INEVITABLE POLICY RESPONSE

The Inevitable Policy Response Forecast Policy Scenario 2023 (IPR FPS 2023)

Bioenergy

September 2023

IPR was commissioned by the PRI[1] and is supported by world class research partners and leading philanthropies, financial institutions, & NGOs

Commissioned by PRI

In 2018, the Inevitable Policy Response was commissioned by PRI to advance the finance industry's knowledge of climate transition risk & support investor efforts to incorporate climate risk & opportunities in portfolio assessment

A Climate Research Consortium

This report was produced by Energy Transition Advisers and Theia Finance Labs[2] with support and analysis from Vivid Economics

NGO partners include Carbon Tracker, Climate Bonds & Planet Tracker

Strategic Partners

In 2021, leading financial institutions joined the IPR as Strategic Partners to provide more in-depth industry input, and to further strengthen its relevance to the financial industry

Core philanthropic support

The IPR is funded in part by the Gordon and Betty Moore Foundation through The Finance Hub, which was created to advance sustainable finance, and the ClimateWorks Foundation striving to innovate and accelerate climate solutions at scale

1. Principles for Responsible Investment
2. The conclusions of the report are solely those of Energy Transition Advisers and Theia Finance Labs

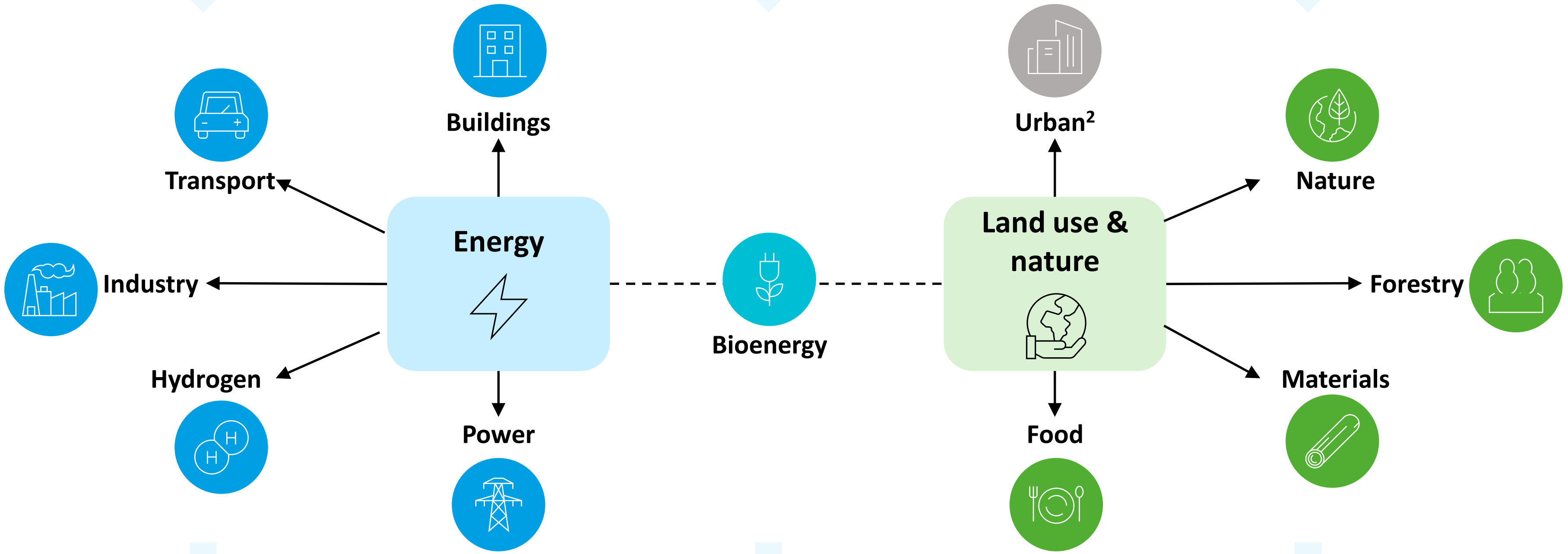
IPR offers a range of applications to help financial institutions navigate the climate transition

Policy forecast

IPR produces **>300 high-conviction policy forecasts** covering 21 countries and 10 policy areas across energy and land use

Policy forecasts feed into a fully **integrated climate and nature scenario model** that elicits the impact of the forecasted policies on the energy, land use, and nature systems up to 2050, tracing detailed effects on all emitting sectors[1]

Modeling



Value drivers

IPR's integrated scenario model outputs detail value drivers across energy and land use. See Value Driver Visualizer

Applications

Fitch Ratings, Morning Star, Paris Agreement Capital Transition Assessment (PACTA), Planetrics, *tilt* (Climate data for SMEs)

1. IPR also develops a '1.5°C Required Policy Scenario'(1.5°C RPS) building on the IEA NZE by deepening analysis on policy, land use, emerging economies, NETs and value drivers. The RPS scenario is also run through the model and can be used by those looking to align to 1.5°C. 2. Urban areas are not modelled in detail in IPR

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IPR has developed global, policy-based forecasts of forceful policy responses to climate change and implications for energy, agriculture and land use

Please see the IPR Home Page for further details

Scenario	Policy Forecast Details	Open Access Database
IPR 2023 Forecast Policy Scenario (FPS) • Models impact of forecasted policies on the real economy	IPR FPS 2023 Summary Report IPR 2023 Policy Forecast IPR FPS 2023 Detailed Energy Results IPR FPS 2023 Detailed Land Use and Nature Results IPR 2023 Bioenergy Report	IPR FPS 2023 Value Drivers IPR Scenario Explorer
IPR 1.5°C Required Policy Scenario (RPS) • Required policies to align to a **1.5°C objective** building on the IEA's Net Zero scenario and deepening analysis on policy, land use, emerging economies and value drivers	IPR 1.5°C RPS Energy and Land Use System Results including Policy Details	IPR RPS 2021 Value Drivers
IPR Forecast Policy Scenario + Nature (FPS + Nature) • First integrated climate and nature scenario for use by investors	IPR 2022 FPS + Nature detailed results	IPR FPS + Nature Value Drivers

IPR has published a set of publicly available outputs from the FPS and 1.5°C RPS that offer significant granularity at the sector/country level, allowing investors to assess their own climate risk across 4,000+ variables

Disclaimer: This is not intended to constitute policy advice, financial advice or any specific advice.

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IPR 2023 forecasts higher climate policy ambition across 10 policy levers covering energy, land use, and nature

Net zero

- Interim emissions target
- Net zero CO2 long-term target

Carbon pricing

- Carbon taxes
- Emission trading systems
- Carbon border adjustment mechanisms (CBAMs)

Clean power

- Targets for a fully decarbonised electricity system
- Renewable capacity auctions
- Renewable subsidies
- Nuclear power targets and and strategies

Low-carbon buildings

- Prohibiting regulations for fossil heating systems
- Purchase subsidies for low-carbon heating systems
- Thermal efficiency regulations for buildings
- Minimum energy performance standards for new appliances

Low-carbon agriculture

- Subsidies for low-emissions practices and technologies
- Emissions regulation including via tax or cap-and-trade systems
- Farmer education and technical assistance programs

Coal phase-out

- Regulations prohibiting coal build
- Emissions performance standards
- Electricity market reforms

Zero emissions vehicles

- ZEV consumer subsidies Targets to fully decarbonise the new sales of road vehicles
- Manufacturer ZEV obligations

Clean industry

- Emissions performance standards for industrial plants
- Subsidies for new or retrofit clean industrial processes

Forestry

- Incentives for reforestation and afforestation
- Penalties for deforestation, supported by consumer pressure
- Mandates to ensure deforestation free supply chains

Nature-based solutions

- Land protection and restoration policy
- Nature incentives for landowners to protect biodiversity hotspots and habitats
- Voluntary biodiversity credit markets

Ratchet pressures increase the likelihood that governments strengthen policy by 2025, and again to 2030 and beyond

Paris Ratchet process triggers a cumulating policy response into 2025, 2030, and beyond

2021	2023	2025	2028	2030
Countries communicate their updated or 2nd round of climate pledges	Global Stocktake (GST) on climate, mitigation, and finance	**2025 Ratchet** Countries submit their 3rd round of climate pledges (NDCs)	Second Global Stocktake (GST) on climate, mitigation, and finance	**2030 Rachet** Countries submit their 4th round of climate pledges (NDCs)

Policy announcements are expected to continue in 2023 -2025, with continued acceleration in 2028-2030. Recognition of Overshoot grows from 2025

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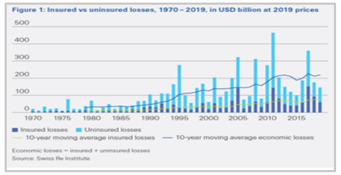
THE DRIVERS OF POLICY MOMENTUM MAKE AN INEVITABLE AND FORCEFUL POLICY RESPONSE MORE LIKELY…SOCIAL TIPPING POINTS ARE KEY

Changes in physical & monetary costs

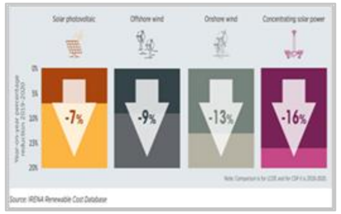
Extreme weather events

Increase in wet-bulb globe temperature

Uninsurable world



Cheaper renewable energy



Increased pressure from society, markets & regulators

Financial markets pressure for net zero

Civil society advocating for 1.5C

Financial regulator interventions

Pressure for global institutions to support EDMEs transition

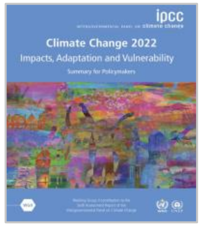
Changes in geopolitics, energy security and research

US IRA impact on industrial policy

Impacts on security

Improved climate collaboration

New climate research



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GLOSSARY

Bioenergy: Energy produced from biological matter, such as vegetation biomass.

Feedstocks: The biological materials used as input for the production of bioenergy. This analysis applies the following taxonomy:

- Wastes and residues that do not require additional land: Crop residues, wood residues, livestock residues (manure), food waste, and waste oils and fats, including tall oil, palm oil mill effluent (POME), used cooking oil (UCO), and animal fats/tallow.
- Feedstocks integrated into existing agricultural lands through cover cropping and agroforestry. Includes both grassy and woody energy crops.
- Feedstocks that require dedicated land for cultivation of energy crops, which can include both 1G and 2G energy crops of grassy and woody types.

First generation (1G) biofuel: Biofuel produced from edible (food) crops. For example, ethanol produced from corn or sugarcane or biodiesel produced from soybean oil.

Second generation (2G) biofuel: Biofuel produced from inedible crops, wastes, and residues. Includes both oily crops such as camelina and pongamia and cellulosic crops such as miscanthus and switchgrass. 2G energy crops typically have higher yields (tons dry matter produced per hectare) than 1G crops, but 2G crops are currently grown almost exclusively in pilot programs and the assumed higher yields have largely not yet been proven at scale.

Carbon capture and storage (CCS): Capture of CO_2 emissions from an industrial process followed by long-term storage of the CO_2 in geological formations. When the feedstock is biomass, this process is known as bioenergy carbon capture and storage (BECCS).

Carbon payback period (CPP): The number of years that a bioenergy crop needs to be grown before it absorbs more carbon from the atmosphere than would be absorbed if that area was re/afforested instead.

Million hectares (Mha): Common unit for land area. 1 Mha (10,000 square kilometers) is roughly the area of Lebanon. 500 Mha (5 million square kilometers) is roughly half the area of Canada.

Exajoule (EJ): Common unit for energy. Global energy supply in 2021 – from all fossil and renewable sources – was around 624 EJ.

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LAND SCARCITY AND ENERGY ALTERNATIVES REQUIRE CLOSELY EXAMINING THE BIOENERGY OUTLOOK

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- **Bioenergy plays a pivotal role** in any climate scenario:
  - It sits **between energy and land systems** and **influences nearly every outcome**, from forest land restoration to decarbonization pathways in hard-to-abate sectors like aviation and cement
  - Modern biomass use is recent and only occupies 83 Mha (~5% of global cropland), but climate scenarios universally project **significant future growth**. Median IPCC 2°C scenarios call for as much as 380-700 Mha (~25-50% of current global cropland) by 2100
- Because modern biomass use for energy is still new, it **remains poorly understood** and therefore **highly uncertain:**
  - Most recent scenarios account for the **economic and direct carbon costs of biomass**, but typically assume the land system supplies whatever biomass the energy system demands
  - In order to account for indirect impacts such as the **land opportunity costs** of growing biomass, more fully integrated approach is required

Source:: Harper, A.B., et al. 2018; Field and Mach 2017

This special report is part of the 2023 update to the IPR Forecast Policy Scenario.

It uses new modelling to examine the tradeoffs associated with biomass to more clearly define its role in the net-zero, nature-positive transition. It consists of five main sections:

Introduction – understanding the current bioenergy landscape and how to measure its tradeoffs (Section 1)

Sustainable feedstock supply – estimating the potential sources of sustainable biomass (Section 2)

Biomass as a source of low-carbon energy – exploring bioenergy in transport and other end uses unlikely to utilize CCS (Section 3)

Biomass as a source of negative emissions – exploring bioenergy paired with CCS in power and industry end uses (Section 4)

Bioenergy forecast and implications – accounting for the policy dynamics of existing bioenergy (Section 5)

Other results, including the land and energy results that form the rest of the scenario forecast, can be found here.

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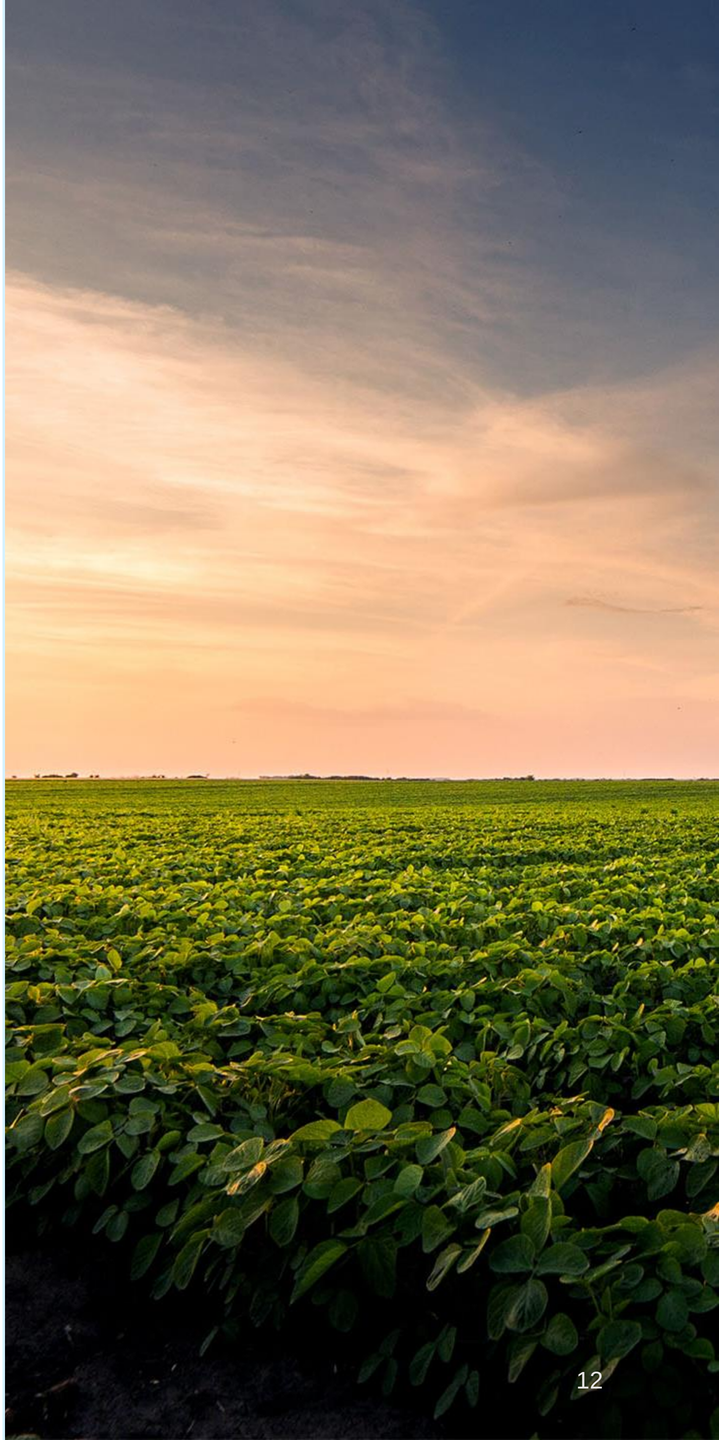
KEY FINDINGS

1. Bioenergy competes for scarce land in a system increasingly asked to provide more food, materials, urban space, and natural ecosystems
   - Bioenergy is costly for the land system to produce, but can facilitate decarbonization by delivering both low carbon energy and negative emissions when used with carbon capture and storage (CCS)
   - There are many competing demands for a fixed amount of land, and bioenergy might displace other uses that currently store carbon. This opportunity cost can be represented as the time required for bioenergy to capture and store the carbon it displaces (the "carbon payback period")
   - To be useful in the energy system, biomass must be either lower cost or more sustainable than other decarbonization technologies
2. Sustainable sourcing policy makes feedstock a critical determinant of bioenergy’s competitiveness
3. Policymakers are expected to increasingly introduce sustainability guardrails for sourcing biomass, including avoiding nature displacement, deforestation, food competition, and irrigation
   - There are ~30 EJ of potential supply of waste and residue feedstocks that minimally compete for land and are currently underutilized. Bioenergy demand beyond that must be met with land dedicated to growing biomass
   - By 2050, IPR FPS uses 91Mha of land with a low carbon payback period, most of which is in arid or cold biomes, and none is in tropical biomes where re/afforestation could be a more efficient store of carbon
   - Current bioenergy capital stock does not match locations of sustainable dedicated supply, implying the industry needs to transition away from 1G crops toward waste and residues and build out new infrastructure
4. Bioenergy without CCS is likely to be outcompeted by lower carbon alternatives in most energy system applications
   - Aviation, shipping and the pulp & paper industry are exceptions - a lack of cleaner alternatives and very inexpensive self-supply of waste and residues make unabated bioenergy cost competitive through 2050
5. Bioenergy with carbon capture and storage (BECCS) in industry and power is costly but offers negative emissions. Significant scale up is possible to ~1 $GtCO_2e$ of BECCS removals, but will then be outcompeted by DACCS
   - Power and cement applications together represent ~13 EJ of BECCs by 2050. This contrasts with other prominent transition outlooks, many of which expect a larger role for bioenergy
   - As with bioenergy in transport, BECCs applications are also expected to transition away from the unsustainable 1G crops currently used, toward agricultural residues and some dedicated 2G lignocellulosic biomass

BIOENERGY: IMPLICATIONS FOR INVESTORS

Takeaways from IPR FPS 2023

1. Land scarcity implies sustainable sourcing policy is expected to constrain bioenergy
2. Unabated biomass plays a long-term role in the aviation, shipping and pulp & paper sectors, but is otherwise outcompeted by cleaner, cheaper alternatives
3. Waste and residues are expected to make up a growing share of feedstock as a more sustainable alternative to the 1G crops currently common. Some 2G dedicated biomass crops will likely be required to meet demand, but is limited to ~91Mha
4. BECCS scales up significantly to ~1GT of removals in power and cement industries, but further growth is constrained by high land opportunity costs combined with increased competition from DACCS
5. There is a mismatch between current bioenergy infrastructure and what is needed in the long term. Location and feedstock mismatches create both investment opportunities and stranding risks.



