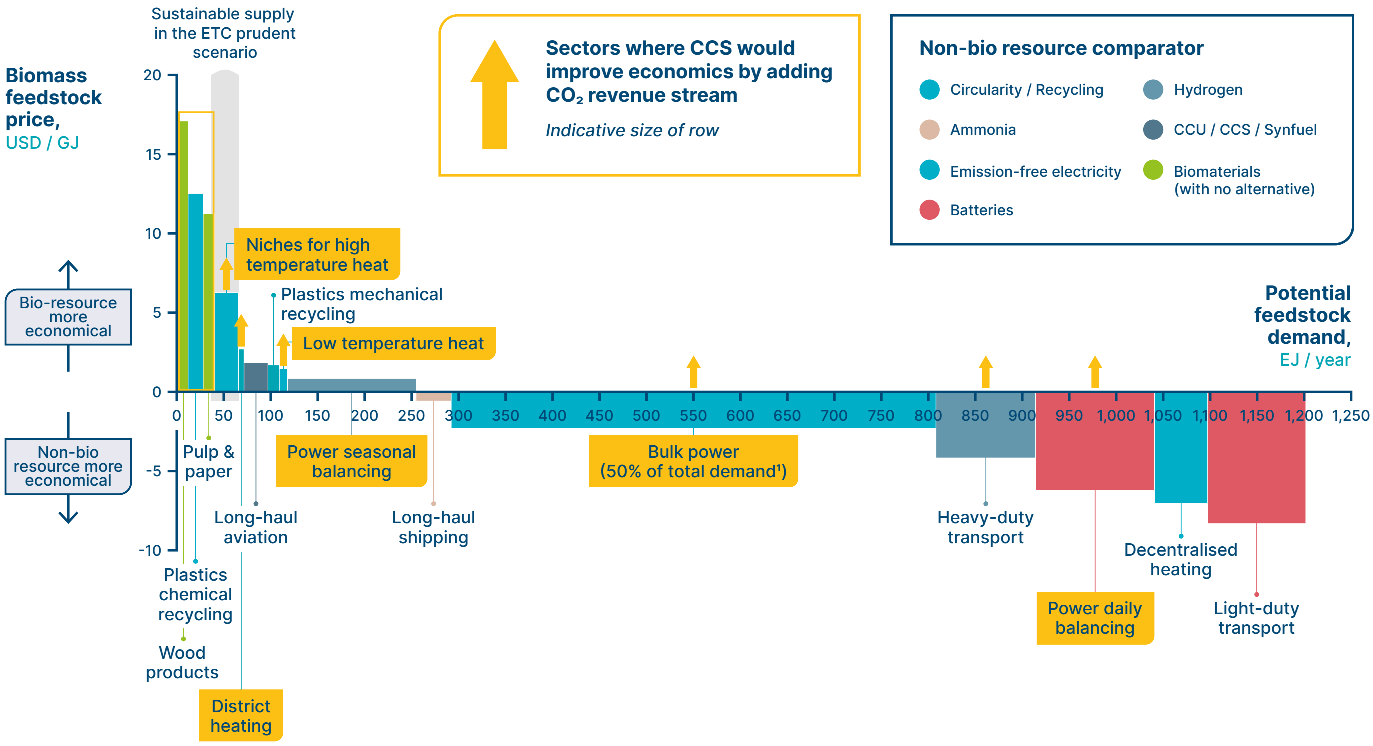


Exhibit 11

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).

25 Fuss et al. (2018), *Negative emissions—Part 2 - Costs, potentials and side effects.*
26 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.*
27 ETC (2021), *Reaching climate objectives: the role of carbon dioxide removals.*

Policies to ensure sustainable supply and highest-value use of bioresources

Even if renewable electricity and hydrogen are developed as rapidly as possible, biomass will play a small but vital role in the future zero-carbon energy and materials system. Total future sustainable supply cannot be precisely estimated and the optimal allocation of constrained supply between alternative uses will vary depending on uncertain future developments. This uncertainty should encourage us to err on the side of caution to avoid any adverse climate and environmental consequences.