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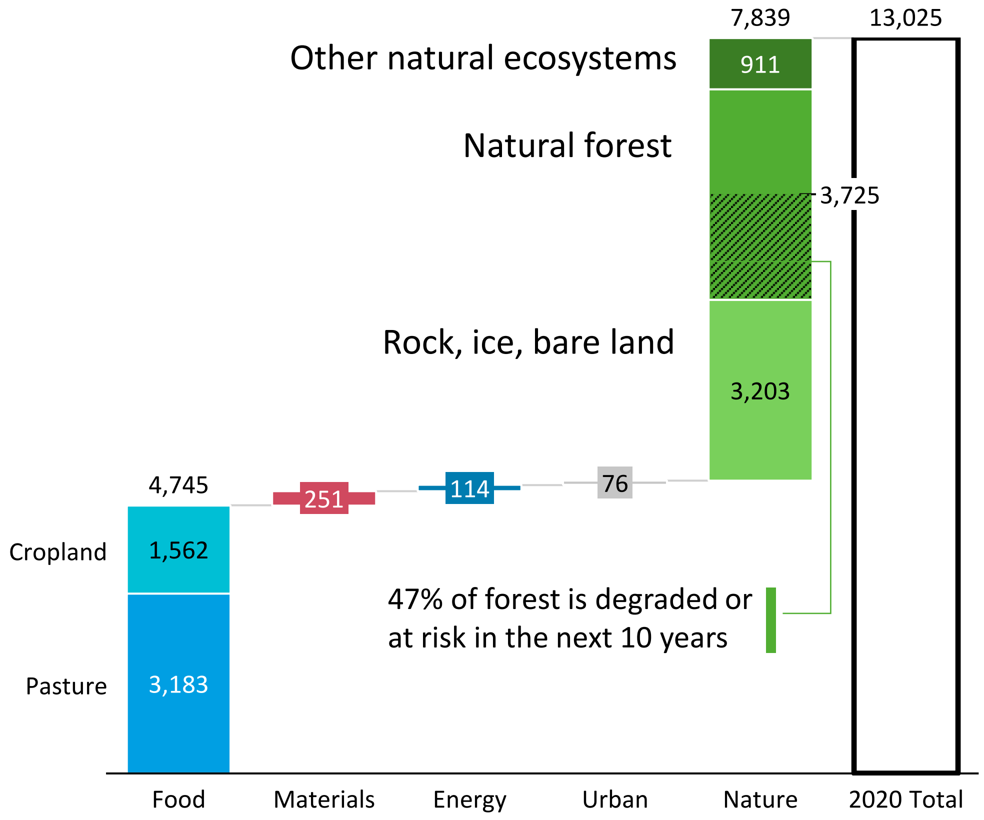
THE WORLD ECONOMY INCREASINGLY DEMANDS OUTPUTS FROM THE LAND SYSTEM: FOOD, MATERIALS, ENERGY, AND SPACE FOR BUILT INFRASTRUCTURE

2020 Global land use[1], Mha



The land system has produced more in the last 30 years. Economic growth is predicated on that continuing for at least the next 30

3.4 x 10^{15} more cal/yr produced compared to 1990

Feeding a population expected to approach **10B by 2050** requires more calories. **Greater wealth** has historically meant more animal protein, which is disproportionately land intensive

370 more Mm³/yr roundwood extracted compared to 1990

Timber and natural fibres represent renewable alternatives to emissions intensive materials like steel, cement, and synthetic fibres. Rising **population, incomes,** and **substitution away from non-renewable sources** all may increase demand

3.5 more EJ/yr generated from modern biofuels compared to 1990

Though use of traditional biomass has slowly declined, it has more than been offset by **accelerating increases** in consumption of **modern biomass**, currently primarily for liquid transport fuels, but increasingly also as a feedstock to help other energy sectors decarbonize

34.6 more Mha of built-up area compared to 1990

Expansion of built-up areas has slowed in developed regions, but **urbanization is accelerating** in much of the developing world

1. Land uses include: food - area used to raise livestock or grow crops to feed both animals and people; materials - area used to produce timber, excluding wood used for bioenergy; energy - area used to produce traditional biomass (e.g., wood fuel), modern biofuels (e.g., 1G starch and sugar crops), or wood pellets; urban - area associated with human-made built structures such as roads, buildings, and other artificial structures; and nature - area associated with natural ecosystems such as forests and grasslands, along with abiotic ecosystems such as permanent snow and ice and bare land (e.g., deserts and rocky areas). Global land cover (13,025 Mha) excludes area associated with inland water bodies (rivers and lakes).

Source: WRI, FAO Forestry, FAO Land Use, FAO Land Cover, IEA; FAO Food Balances; ESA CCI; Our World in Data; Smil 2017; BP's Statistical Review of World Energy 2022

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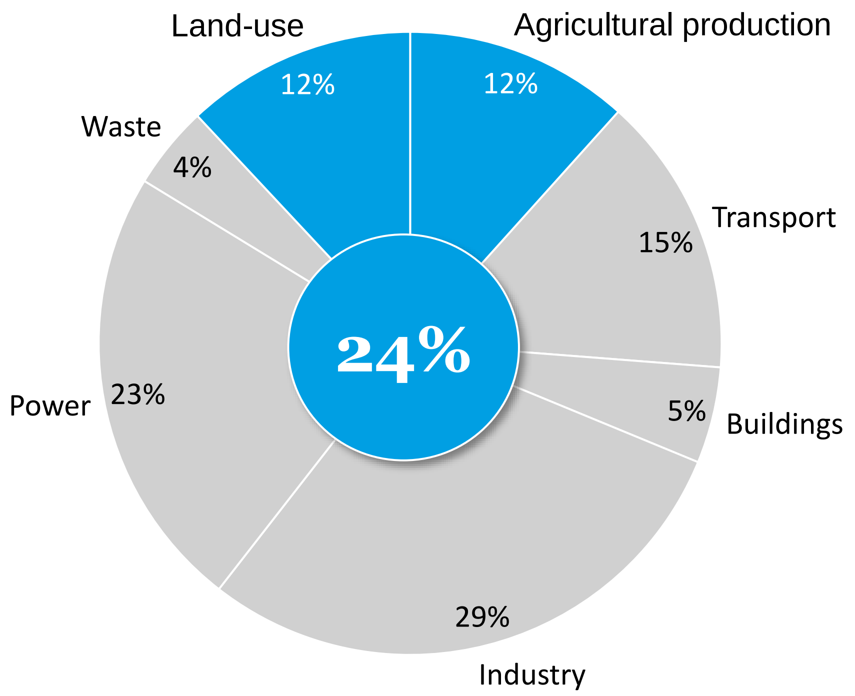
EXPECTATIONS ARE INCREASING FOR LAND TO CONTRIBUTE TO CLIMATE REGULATION AND NATURE RESTORATION WHILE MAINTAINING AFFORDABILITY

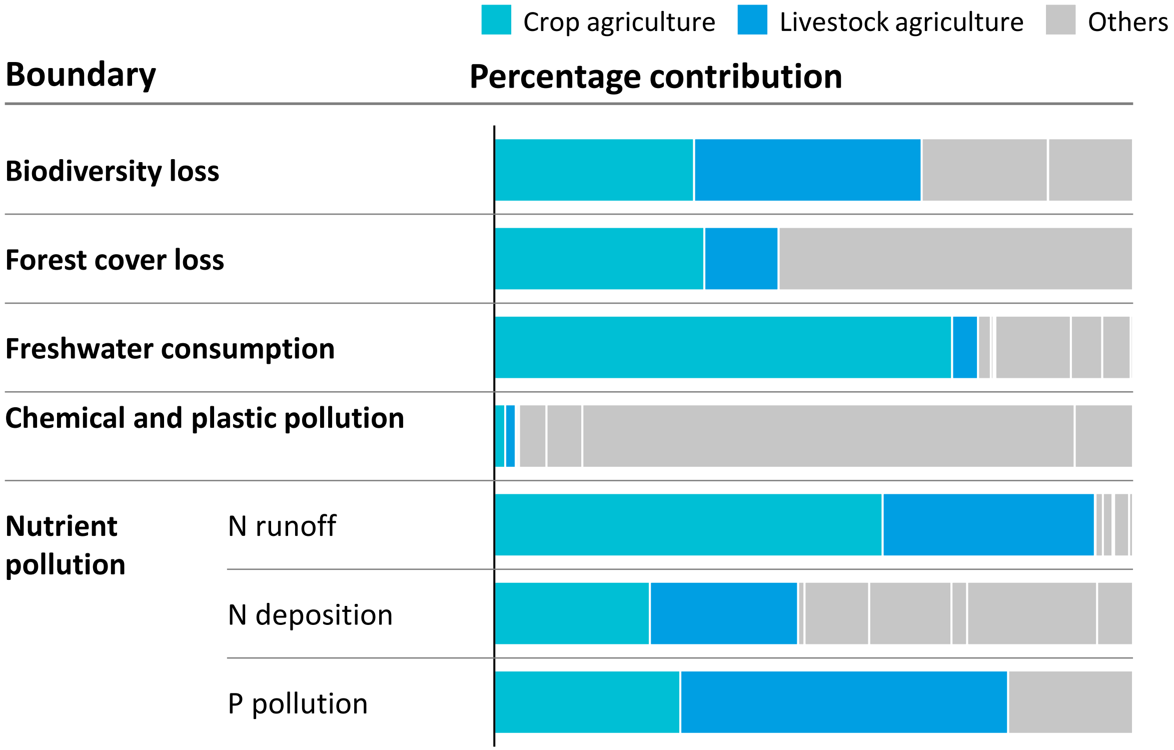
Agriculture influences 24% of global GHG emissions… **…is the largest contributor to exceeding planetary boundaries…**

2019 GHG emissions by sector, $GtCO_2e$, 100-yr GWP[1] (%). Total = 56 $GtCO_2e$



Sectoral contributions[1] toward each planetary boundary

Percent on relative scale



…and is expected to promote the widespread availability and affordability of nutritious food

Source: British Geological Survey; Carbon Dioxide Information Analysis Center; ESA Climate Change Initiative - Land Cover led by UCLouvain (2017); Fei Lun et al. (2018); FAO; de Vries et al. (2013); Global Runoff Data Centre; Gütschow et al. (2016); PREDICTS (Hudson et al. (2016)); Schulte-Uebbing et al. (2022); Zomer et al. (2022); Crippa et al. (2019); Natural History Museum London; NOAA; Defourny et al (2017); Hogeboom et al (2018); Geyer et al. (2017); Borrelle et al. (2020); Stockholm Resilience Center; Newbold et al. (2016); Gasser et al. (2020); Water Footprint Network; Steffen et al. (2015); Lau et al. (2020); World Bank

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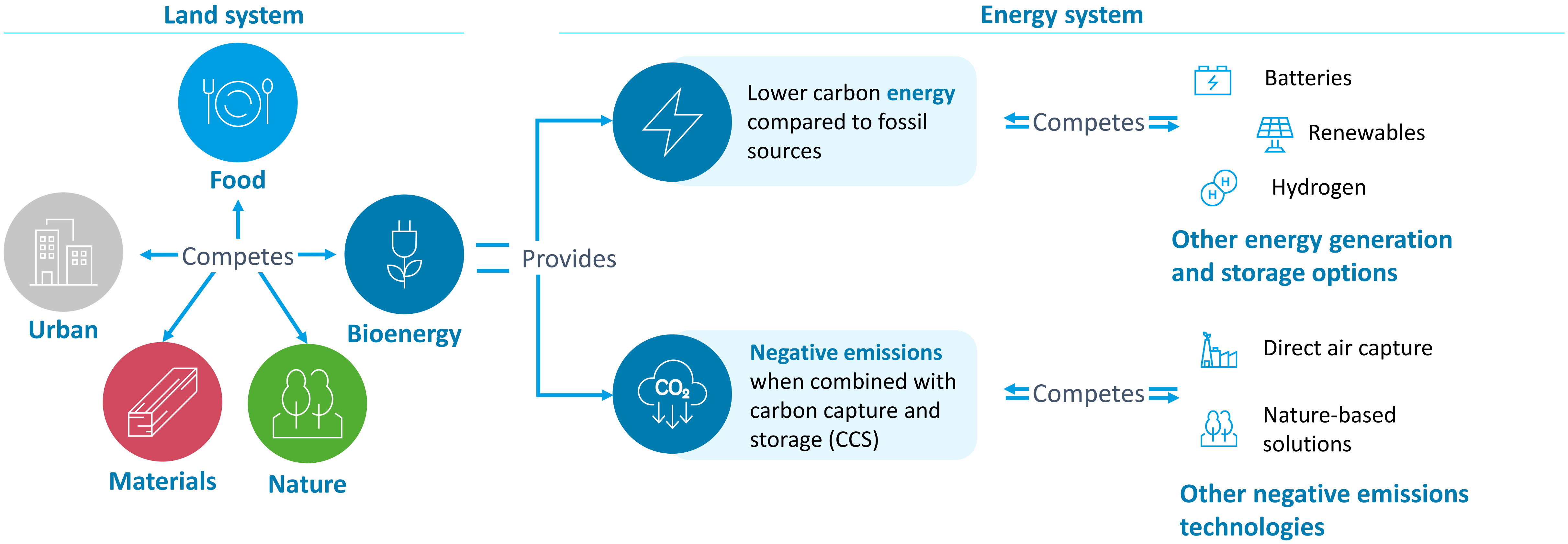
BIOENERGY BRIDGES LAND AND ENERGY: COMPETITION FORCES DIFFICULT TRADE OFFS BETWEEN COMPETING USES

Climate, nature, and **affordability** outcomes represent **constraints on the outputs** we consume from the land system. Maintaining and restoring forested area, for example, is necessary for emissions and biodiversity targets to be realized



Improving yields, changing consumption habits, and **reducing waste** can all **ease competition** and improve tradeoffs

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BIOENERGY INCURS COSTS IN LAND TO FACILITATE DECARBONIZATION

Growing biomass incurs two types of costs in land…

Carbon

Growing biomass creates emissions in the land system:

- **Directly** if the land used had an existing carbon stock, through any fertilizers or machinery used in production, and in any transport or processing required to prepare the fuel for use
- **Indirectly** to the extent that the land could have otherwise been used for food, materials, or urban space, that displacement **induces carbon loss elsewhere**

Land

Land dedicated to biomass displaces other uses, creating a variety of non-carbon costs, including:

- Loss of biodiversity
- Increased pressure on food prices
- Increased water consumption
- Increased water pollution from agricultural runoff

Both carbon and land costs vary substantially by the type of bioenergy feedstock used

… to provide two types of benefit

Lower carbon energy

Carbon intensity (CI) is the common metric that defines the emissions impact of fuels. The CI score gives the total quantity of **emissions from growing, manufacturing, transporting, and using** biomass

Biomass sources generally have lower CI than fossil alternatives, but the size of the emissions saving benefit **varies widely by feedstock and growing method**

Biomass sources are often not the lowest CI option – they increasingly compete with other energy sources such as renewables paired with batteries or hydrogen

Negative emissions

When paired with carbon capture and storage (CCS), using bioenergy can create negative emissions by sequestering a part of the feedstock's carbon content.

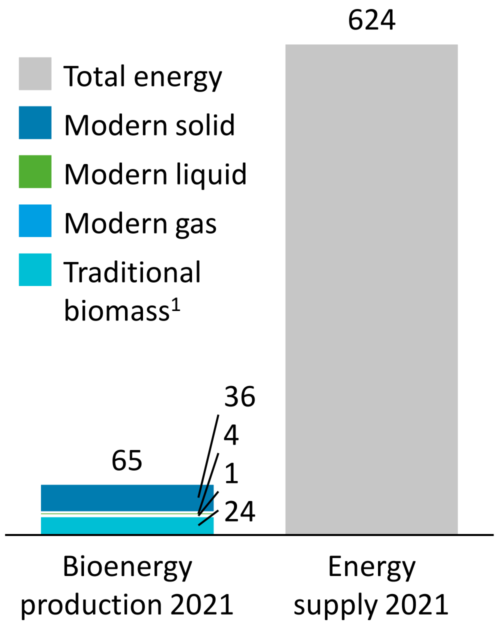
CCS is expected to be practical for **stationary, concentrated point-source emissions** – making it a potential option in **power or industry** but not in distributed or mobile applications like transport or buildings.

BECCS is **one of only a few potential negative emissions technologies** but is not currently deployed at scale. Other technologies that could provide negative emissions include nature-based solutions and direct air capture

Source: US EPA, US Department of Energy, ICCT, CARB GREET 4.0

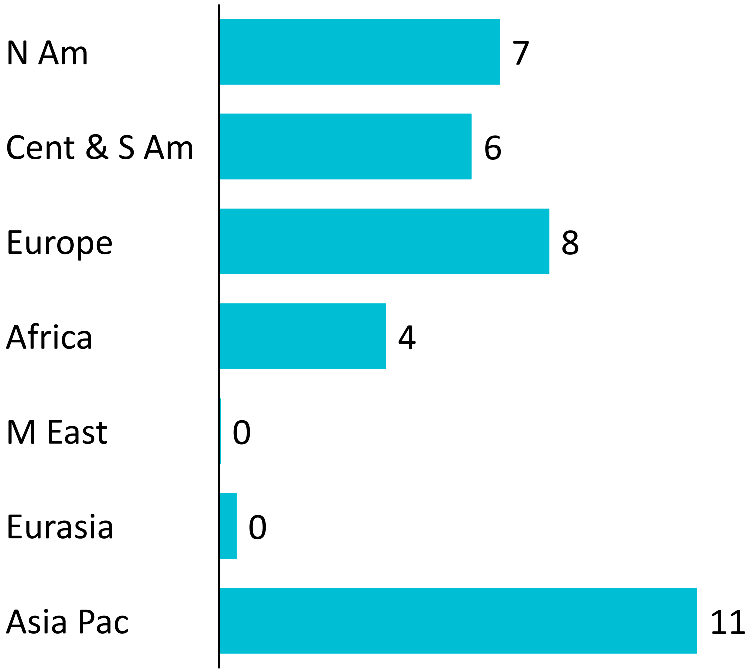
BIOENERGY TODAY USES 83 MHA OF LAND TO PRODUCE MODERN LIQUID (33 MHA) AND SOLID (~50 MHA) BIOFUELS

Bioenergy production today plays a small part in the energy system, EJ



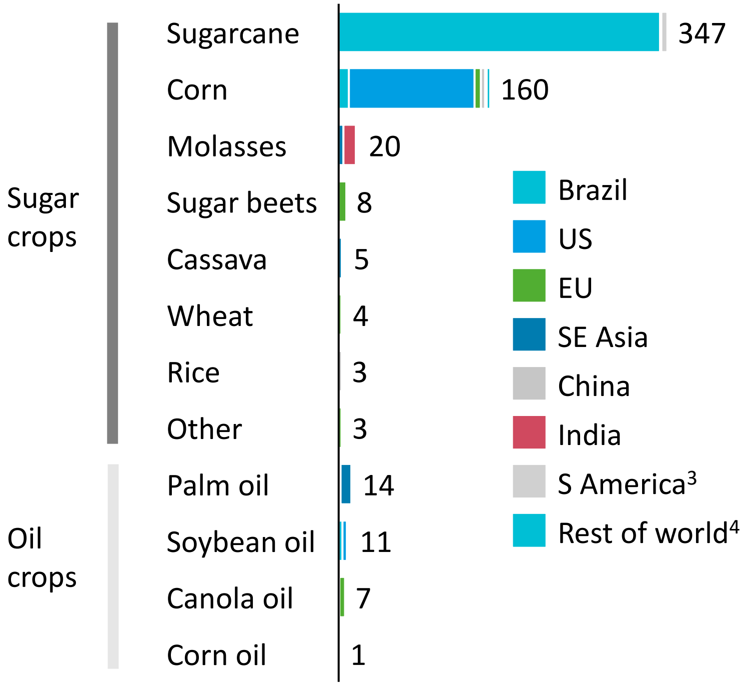
- Current production of modern liquid biofuels is almost exclusively first-generation bioenergy
- Biofuels represented about 4% of transport fuel demand in 2021

Use of modern solid biomass[2] is geographically dispersed today, EJ



Current production of modern liquid biomass is concentrated in the US and Brazil

1st generation feedstock consumption for biofuels, 2022 (million tons)



1. Includes wood fuel and animal manure.
2. Around 16 EJ is estimated to be sourced from tree plantations and short-rotation crops, which require dedicated land.
3. Excluding Brazil.
4. Mainly Canada and Australia.

Source: IEA, FAO, Bishop et al. (2022), Columbia Climate School, US Energy Information Administration, USDA Foreign Agricultural Service reports, IEA Bioenergy

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THE CARBON AND LAND COSTS OF BIOMASS VARY SUBSTANTIALLY ACROSS THE THREE CATEGORIES OF POTENTIAL BIOENERGY FEEDSTOCKS

Low cost | High cost

	Feedstock category	Example feedstock	Example fuel	Example energy system end use	Carbon cost	Land cost
Residues & wastes	Crop residues	Wheat straw	Ethanol	Passenger cars	Low carbon emissions (low cost)	No change in land cover (low cost)
	Livestock residues	Cow manure	Biogas, RNG	Vehicles, on-site power generation	Carbon negative (low cost)	No change in land cover (low cost)
	Food and industry waste[1]	Food waste, used cooking oils	Biogas, SAF	Vehicles, on-site power generation	Low carbon emissions (low cost)	No change in land cover (low cost)
Non-edible crops and trees[2]	2G woody crops	Poplar	SAF, biomass	Aviation, power	Can be carbon negative with CCS (low cost); Higher carbon intensity (high cost)	Improves yields (low cost); Increased land cover (high cost)
	2G grassy crops	Miscanthus, pennycress	SAF, biomass	Aviation, power		
Edible crops	1G sugar crops	Corn, sugarcane	Ethanol	Passenger cars, as blends up to E85	Can be carbon negative with CCS[3] (low cost); Higher carbon intensity (high cost)	Increased land cover (high cost)
	1G oil crops	Soybeans	FAME, HVO, HEFA	Passenger cars, trucks, aviation		

1. Includes food waste, wood residues, and waste oils and fats, such as tall oil, palm oil mill effluent (POME), used cooking oils (UCO), and animal fats/tallow.
2. Includes bioenergy crops that require dedicated land or those integrated into existing agricultural systems, such as through cover cropping or agroforestry.
3. Edible crops are typically only used for transport fuels, so CCS cannot be used at point of consumption, but can be at point of production.

Source: US EPA, US Department of Energy, ICCT, CARB GREET 4.0

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MOST END USES OF BIOMASS SIMPLY PROVIDE ENERGY, BUT ADDING CCS CAN ALSO PROVIDE NEGATIVE EMISSIONS IN POWER AND INDUSTRY

Energy provision

Bioenergy has a similar chemical composition to fossil fuels so releases a similar amount of energy. However, the carbon sequestered by growing biomass means the **lifecycle emissions are lower than fossil fuels**. Because they are similar, bioenergy can often be used with **existing fossil infrastructure.**

End-uses for which biomass can only provide energy include:

- Road transport
- Shipping
- Aviation
- Buildings

These end-uses cannot be used for negative emissions because sources are not sufficiently concentrated for CCS

Carbon removals (Negative emissions)

For end-uses with concentrated sources of CO_2 emissions, **CCS can be added to provide net-negative emissions**. This is bioenergy with carbon capture and storage: BECCS. Because CCS captures most “tail-pipe” emissions, the amount of carbon sequestered by growing biomass is greater than the amount emitted during combustion.

End-uses for which biomass can provide negative emissions in addition to energy include:

- Power
- Industry

These negative emissions applications compete against alternatives such as Direct Air Carbon Capture and Storage (DACCS)

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Sustainable sourcing policy makes feedstock a critical determinant of bioenergy's competitiveness

This section explores sustainable sourcing for bioenergy

Supply	• There are ~30 EJ of waste and residues available by 2050 that compete minimally for land. These sustainable feedstocks are widely distributed and currently underutilized • There are **567 Mha** that meet basic land sustainability guardrails • Between **310 and 396 Mha** of that land has a carbon payback period (CPP) below 15 years, implying bioenergy could be a more efficient store of carbon than re/afforesting that land instead • Most of the low-CPP land is in arid or cold biomes, and **none is in tropical biomes**
Forecast	• Current bioenergy infrastructure is not proximate to the land that passes the sustainability guardrails. That means that the industry needs to secure new sustainable feedstock and build new infrastructure • IPR FPS 2023 uses **~91Mha** of land for dedicated bioenergy crops by 2050

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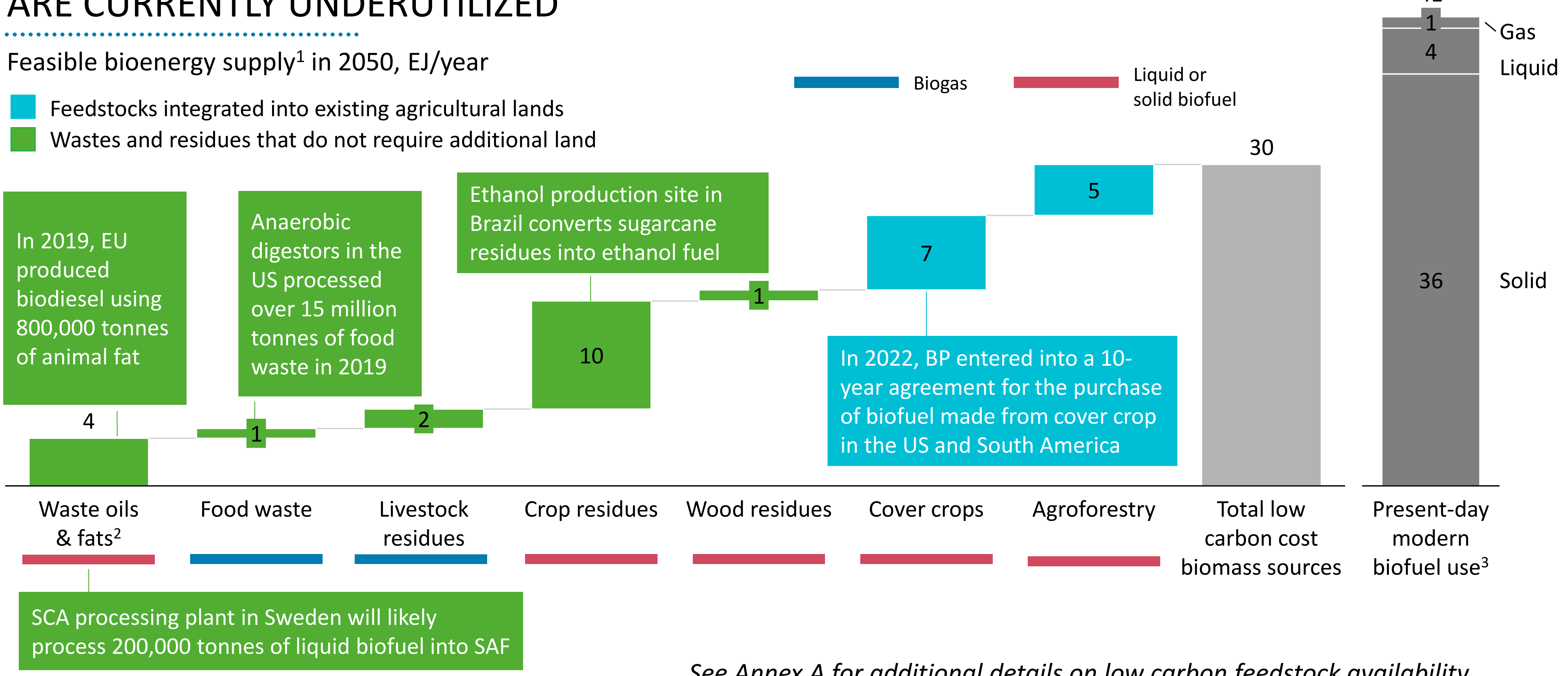
LOW CARBON COST BIOMASS SOURCES BECOME LIMITED IN AVAILABILITY, BUT ARE CURRENTLY UNDERUTILIZED

Feasible bioenergy supply[1] in 2050, EJ/year



See Annex A for additional details on low carbon feedstock availability

1. Estimates represent final energy consumption, following conversion losses.
2. Includes tall oil, palm oil mill effluent (POME), used cooking oil (UCO), and animal fats/tallow.
3. Around 16 EJ of solid biomass is estimated to be sourced from tree plantations & short-rotation crops, which require dedicated land. The liquid biofuels category likewise includes a large fraction sourced from 1G crops for transport fuels (ethanol & biodiesel).

Source: US EPA, SCA, Toldrá-Reig et al. (2020), ICCT, Upstream, Raizen

LOW CARBON COST FEEDSTOCK SUPPLY IS WIDELY GEOGRAPHICALLY DISTRIBUTED

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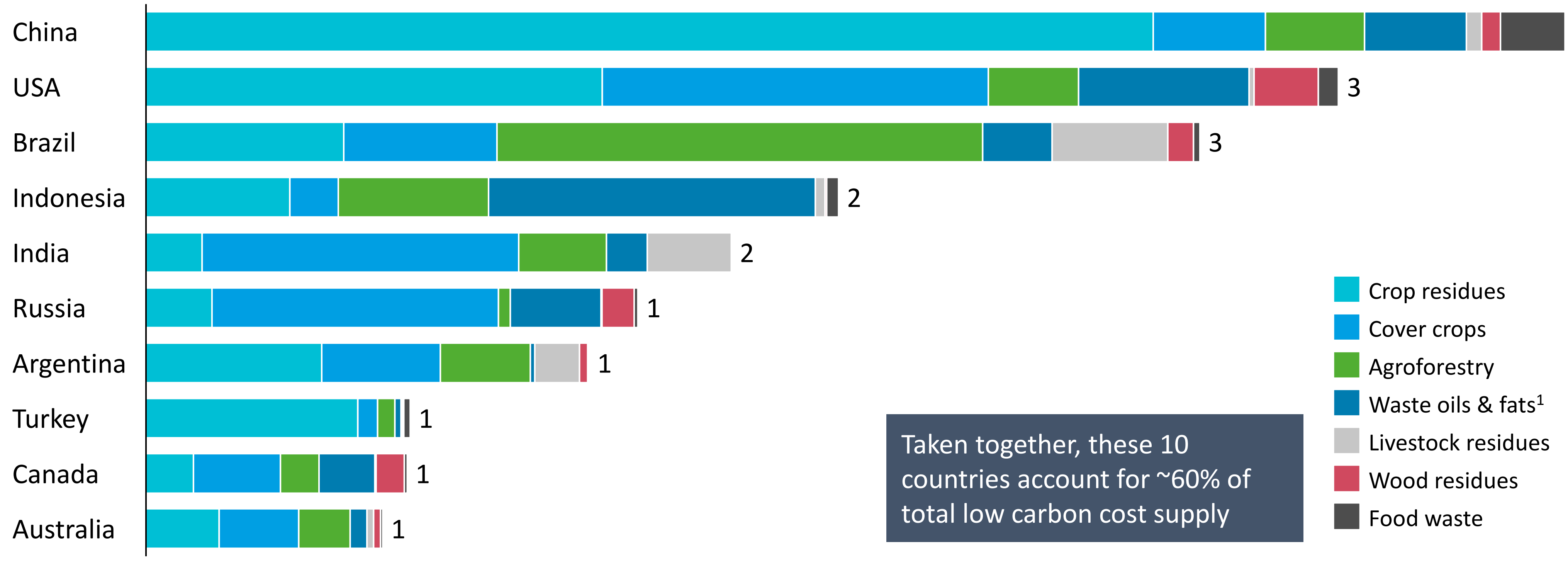
Feasible bioenergy production from low carbon cost sources in 2050 (EJ), excluding dedicated crops



1. Includes tall oil, palm oil mill effluent (POME), used cooking oil (UCO), and animal fats/tallow.

APPLYING FOUR GUARDRAILS CAN LIMIT THE HIGH ENVIRONMENTAL COSTS OF DEDICATED BIOMASS

Policymakers are expected to increasingly move toward sustainable biomass sourcing requirements

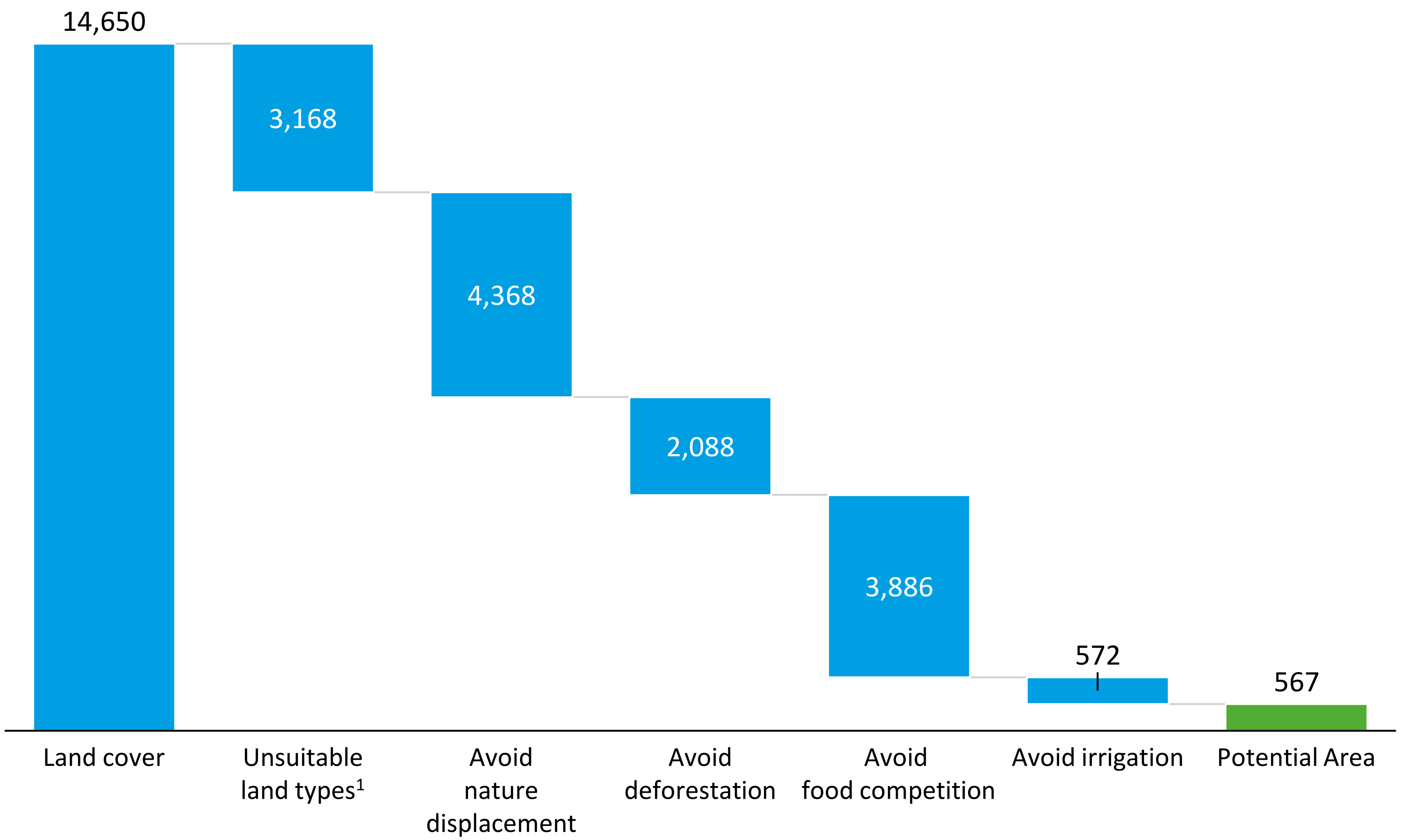
Policy driver	Description	Example policy
No nature displacement	Recent drive for **land sparing to protect high biodiversity areas, restricting alternative uses for the land**. We exclude land area that is included in the World Database on Protected Areas (WDPA) and that has a score above 400 on the IUCN species richness index.	In summer 2022, over **100 countries (including EU) committed to 30x30 protection**: to protect at least 30% of land and oceans by 2030.[1]
No deforestation	Policies implemented to **restrict dedicated bioenergy crop** production in areas of high carbon stock value. Cutting mature carbon stock further increases the **opportunity costs of planting bioenergy** crops vs. alternative options such as planting forest. We exclude land with an above-ground vegetation carbon stock higher than 30 tC/ha, soil carbon higher than 100 tC/ha, and peatland, which has extremely high carbon density.	EU's Renewable Energy Directive **limits fuel produced on previously high carbon land** such as forests, wetlands and peatlands.[2]
No food competition	**First generation bioenergy crops directly compete with food production** and are therefore subject to government restrictions especially in the context of current geopolitical conflict. We exclude all areas that are in the top 30% of yields for maize, rice, wheat, and soybean.	Germany moved to **ban food crops in biofuel production** in response to high food prices after the invasion of Ukraine.[3] **UK bioenergy support schemes** limit food crops for bioenergy, due to **food security and indirect land-use change emissions**[5].
No irrigation	Recent literature finds that the use of **irrigated biomass would double the global area and population under water stress** thereby exceeding the effects of climate change itself.[4] We exclude all areas that need to be irrigated in order to grow bioenergy crops.	UK biomass policy statement defines the effect of biomass production on water as a key concern.[5]