To ensure the future scale of bioresource production and its allocation between sectors remains sustainable, the market for bioresources must be shaped by the interaction between tightly defined and enforced sustainability standards, and carbon pricing mechanisms to guide optimal allocation. However, carbon pricing alone cannot produce an optimal solution, and could encourage transitional solutions that further exacerbate stranded assets risks. Policies should therefore reflect reasonable expectations of future technological and cost developments. Concurrently, policy should spur the development of non-bio-based decarbonisation alternatives which may be costlier than biomass today but could become cost-competitive rapidly. Policy action must also discourage the use of bioenergy in applications where it is likely to be uneconomic in the long-term to avoid path dependence.[28]

Strategies to ensure an appropriate role for bioresources therefore need to entail:

Defining and enforcing clear sustainability standards for biomass supply. Action here should combine:

- Defining clear sustainability standards for biomass supply. 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 A].
- Immediate bans on any conversion of preserved natural ecosystems (e.g., tropical forests) or high carbon-storing soils (e.g., peatlands) to commercial biomass exploitation, together with transparency tools to monitor for land use change, illegal logging, and biodiversity loss and to accelerate and enforce the adoption of 'deforestation-free' supply chain commitments.
- Developing tools and mechanisms to enforce standards more effectively, including: mechanisms 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; improved data analysis and monitoring to inform land use policies and monitor impacts on biodiversity; and, improved definition and monitoring of the net-carbon content of biofuels.
- Underpinning legal protection and enforcement of carbon-rich ecosystems with policies, investment, and incentives that support alternative livelihoods for indigenous peoples and local communities (e.g., payments for carbon mitigation and ecosystem services).[29]

Supporting the development of additional sustainable biomass supply via:

- Improving waste collection and segregation.
- Encouraging innovations in macroalgae production for energy.
- Encouraging and supporting both diet change and technological developments (e.g., genetic engineering and cultured meats) that could reduce the amount of land needed for food production.

Creating the conditions for optimal use of bioresources via:

- **The use of carbon pricing** to incentivise development of lower-carbon non-bio decarbonisation options and optimal allocation of bioresources, including, in particular, to support an optimal approach to carbon removals.
- **Deliberate policies to discourage suboptimal use of bioresources** (such as in road transport), to encourage priority use (e.g., in plastics feedstocks and aviation), and to develop alternative decarbonisation options (e.g., in shipping, residential heat, and seasonal power balancing).
- **The development of explicit national and local strategies** that take into account the specificities of local land use and sustainable biomass supply, the availability of other decarbonisation options, the role of nature-based carbon removals, BECCS/BiCRS, and materials, as well as other local bio use cases.

28 ETC (2020) *Making Mission Possible.*
29 Food and Land Use Coalition (2021 ***in press***), *Accelerating the 10 Critical Transitions: Positive Tipping Points for Food and Land Use Systems Transformation.*

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 A

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*.

Supporting key technologies to enable sustainable supply and efficient use of bioresources by improving the efficiency of existing land use, increasing and improving waste collection, and targeting funding (including R&D, and pilot funding) towards emerging bioenergy (e.g., algae, biomass gasification) and biomaterial (e.g., bio-based plastics) technologies [Exhibit 12].

Exhibit 12

Support key technologies enabling efficient, sustainable supply and use of bioresources

- Breakthrough R&D
- Incremental R&D
- Commercial scale up
- 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)

Energy Transitions Commission

ENSURING A SUSTAINABLE APPROACH TO BIORESOURCES

Marginal land, freed up crop land

Waste & residues

Aquatic

Sustainable, low lifecycle GHG emissions biomass supply

in balance with

Optimal use of bioresources in a net zero economy

Materials

Bioenergy

Carbon Dioxide removals

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)
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

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
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

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
5. De-risk pilot projects in biogasification for jet fuels and for plastics biofeedstocks

SUPPORT KEY TECHNOLOGIES TO ENABLE EFFICIENT, SUSTAINABLE SUPPLY & USE OF BIORESOURCES

SCALE NON-BIO-BASED DECARBONISATION OPTIONS WHICH ARE LESS SUBJECT TO SUPPLY CONSTRAINTS

Clean energy

Clean hydrogen

Fossil fuels + CCS/U

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.

Climate-Smart Forestry: Strategies are aimed at (i) "increasing carbon storage in

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.*

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 forests, wetlands, grasslands, agricultural lands, and oceans".[9] NCS can be coupled

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.*

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

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.

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

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

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Bioresources within a Net-Zero Emissions Economy:

Making a Sustainable Approach Possible

July 2021

Version 1.0

Energy Transitions Commission

Executive Summary