Note: After applying the sustainability guardrails, a carbon payback period is calculated for the remaining available land to determine the most effective method of storing carbon assuming that land is optimizing for carbon storage. Note also that these guardrails focus on environmental impact, but policymakers may also introduce social guardrails, such as avoiding the displacement of native populations

1. World Ocean Day, 2. European Commission, 3. Clean Energy Wire, 4. Stenzel et al. (2021), 5. UK Department for Business, Energy and Industrial Strategy

567 MHA IN FIVE DIFFERENT BIOMES SATISFY BASIC SUSTAINABILITY CRITERIA

Potential area for dedicated biomass crops after applying sustainability guardrails, Mha



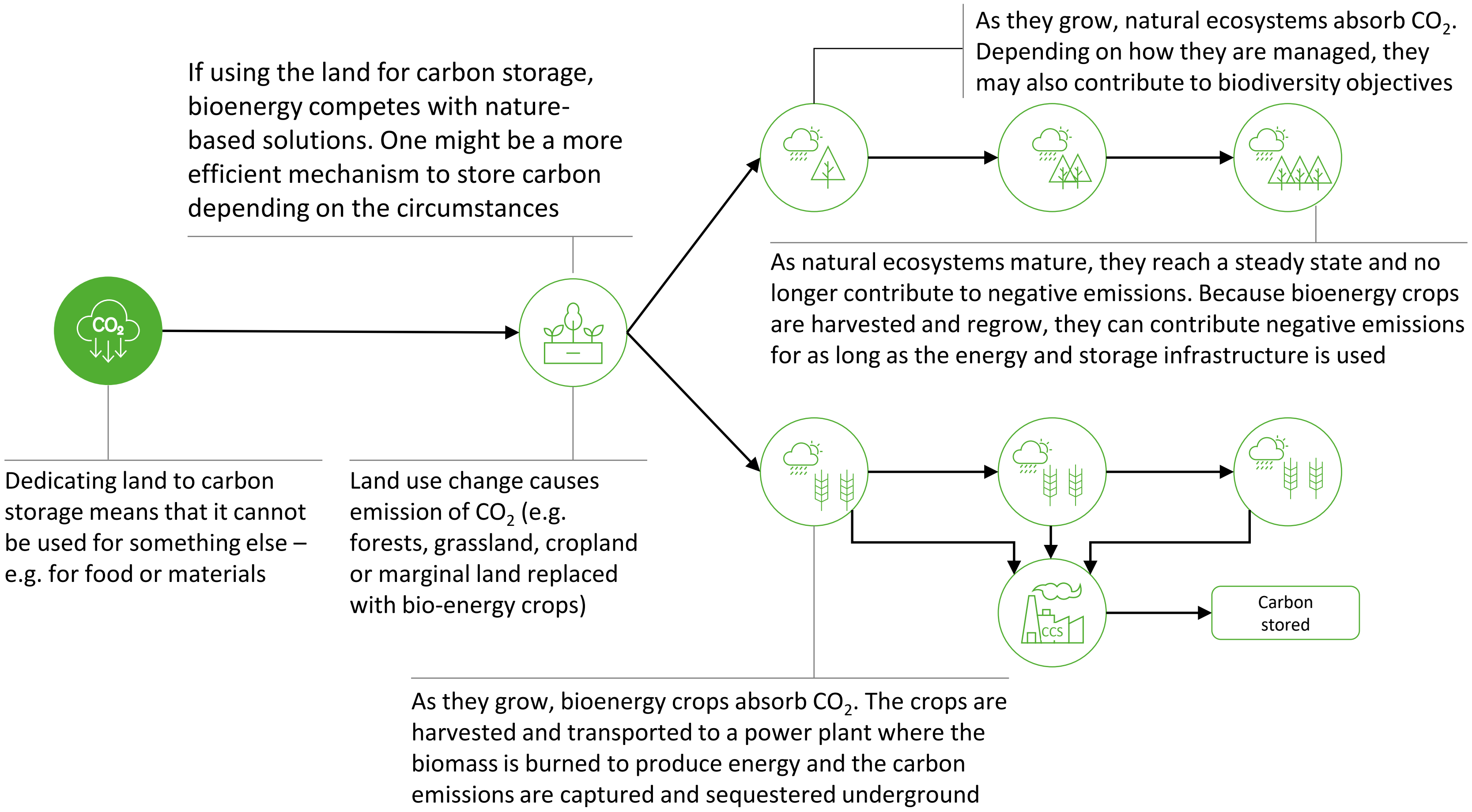
After applying the sustainability guardrails, a carbon payback period is calculated for the remaining available land to determine the most effective method of storing carbon

1. Exclusion of bare lands (e.g., deserts), urban areas, inland water bodies (lakes and rivers), and areas of permanent snow and ice.

Source: ESA CCI medium-resolution land cover; UNEP/IUCN (WDPA); IUCN; Spawn et al. Sci Data 2020; Xu et al. 2017 PEATMAP; Heiderer & Kochy 2012; Monfreda et al. GBC 2008; Biradar et al. 2009

INEVITABLE POLICY RESPONSE

GROWING BIOMASS HAS OPPORTUNITY COST - RESTORING NATURAL ECOSYSTEMS IS LOWER COST CARBON STORAGE



Source: Adapted from Fajardy and MacDowell 2017, Fajardy et al. 2019

For bioenergy crops to be ‘worth it’ from a net carbon sequestration perspective:

1. It has to make sense to dedicate land to carbon storage instead of another use
2. Bioenergy crops have to be a more efficient store of carbon than a natural ecosystem, which is a simpler and cheaper store of carbon

The length of time that bioenergy crops require to ‘break even’ depends on:

- What the crop has replaced and the associated land use change emissions
- The yield of the bioenergy crop
- The natural ecosystem that could otherwise store carbon in that location
- How many harvests the bioenergy crop will be used for, and therefore how much carbon can be stored

CARBON PAYBACK PERIODS MEASURE THE CARBON OPPORTUNITY COST OF LAND DEDICATED TO BIOENERGY CROPS

INEVITABLE POLICY RESPONSE

Carbon payback period (CPP) is the **amount of time** that a **bioenergy crop** needs to be grown before it absorbs more **carbon than if that area was re/afforested instead**

$$CPP_i = (ACSi + ACPi)/((1 - c) * yi * CS)$$

y = yield of biomass crop in area i

CS = carbon content per ton of biomass crop

CPP = carbon payback period of area i

ACS = current above ground carbon stock associated with area i

ACP = above ground carbon potential associated with a mature forest in area i

c = carbon losses resulting from conversion to energy and subsequent capture and storage

The carbon payback period varies due to differences in **yield** and the **carbon potential** achievable in each locality

Long carbon payback periods imply that biomass crops must be used with CCS for many years before they store enough carbon to be a better option than letting the land naturally regenerate

CPP is a measure of opportunity cost:

- CPP is zero for biomass that does not compete for land such as residue and waste sources
- Biomass that displaces existing carbon stock has a higher CPP
- CPP can be high even for degraded land that does not currently have a high carbon stock if a forest could go there instead
- Note that CPP does not measure impact on biodiversity, water, and food security, so is not the only measure of sustainability
- Policymakers are likely to be **skeptical of subsidizing biomass grown in areas with long carbon payback periods**

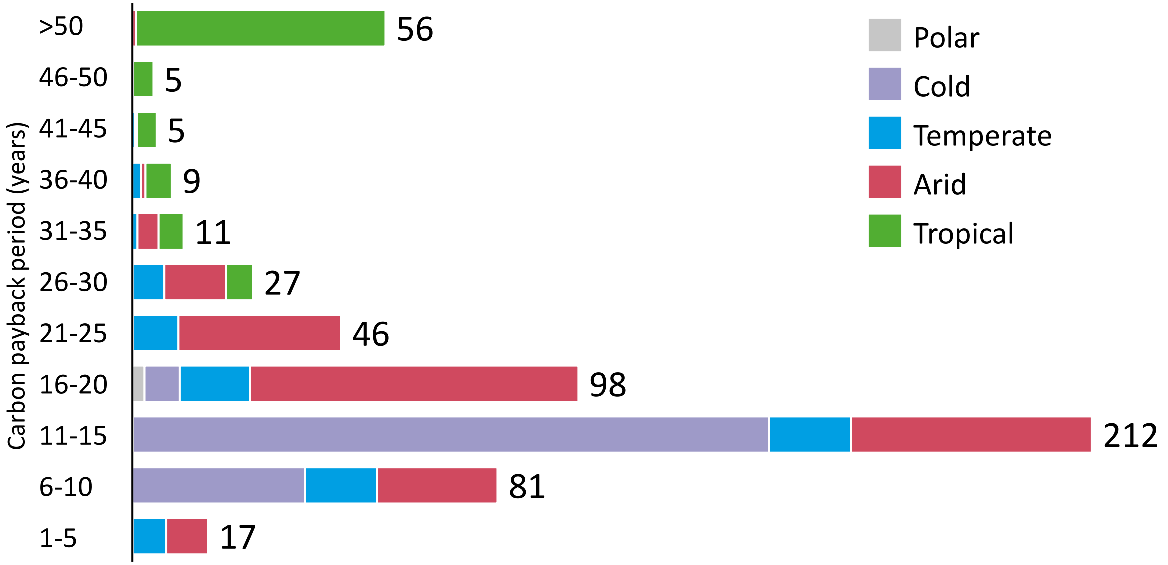
Source: Energy Transitions Commission, analysis based on MAgPIE land system model

INEVITABLE POLICY RESPONSE

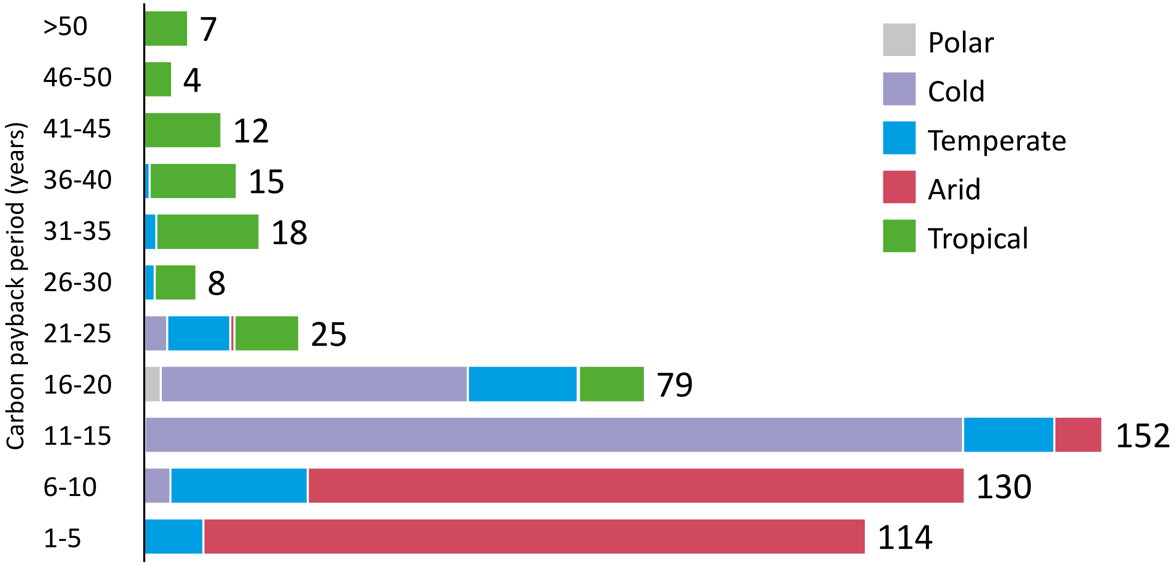
RE/AFFORESTATION ARE VERY EFFICIENT STORES OF CARBON FOR MOST LAND IN TROPICAL BIOMES, BUT ARE LESS EFFICIENT IN ARID, COLD, AND SOME TEMPERATE REGIONS

CPP can vary substantially depending on what yields could be achieved by the bioenergy crops

Potential area (Mha) for dedicated biomass crops after applying sustainability guardrails (assuming 1G yields)



Potential area (Mha) for dedicated biomass crops after applying sustainability guardrails (assuming 2G yields)



- Carbon payback periods account for conversion losses but **assume local processing and use** – transport can make up to 15% of lifecycle emissions. Transport costs would be highest for regionally specific feedstocks that are produced far from demand sources – for example oil palm makes up 23% of the EU's current biodiesel mix
- The 2G yields modelled on the right are relatively optimistic – they **assume yields from research pilots are achievable at scale** and that the necessary infrastructure and markets are created to make them commercially viable

Notes: Biomes are based on Köppen-Geiger climate classification maps. The Köppen-Geiger system divides the world into climate zones based on temperature and dryness, which is a general proxy for the types of vegetation occurring in each climate biome.

Source: Beck et al. (2018), Garcia et al. (2011), Reuters

SUSTAINABLE DEDICATED BIOMASS IS LARGELY PREDICATED ON 2ND GENERATION CROPS BECOMING COMMERCIALLY VIABLE

INEVITABLE POLICY RESPONSE

First generation bioenergy crops such as corn, sugarcane, and soybeans compete directly with food provision and **violate the four sustainability guardrails** increasingly adopted by governments and regulators. **1G yields** are also **much lower** than 2G crops and result in **carbon payback periods as much as 2.5x higher**

Existing 1G crops phase out of use in all but the hardest to decarbonize end uses

Second generation bioenergy crops are **currently almost exclusively grown in pilot programs.**

- The 2G carbon payback periods in this section assume that yields observed in those pilots are achievable at scale. Research suggests this is possible but not guaranteed[1, 2, 3]
- They also assume that the technology required to convert ligno-cellulosic crops, including CCS, will not be prohibitively expensive. There are already some existing commercialization accelerators and policy incentives designed to bring down CCS costs[4, 5, 6]
- Conversion of ligno-cellulosic biomass is easier in power where biomass is simply burned, but harder for liquid fuels, which require chemical conversion to be usable in most engines

2G biomass are largely be used for power/industrial heating, though 2G oily biomass may be a supplemental feedstock in very hard to decarbonize transport fuels like aviation

The commercial success of 2G biomass also requires **infrastructure investments** that facilitate the widespread adoption of new crops

Upstream input and seed providers need to develop and supply farmers with new varietals, particularly those suited to **cold and arid biomes**

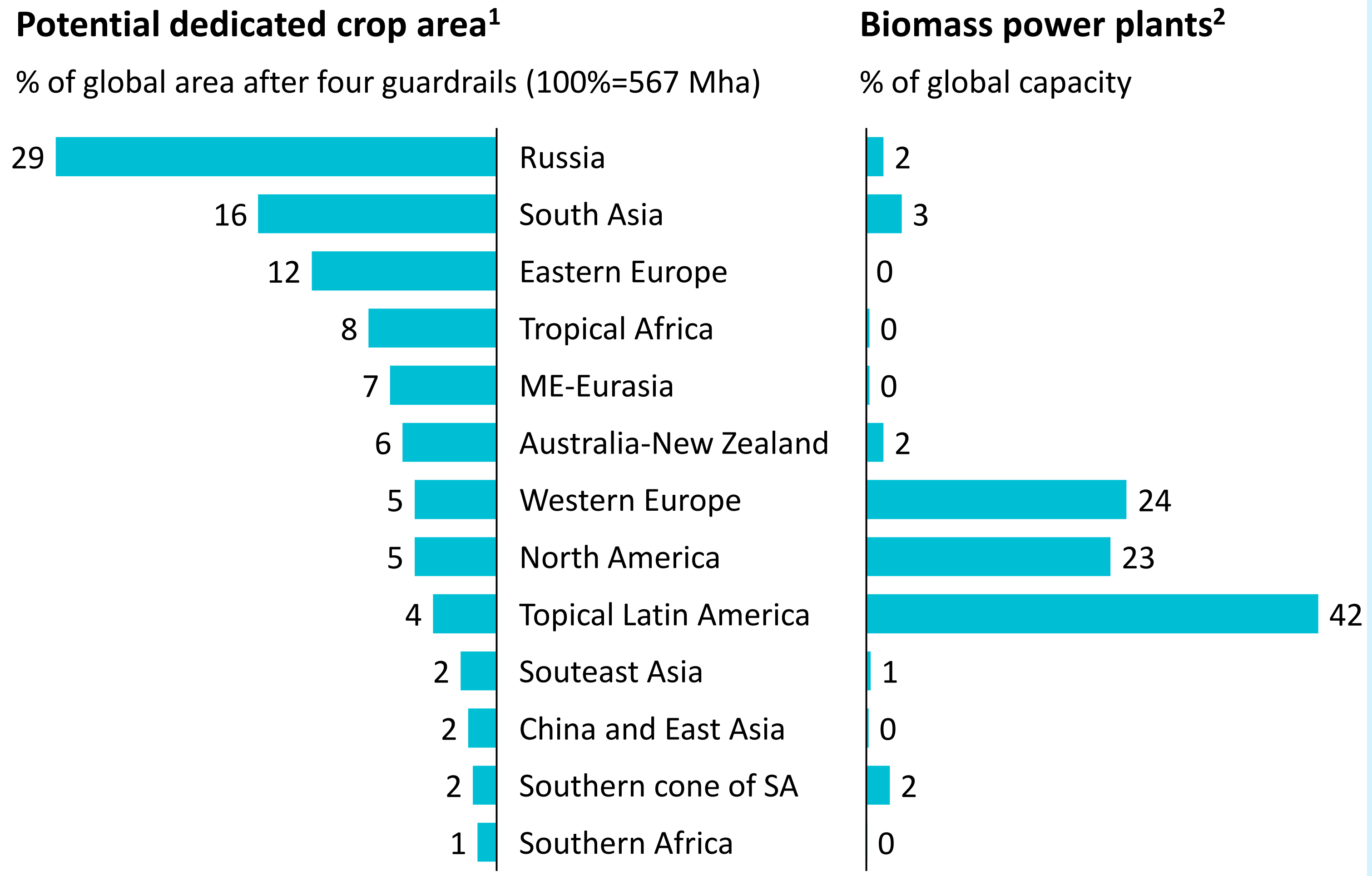
New transport, storage and processing facilities are required as biomass demand expands, biomass markets develop, and supply chains mature

Commercial-scale conversion technology for 2G crops, such as power plants optimized for efficient biomass consumption, needs to be developed and deployed

Source: WRI, McKinsey, Kam et al. (2020), Parliamentary Office of Science and Technology, IEA, European Commission

INEVITABLE POLICY RESPONSE

LAND SUITED TO BIOENERGY IS TYPICALLY FAR FROM CURRENT DEMAND



Land for dedicated bioenergy is available, though not where there is existing demand

For example, the largest biomass power plant capacity of 12,800 MW is in Brazil, where there is very little potential for energy production from sustainable dedicated bioenergy crops (< 0.1 EJ). However, there is around 3 EJ available from waste streams in Brazil.

That implies that relatively little of the bioenergy capital stock currently deployed is well positioned for sustainable long-term supply. Feedstock sourcing is an important challenge for these plants if they are to continue operating long term.

1. Area that has met the sustainability guardrails to avoid nature displacement, deforestation, food competition, and irrigation.
2. Source: Global Power Plant Database . Dataset for 2021 includes power plants that use biomass feedstocks and is non-exhaustive for infrastructure associated with the bioenergy industry (e.g., biofuel refineries).

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INEVITABLE POLICY RESPONSE

BIOENERGY WITHOUT CCS IS A TRANSITION FUEL, CONSTRAINED IN THE LONG TERM AS IT GETS OUTCOMPETED BY LOWER CARBON ALTERNATIVES

This section motivates bioenergy without CCS in FPS23 for transport and buildings, starting with demand

Demand	• Most end uses of bioenergy without CCS are **not cost competitive** in the long run with lower carbon alternatives involving hydrogen or batteries • Sustainable Aviation Fuel (SAF) is an exception – **biofuels are expected to the lowest cost** fossil alternative until 2040 or beyond • Biomass used for low temperature heating in the **pulp and paper industry** is another exception due to the industry's unique ability to **self-supply with forestry residues**
Supply	• Waste oils are expected to make up a growing share of transport fuels. Despite being currently underutilized, limited supply means competition for feedstock with dedicated crops filling the gap • 1G vegetable oil products (such as HVO or HEFA produced from oilseeds and waste oils) are likely to still have a **near term role** while waste oil supply chains improve and oilseed cover crops mature. Longer term demand for oils from dedicated crops may be met by 2G crops not currently at commercial scale
Forecast	• There is a limited role for bioenergy in heavy duty vehicles while electrification options catch up, peaking in 2030-2035 • The shipping sector uses ~**1 EJ of biofuel by 2050**, but ammonia dominates as the largest low carbon alternative • SAF markets are expected to grow to **nearly 5 EJ**, making up **more than a quarter** of the aviation fuel market by 2050

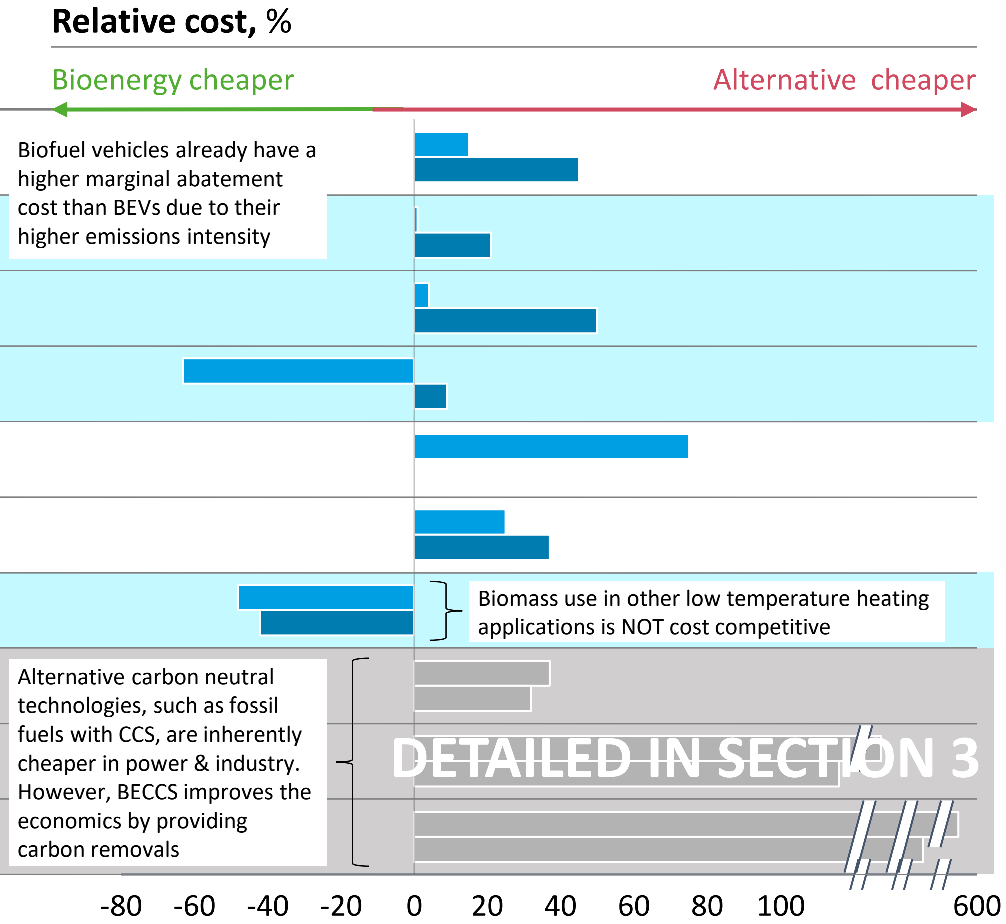
INEVITABLE POLICY RESPONSE

DEMAND: BIOENERGY IS A LONG-TERM DECARBONIZATION OPTION IN AVIATION AND SOME NICHE USES, BUT IS NOT COST COMPETITIVE OTHERWISE

Deep dive to follow | Removals discussed in next sub-section | ⊗ Unlikely (other than for niche or transition uses) | ✓ Likely | 2030 | 2050

SELECTED END USES, NOT EXHAUSTIVE

Sector	End use	Feedstock: Current	Feedstock: Future	Alternative	Long-term option
Transport	Light-duty vehicles[1]	1G crops	N/A	BEV	⊗
	Heavy-duty vehicles[1,2]	1G oil crops	Residues	BEV	⊗
	Shipping[1]	1G oil crops	N/A	Ammonia	⊗
	Aviation	1G oil crops	Residues	Synfuels	✓
Buildings	Space heating[3]	Wood residue	N/A	Electrification	⊗
Industry	Iron & steel (no CCS)	Wood pellets	N/A	H2DRI EAF	⊗
	Pulp and Paper process heating[4]	Wood residue	Wood residue	Electrification	✓
	BECCS for cement	Wood pellets	2G crops	Gas CCS	✓
	BECCS for other high T industry	Wood pellets	2G crops	Gas CCS	✓
Power	BECCS for power	Wood pellets	2G crops	CCGT CCS	✓



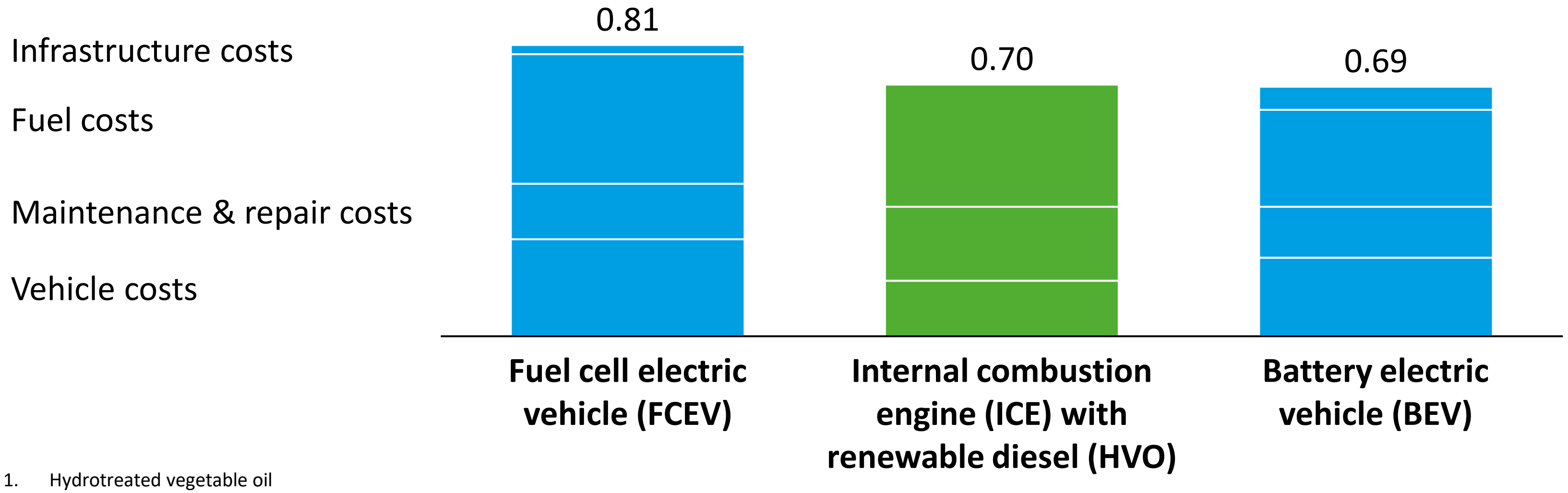
Note: BECCS technologies are compared here against alternative focused only on end use, and as such relative costs do not incorporate any possible payment for removals. See next sub-section for further comparison against alternative emissions removals options

Source: 1. ETC, 2021, Bioresources within a Net-Zero Emissions Economy; 2. Transport and Environment, 2020, How to decarbonise the UKs freight sector by 2050; 3. Khan et al, 2023, Life cycle cost analysis (LCCA) of Stirling-cycle-based heat pumps vs. conventional boilers (assuming biogas boiler); 4. Pulp and paper is one application of low temperature process heating, and is the only industrial application in which biomass is lower cost than other low carbon alternatives because it can self-supply the wood residues

DEMAND: **HEAVY DUTY VEHICLES** – BIOFUELS ARE USEFUL FOR BLENDING EARLY BUT BEVS START TO BE COMPETITIVE BY 2030

Emissions intensity ($kgCO_2e/km$)[4]

Total cost of ownership, 2030 (based on UK long haul trucks), 2020USD per vehicle per km



1. Hydrotreated vegetable oil
2. Fatty acid methyl ester
3. ETC, 2021, Bioresources within a Net-Zero Emissions Economy
4. ICCT, 2023, A COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF EUROPEAN HEAVY-DUTY VEHICLES AND FUELS

Source: Transport and Environment, 2020, How to decarbonise the UKs freight sector by 2050. Renewable diesel (HVO) based on fossil diesel truck assuming 15% higher fuel costs. Converted from GPB to USD based on 2020 average exchange rate (1 GPB = 1.28 USD). Excludes vehicle taxes and road charges

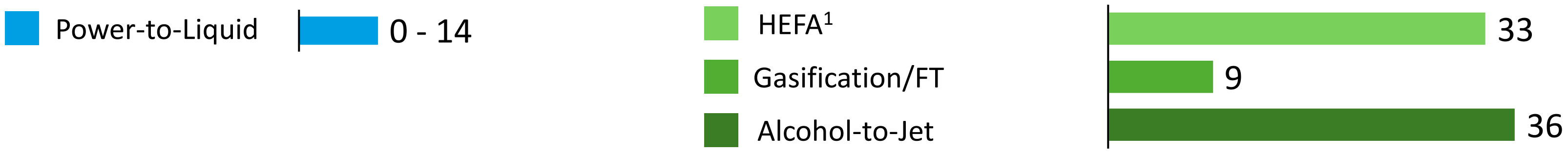
By 2030, BEVs start becoming cheaper than ICE trucks running on 100% renewable diesel (HVO[1]) – the only drop-in biofuel for road transport. By 2050, FCEVs are 20% - 60% cheaper than HVO trucks[3]. ICEs running on biodiesel already have a higher marginal abatement cost than BEVs due to their higher emissions intensity

Biodiesel (FAME[2]) is another biofuel that can be blended in ICEs. Alongside HVO, it can be used to decarbonize the current fleet. Biofuels continue to be used until alternatives become cheap and enabling infrastructure (e.g. BEV charging stations) is widespread

INEVITABLE POLICY RESPONSE

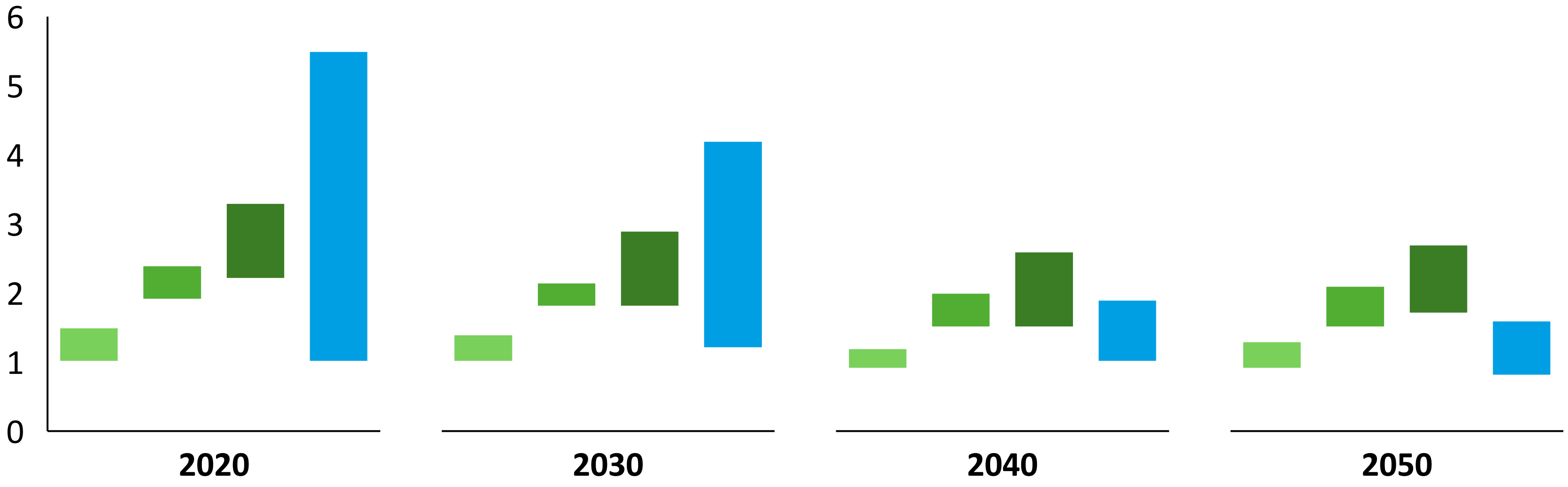
DEMAND: **AVIATION** – BIOFUELS ARE LIKELY TO BE CHEAPER THAN SYNFUELS FOR THE NEXT ~20 YEARS

Synfuel: **Biofuel pathway:** **Emissions intensity** (gCO_2e/MJ)[2,3]



Sustainable aviation fuel production cost

Thousand USD/t of kerosene



1. Hydroprocessed Esters and Fatty Acids. Advanced biofuel produced from oily feedstocks
2. EASA, 2023, Fit for 55 and ReFuelEU Aviation; Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport
3. ICAO, 2022, Life Cycle Emissions of CORSIA eligible fuels

Aviation biofuels are currently the only decarbonization option and will likely be competitive until at least 2040. RefuelEU targets > 50% of biofuels in the sustainable fuel mix out to 2050[2] Feedstocks for these fuels are currently mostly 1G oil crops, but increasingly move toward utilizing waste oils

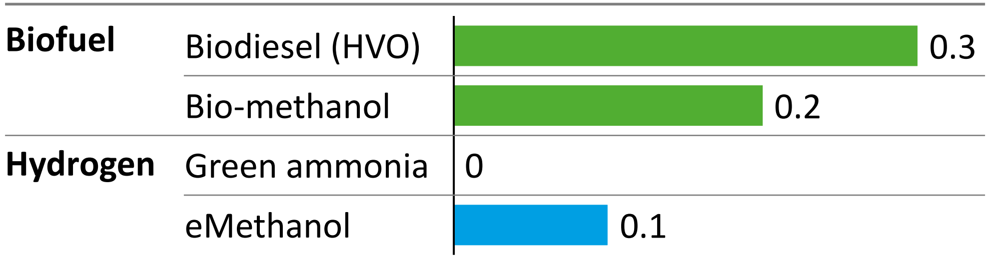
Synfuels potentially have advantages in terms of resource use (e.g., water, land), but their emissions intensity depends on the source of CO_2

Synfuel costs depend on the cost of green power and the source of CO_2 capture: DACCS based fuels currently ~ 5x more expensive than fuels with CO_2 from local CCS

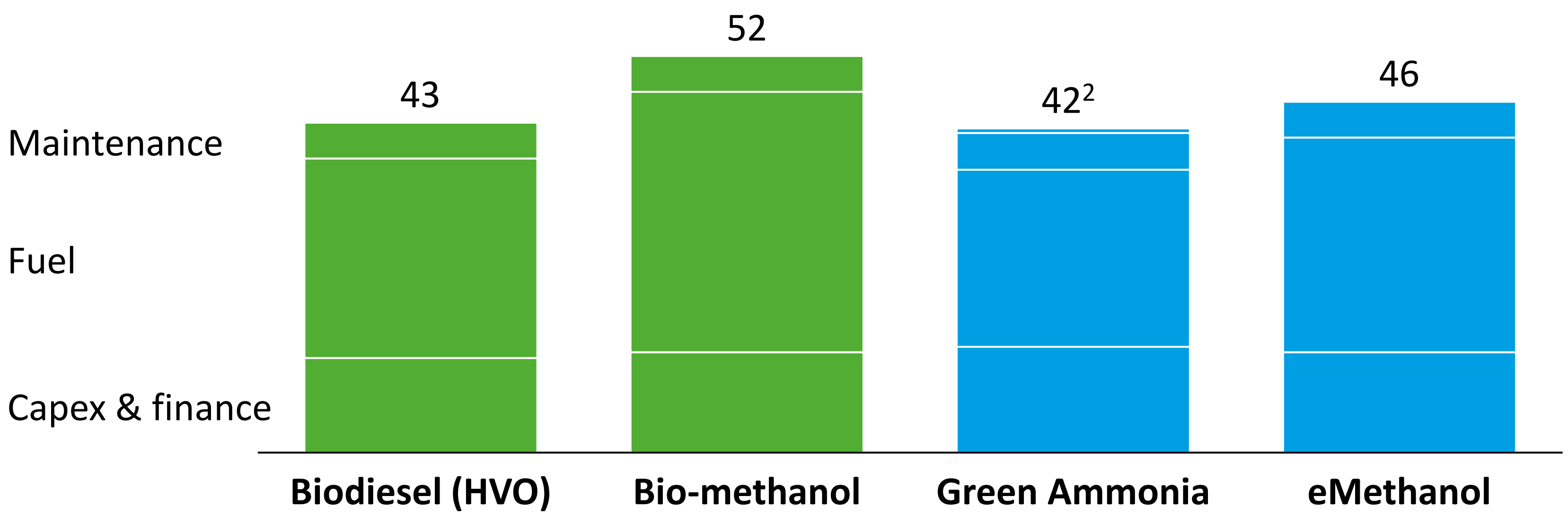
While synfuels could potentially be cost competitive by 2040 or 2050, there remains a great deal of uncertainty relative to biofuels

DEMAND: **SHIPPING** – AMMONIA BECOMES CHEAPEST, BUT BIO-METHANOL AND BIOFUELS CAN BE USED TODAY

Emissions intensity (relative to HFO = 1)[3]



Total cost of ownership[1], 2030 , mUSD/ year



1. 14,000 TEU containership, Deployed globally, using weighted average price of Rotterdam, Fujairah and Singapore. Excludes Port/canal fees and carbon price
2. Includes 1mUSD/year of cargo capacity loss
3. Chin Law et al, 2021, A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost

Ammonia from green hydrogen dominates the fuel mix by 2050 due to its lower costs and emissions intensity. However, ammonia ships are not expected before ~ 2025

Bioenergy can play a role today with blending of biofuels up to 20%

Bioenergy might also play a role in future with bio-methanol which can be dropped-in as a ship fuel. Maersk plans to deploy three 100% methanol ships by 2023

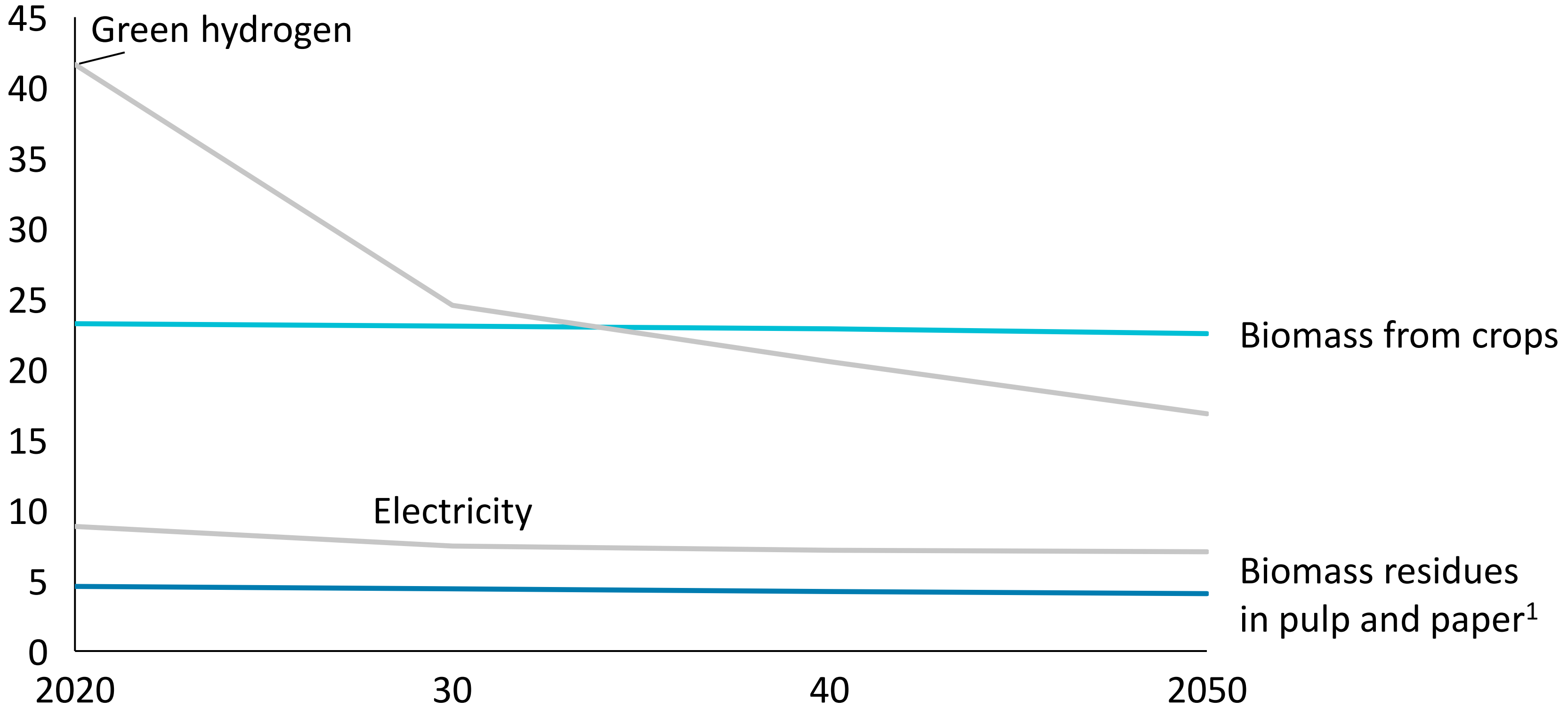
However, by 2030 eMethanol from renewable electricity is preferred on a cost basis to bio-methanol by 2030

INEVITABLE POLICY RESPONSE

DEMAND: **LOW TEMPERATURE HEATING** – ONLY PULP AND PAPER RESIDUES CAN COMPETE WITH ELECTRICITY

Levelized cost of heat

M$/PJ



1. Assumes no biomass cost
2. ETC, 2021, Bioresources within a Net-Zero Emissions Economy

Electrification is the greenest and cheapest option in most low temperature heating processes. Biomass only remains competitive in the pulp and paper, and sugar, industries which use cheap self-supplied residues (e.g., bark)

Even in the manufacturing of pulp and paper, and sugar, BECCS is likely to be too expensive. They may be better off selling residues to BECCS plants in power and high temperature industries[2]

INEVITABLE POLICY RESPONSE

SUPPLY: THE FEEDSTOCK MIX IN THE TRANSPORT SECTOR SHIFTS AWAY FROM 1G ENERGY CROPS TOWARD WASTE OILS AND FATS

Waste oils & fats[1] Integrated energy crops[2] Dedicated energy crops[3]

Aviation

Bioenergy demand increases by 9x in the aviation sector between 2025-2050, with strong demand for waste oils

Energy crops such as oilseeds have a role to play throughout the period, both on dedicated land and integrated into existing agricultural systems

Shipping

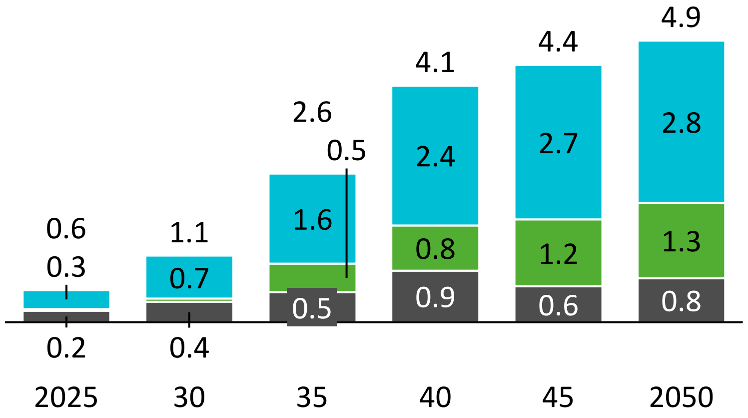
Like aviation, the shipping sector acts quickly to secure supply of more sustainable feedstocks as demand for biofuels continues to increase through 2050

A 50:50 mix of energy crops and waste oils and fats can meet 2050 demand

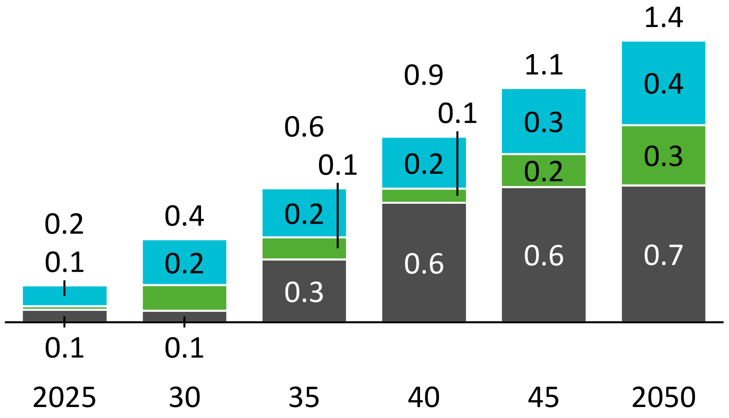
Road transport

Present-day liquid biofuels for road transport largely rely on 1G energy crops for production of ethanol and biodiesel. Demand for these 1G crops fades over time as biofuels are replaced by more sustainable alternatives, freeing up land, especially in the U.S. and Brazil

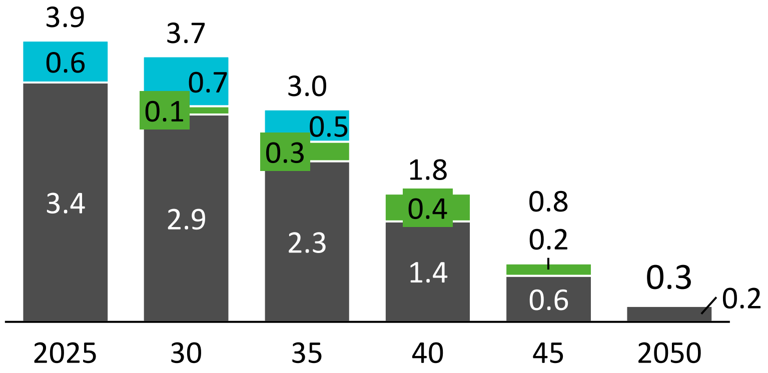
Feedstock supply[4] for aviation, EJ



Feedstock supply[4] for shipping, EJ



Feedstock supply[4] for road transport, EJ



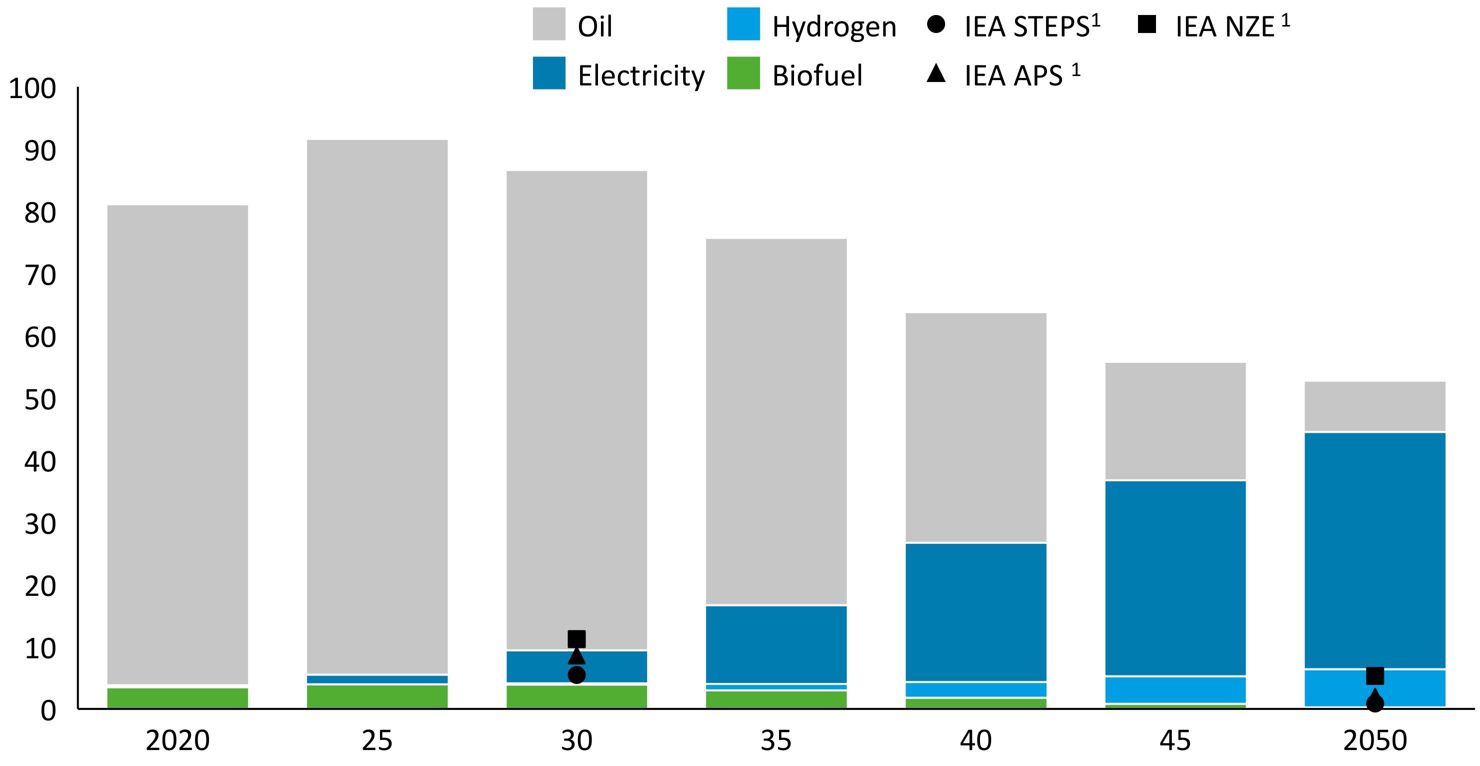
1. Includes feedstocks such as tall oil, palm oil mill effluent, used cooking oil, and animal fats/tallow.
2. Energy crops that are integrated into existing agricultural systems through agroforestry and cover cropping.
3. Energy crops on dedicated land
4. End uses are likely to compete for scarce waste and residue feedstock supply because of lower carbon intensities. Actual feedstock mix within each end use will therefore depend on securing supply

INEVITABLE POLICY RESPONSE

FORECAST: **ROAD** – BIOFUELS ARE USED FOR THE NEXT 20 YEARS BUT ARE EVENTUALLY PHASED OUT

Demand peaks in the 2020s and drops to almost 0 by 2050

FPS23 energy demand, EJ



1. Applies bioenergy shares from IEA World Energy Outlook, 2022 to FPS23 demand

Electrification (and eventually fuel cells in some applications) is the **greenest and cheapest decarbonization** option in road transport. 1G biofuels will likely continue to be used in the current fleet

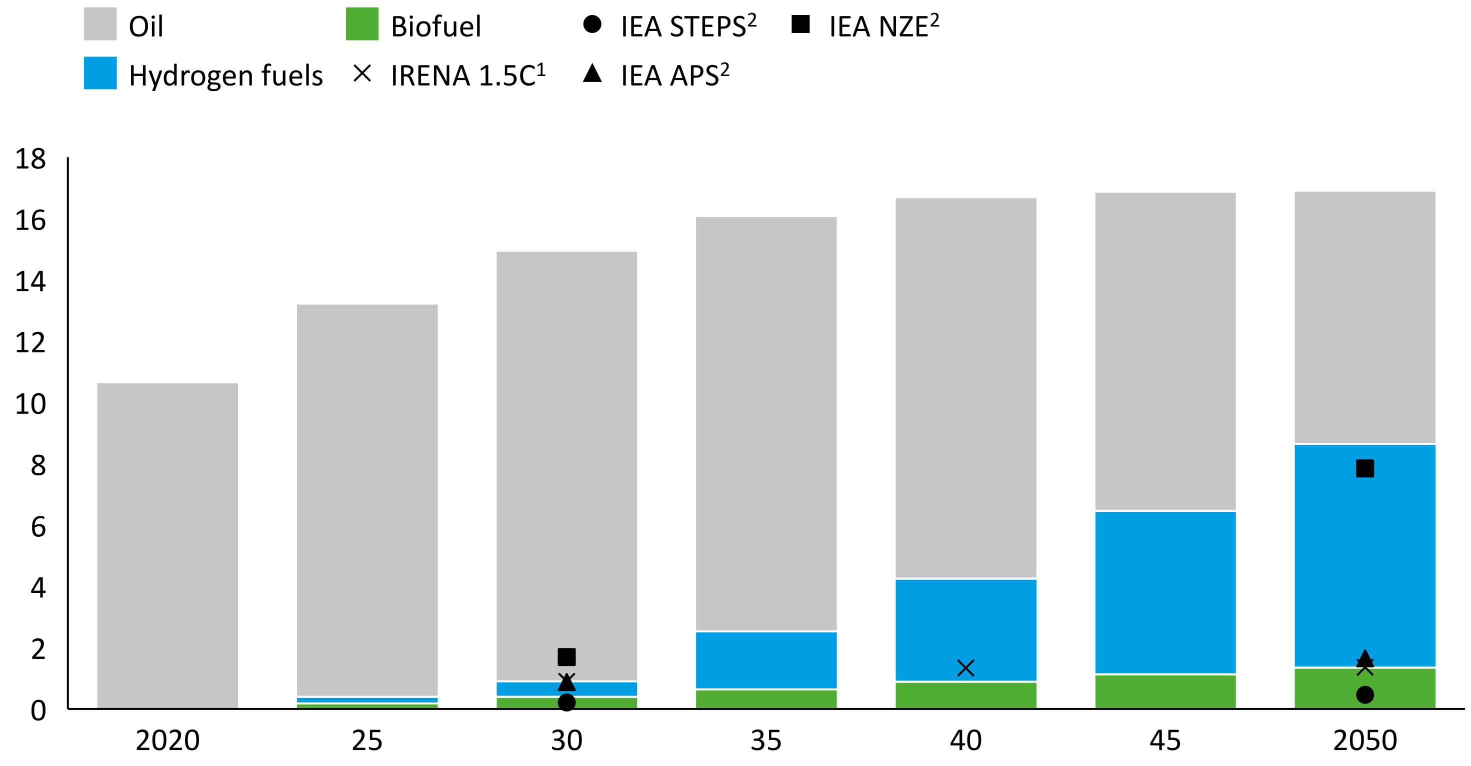
Ethanol, produced from sugar crops, is **already being phased out** in most countries so FPS23 demand peaks in 2025 for light duty vehicles

However, FPS23 biodiesel demand from 1G oil crops **peaks in 2030** for heavy duty vehicles where alternatives are less mature

INEVITABLE POLICY RESPONSE

FORECAST: **SHIPPING** – THE USE OF BIOFUELS GROWS BUT AMMONIA TAKES OVER FROM 2035

FPS23 energy demand, EJ



1. IRENA, 2021, A pathway to decarbonise the shipping sector; 2. IEA, 2022, WEO. Based on combined shipping and aviation share of biofuels

Ammonia is likely the best and cheapest long-term decarbonization option in shipping but requires a new fleet so adoption could be slow

Bio-methanol – the next alternative alongside e-methanol – is already used today. However, it plays a smaller long-term role than ammonia

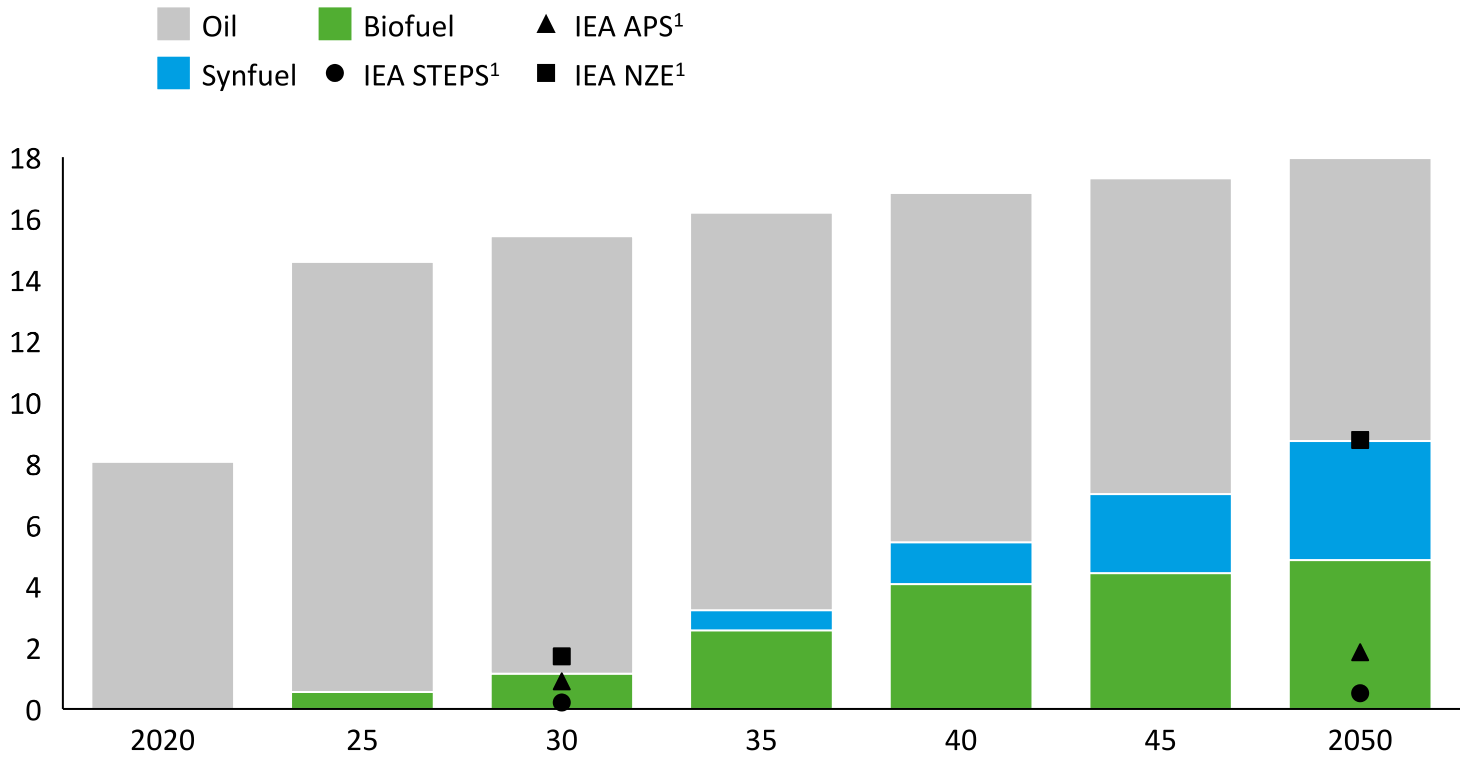
In FPS23, HVO blending also plays a minor role in the shorter-term alongside bio-methanol

INEVITABLE POLICY RESPONSE

FORECAST: **AVIATION** – BIOFUELS ARE THE MAIN DECARBONIZATION OPTION OUT TO 2050

Biofuels still make up over 50% of the mix from 2050 but synfuel share grows

FPS23 energy demand, EJ



1. IEA, 2022, WEO. Based on combined shipping and aviation share of biofuels

Synfuels have a potential advantage over biofuels due to their lower resource use. Although currently immature and costly, there is potential for synfuels to be cost competitive with HEFA (the lowest cost biofuel) by 2040

In FPS23, biofuels play the dominant role over the next 20 years and synfuels begin to gain significant share by the 2040s

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INEVITABLE POLICY RESPONSE

BECCS IS A LONG TERM REMOVALS OPTION THAT COMPETES WITH DIRECT AIR CAPTURE AND NATURE BASED SOLUTIONS

This section motivates bioenergy with CCS in FPS23 for power and industry

Demand	• **Current bioenergy capital stock does not match locations of sustainable dedicated supply**, implying the industry will likely need to secure sustainable feedstock and build out new infrastructure • Because DACCS is not as land-intensive as BECCs, it could become **cost-competitive with BECCS by 2050** • **BECCS is likely limited to using only biomass from land with relatively low payback periods**, it is simply too costly for more widespread use once accounting for land impacts
Forecast	• BECCS is expected to play a role in power and cement sectors, growing to ~**13 EJ by 2050**. This equates to ~1GtCO_2e removals annually

INEVITABLE POLICY RESPONSE

DEMAND: THE ATTRACTIVENESS OF BECCS DEPENDS ON THE PAYBACK PERIOD AND STAKEHOLDER'S TOLERANCE FOR OVERSHOOT

Further assessment to follow

The land-related carbon loss could lead to an additional penalty to BECCS LCOR of 10 – 300 $/tCO2

	'No tolerance' case	'Low tolerance' case	'High tolerance' case
Illustrative narrative	A hypothetical scenario where net removals are demanded (almost immediately) The CPP and associated positive net emissions means **BECCS is not a viable approach**	Rising physical risks and potential climate tipping points drive increased decarbonization effort and less tolerance for slow-to-pay-back negative emissions This need for rapid removals makes **BECCS relatively less attractive**	A focus on temperature outcomes by the end of the century means society is more willing to backload the removals required to return to safe levels This longer term assessment means the initial loss in removal potential can be spread across a longer period, and so **BECCS becomes more attractive**
Removal period	<5 years	25 years	75 years
Share of time spent repaying land-related carbon loss[1]	>100%	20% – 60%	7% – 20%
Penalty added to BECCS LCOR[2]	Infinite	50 – 300 $/tCO$_2$	10 - 50 $/tCO$_2$
		If CPP = 10 years and tolerance = 25 years then the sequestration that can be claimed is 40% lower. The associated 40% reduction in carbon sequestration payments is equivalent to a ~ $130/tCO$_2$ penalty	*When tolerance increases to 75 years, the sequestration that can be claimed, and hence the optimal carbon price paid, is only 13% lower so the penalty is reduced to ~ 30 $/tCO$_2$*

1. Range based on 5 - 15 year CPP. Global average CPP for 2G crops is 10 years
2. Uses current mean BECCS LCOR of ~ 190 USD2022/tCO2e

BECCS is only viable when the carbon price paid by stakeholders (e.g., policymaker or corporates) exceeds the levelized cost of removals (LCOR)

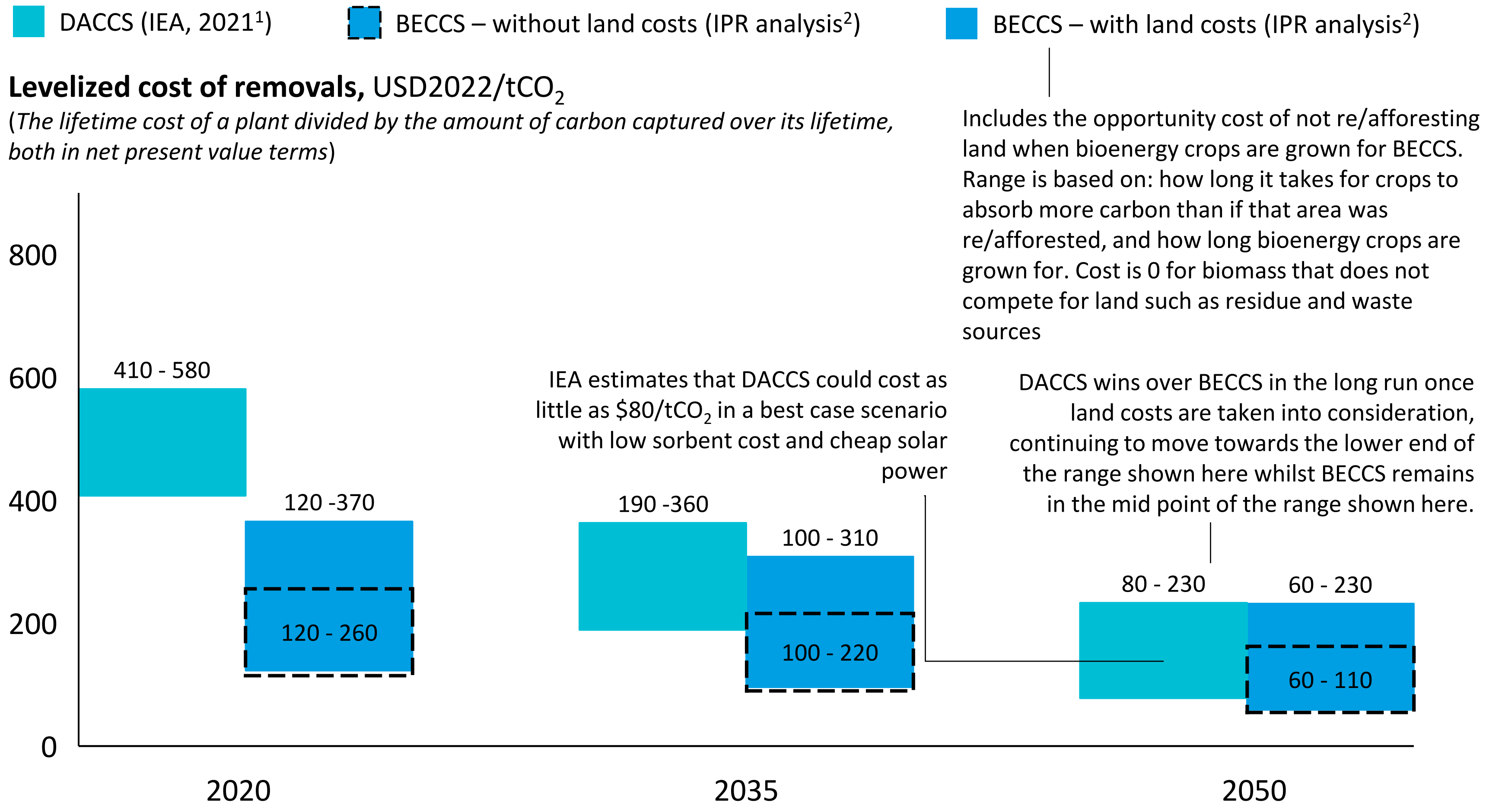
Accounting for the carbon payback period (CPP) reduces the amount of sequestration that BECCS plants can claim because some carbon would have been sequestered by re/afforesting the area

As a result, the carbon price is also reduced to reflect the lower than claimed sequestration. The reduced carbon price is equivalent to a penalty to LCOR

The penalty depends on the CPP and the time period over which removals are needed: the "tolerance". Longer CPP and/or lower tolerance means a larger penalty

INEVITABLE POLICY RESPONSE

DEMAND: ONCE LAND-BASED COSTS ARE CONSIDERED, DACCS IS EXPECTED TO BE MORE ATTRACTIVE THAN BECCS BY 2050



1. Primarily based on IEAGHG Technical Report, 2021, Global Assessment of Direct Air Capture Costs. Assumes FOAK is 2020 and NOAK is 2050. Range is from base case (lower) to very ambitious (upper)
2. No land cost estimates in line with Fuss et al, 2018, Negative emissions—Part 2: Costs, potentials and side effects. Land costs calculated based on how long it takes for crops to absorb more carbon than if that area was re/afforested: the carbon payback period (CPP), and how long bioenergy crops are grown for: the removal period . Lower bound = 75-year removal period with 5-year CPP, upper bound = 50-year removal period with 15-year CPP
3. BECCS and DACCS represent two of the most often discussed technology-based removals, however other approaches such as biochar or enhanced weathering also offer potential for removals.

There are multiple considerations in estimating the true levelized cost of removals for BECCS. In particular, land costs are considered explicitly in the modeling for FPS 2023 (see footnote 2), whilst others' estimates typically may not

BECCS applies a relatively mature technology and so is unlikely to experience significant cost reductions. BECCS costs increase if the land impact of growing biomass is considered

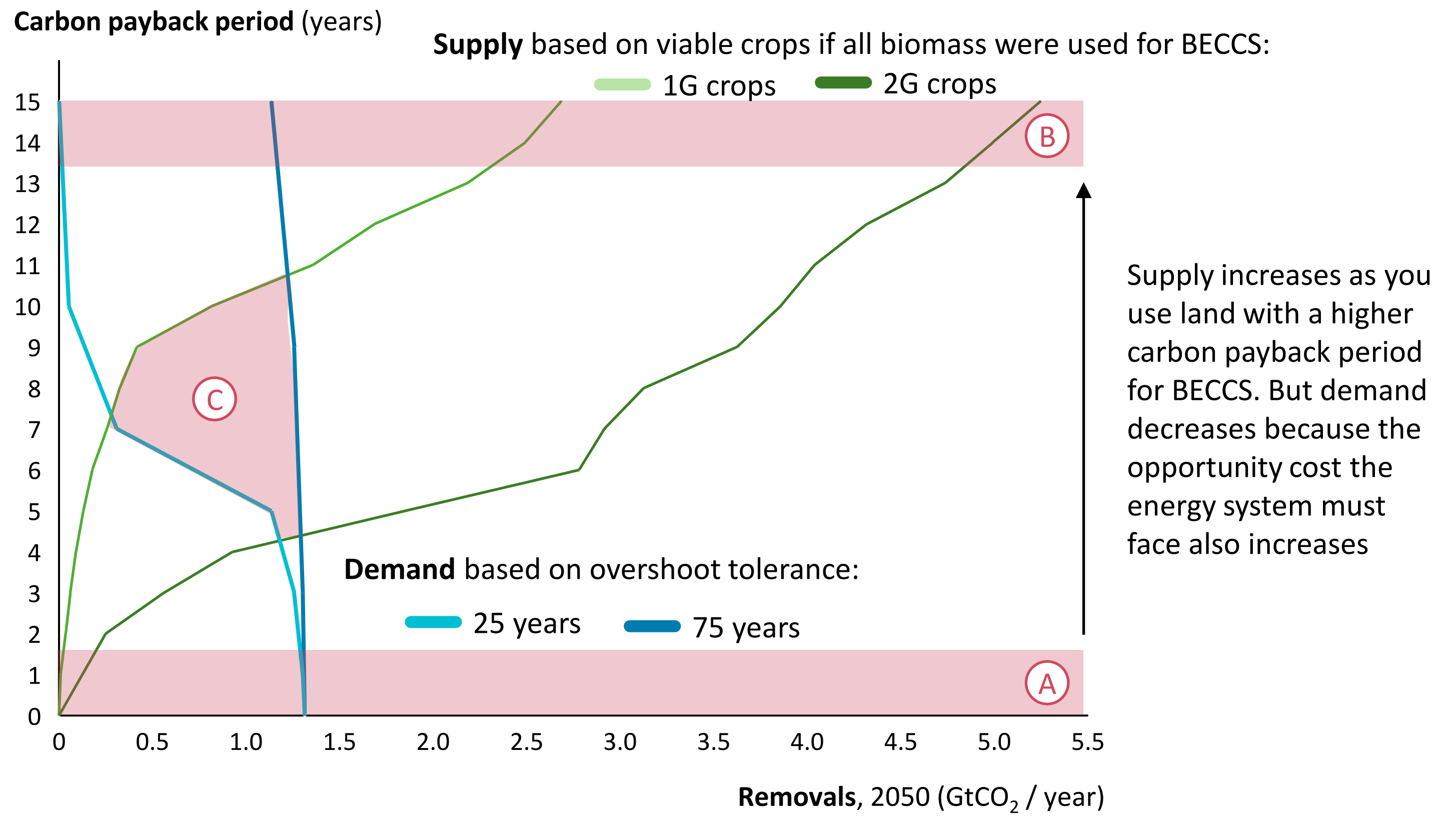
Direct Air Carbon Capture and Storage (DACCS) removes carbon from ambient air and has the benefit of limited land constraints[3]. While it starts from a high baseline, it could see rapid cost reductions as today's demonstrator plants scale, and with access to low-cost renewable energy

INEVITABLE POLICY RESPONSE

DEMAND: BECCS IS LIKELY LIMITED TO USING ONLY BIOMASS FROM LAND WITH LOWER PAYBACK PERIODS

There is ~ 1 $GtCO_2$ of BECCS by 2050 in FPS 2023 based on feasible supply and demand

A B C Denote different possible "states of the world" which vary by carbon payback period



1. The amount of CO_2 removal per unit of energy production in the modeling varies by process and feedstock, but a rough approximation is 1 $GtCO_2$ per 10 EJ. For comparison, BECCS removals in 2050 in the IEA NZE scenario are 1.3 $GtCO_2$ per year.

A **Maximum demand but minimum supply**

- All biomass used for BECCS comes from land with low payback periods so there is almost no opportunity cost for BECCS: it is relatively cheap so there is a lot of it
- However, there is little land with low payback periods so biomass supply cannot meet demand

B **Maximum supply but minimum demand**

- There is a lot of land available with high payback periods
- However, because the payback period are high, using biomass from that land adds a large opportunity cost to BECCS: it is relatively expensive so there is little of it demanded

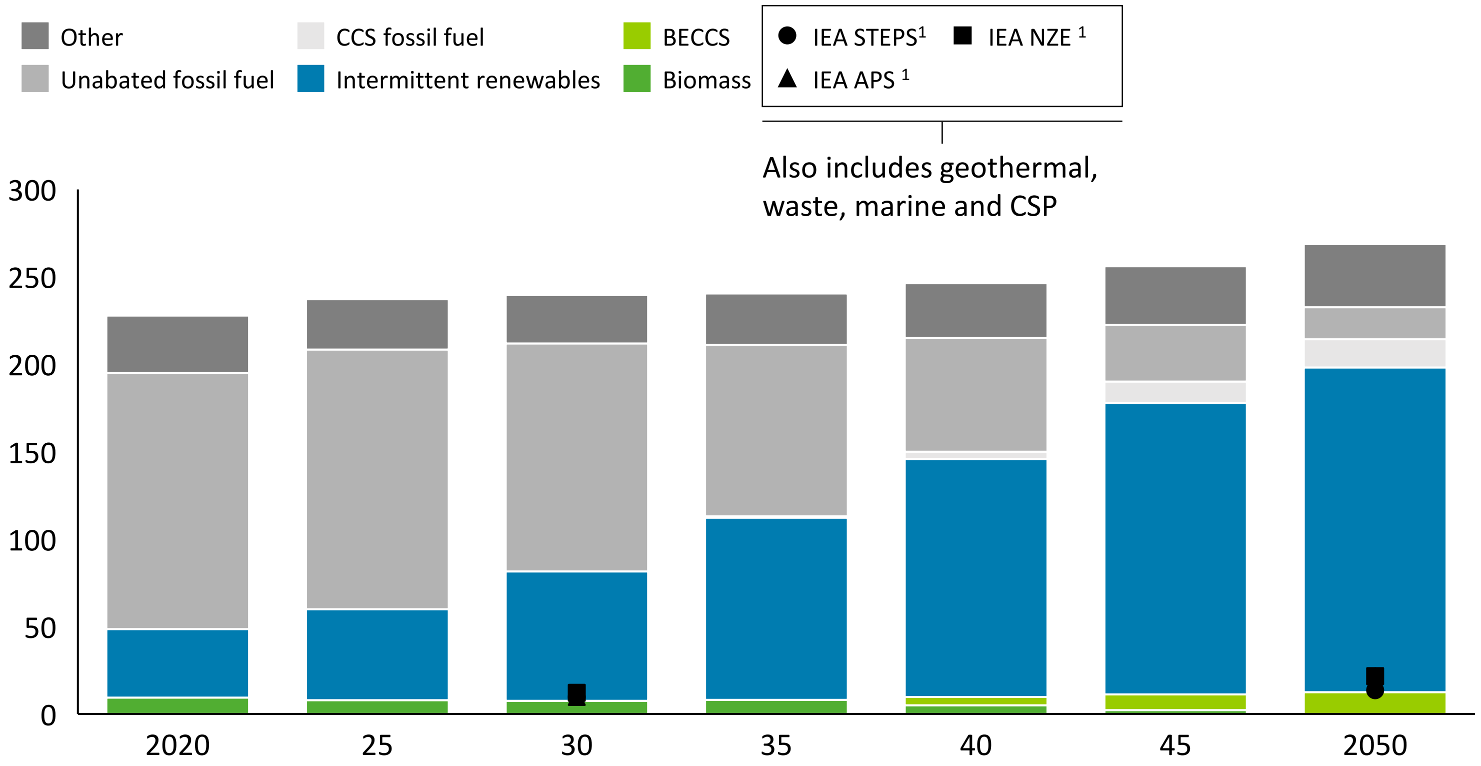
C **Feasible range of BECCS removals where demand matches supply: ~ 1$GtCO_2$ by 2050.**[1] The actual amount of BECCS will likely depend on:

- The viability of high-yield 2G crops which provide more supply than 1G crops
- How much biomass is used for other end uses
- The tolerance for overshoot which determines the additional cost of BECCS
- The relative cost of alternative removal technologies such as DACCS

INEVITABLE POLICY RESPONSE

FORECAST: **POWER** – BECCS REMOVES ~1 GTCO_2 PER YEAR BY 2050 AS UNABATED BIOMASS IS PHASED OUT

FPS23 energy demand, EJ



1. IEA, 2022, WEO. Includes "other renewables" such as waste, geothermal, CSP and marine power;

In FPS 2023, intermittent renewables make up most the generation mix complemented with gas CCS and hydrogen for dispatchable generation

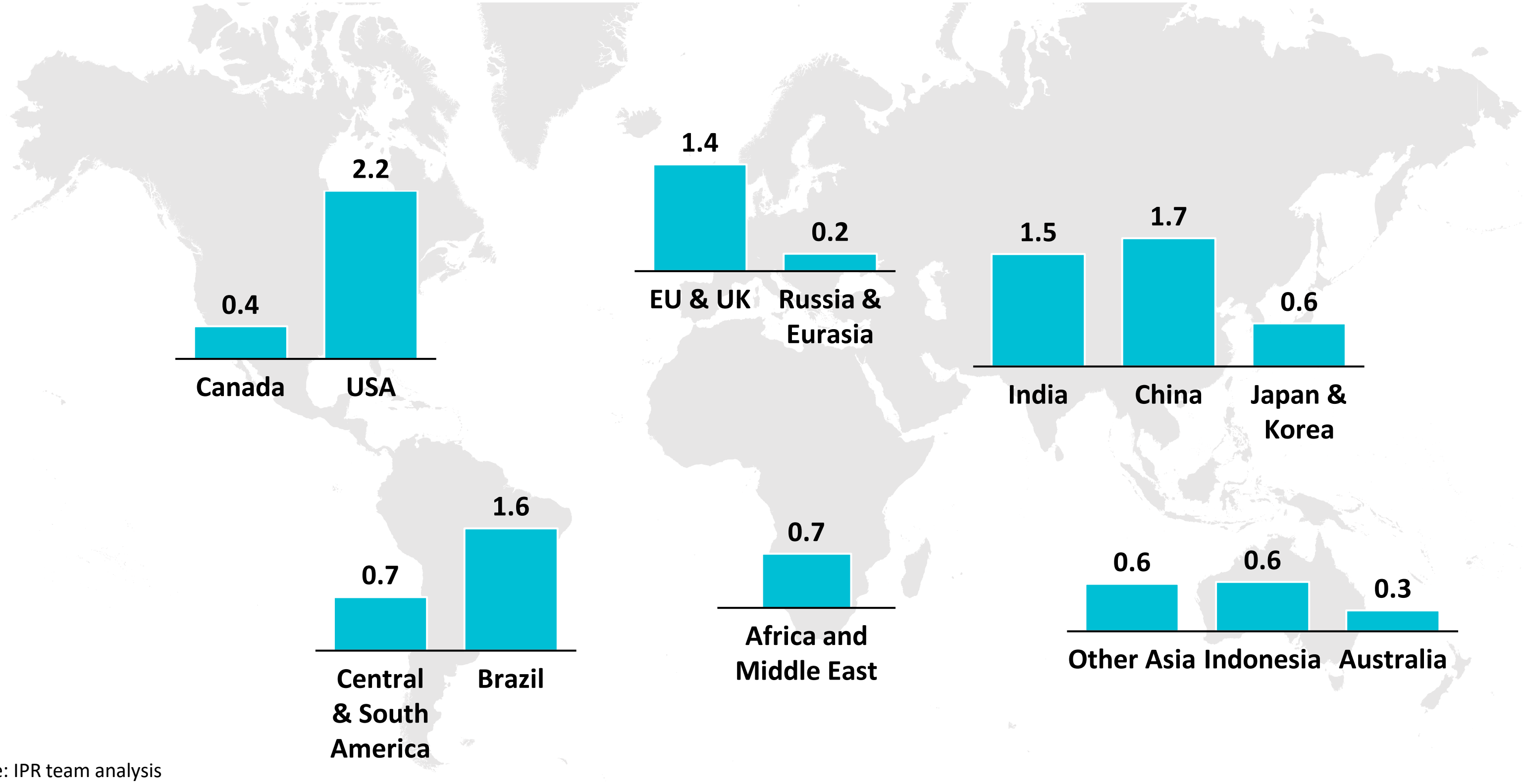
BECCS is used for carbon removals but also provides a source of baseload power

INEVITABLE POLICY RESPONSE

FORECAST: **POWER** – BECCS PLAYS A ROLE WHERE REMOVALS ARE VALUED BY POLICYMAKERS AND SUPPLY IS AVAILABLE

BECCS plays a role in baseload under particular policy conditions, particularly where removals are valued highly by policymakers

FPS23 bioenergy demanded for BECCS power generation in 2050, EJ



Source: IPR team analysis

Note: For comparison, power sector demand in IEA scenarios is 13.4 EJ (STEPS), 21.5 EJ (APS), and 21.5 EJ (STEPS), but note that these estimates also include "other renewables" such as waste, geothermal, CSP, and marine power. Source: IEA, 2022, WEO.

In FPS 2023, all bioenergy use in power is BECCS by 2050. Unabated bioenergy cannot compete with renewable, baseload, or dispatchable generation

BECCS is an expensive technology so is used where there are the strongest incentives for removals and where supply is readily available

INEVITABLE POLICY RESPONSE

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INEVITABLE POLICY RESPONSE

CURRENT BIOENERGY USE IS NOT CONSISTENT WITH A LONG RUN EFFICIENT, SUSTAINABLE USE OF BIOMASS IN THE CONTEXT OF LAND SCARCITY

	Modern bioenergy demand, 2020 (EJ)	**Land impact of dedicated feedstock**	**Alternatives in energy system**
Transport	5	Transport currently uses liquid biofuels from 1st generation sugar and oil crops which compete with food production and are drivers of deforestation and GHG emissions	Biofuels are used in the current fleet of internal combustion engines. Because the fleet is already being replaced by electric vehicles their use declines over time
Buildings	5	Buildings, industry and power generally use solid bioenergy such as wood pellets. If not from residues, then this solid bioenergy often has adverse land-use and biodiversity impacts. In extreme cases, the bioenergy is produced by cutting down native forests. Biogas, usually from waste, can also be used as a direct replacement for natural gas	Heat pumps have become the cheapest, greenest and most efficient low-carbon option
Industry	12		CCS is the cheapest option in hard to decarbonize end-uses and the use of electricity and H_2 is increasing
Power	13		Renewables are now the cheapest source of green power generation. Gas CCS turbines are emerging as the most viable solution to provide flexibility

INEVITABLE POLICY RESPONSE

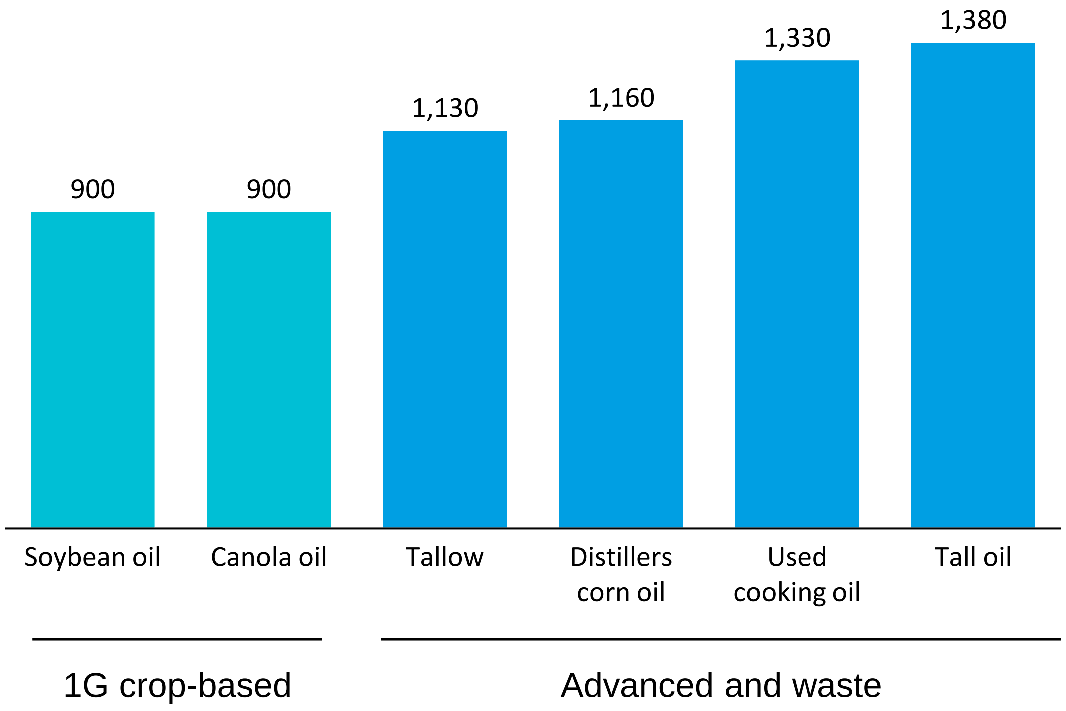
POLICY IS INCREASINGLY REFLECTING THE PRESSURE BIOENERGY CAN PUT ON LAND SYSTEMS

The EU and Australia cap the use of unsustainable feedstocks

- The EU's Revised Renewable Energy Directive (RED II) sets a **maximum** share for biofuels from **1G crops** but a **minimum** share for **waste and advanced biofuels**
- In addition, biofuels from **1G crops** are **not allowed in aviation** and biofuels from **palm oil** are **banned** in the EU
- In Australia, **native forest biomass is no longer eligible** as under the national Renewable Energy Target, and electricity it generates cannot be used to create tradeable Large-scale Generation Certificates

The US subsidizes more sustainable feedstocks more heavily

Incentive value (post-IRA)[1], $ / t



Source: European Commission; Commonwealth of Australia; USDA; NARA; Expert interviews; LCFS certified pathways

1. Post-IRA scenario assumes Clean Fuel Production Credit for SAF (up to $550 / t adjusted by CI) rather than BTC ($306 / t)

INEVITABLE POLICY RESPONSE

THE ENERGY SYSTEM TRANSITION IN FPS23 MAKES USE OF ALTERNATIVE DECARBONIZATION OPTIONS SUCH AS ELECTRIFICATION

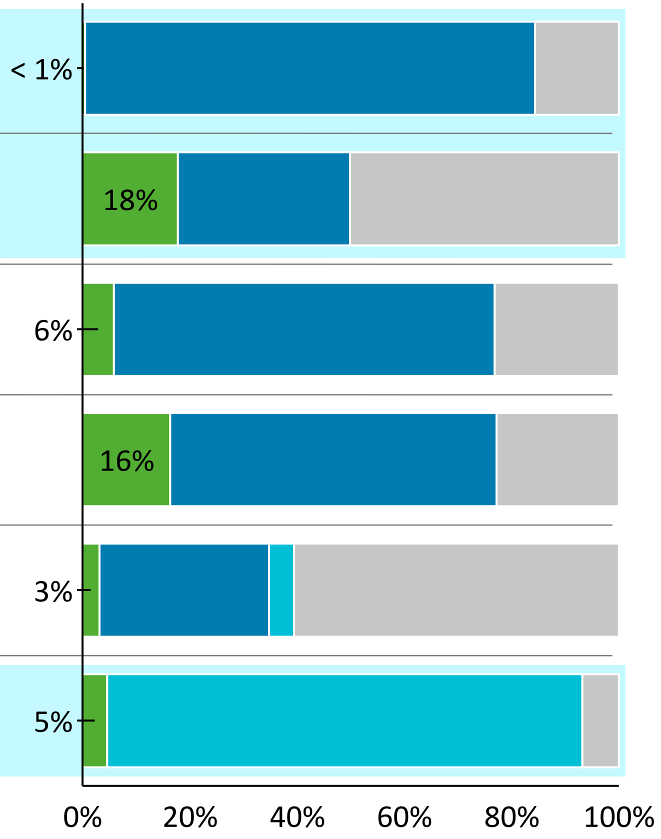
A detailed analysis of energy system decarbonization is available in the energy report

Deep dive to follow | Bioenergy | Electricity or Hydrogen | Other low carbon | Unabated fossil fuel

SELECTED END USES, NON-EXHAUSTIVE

Sector	End use	Likely technological and policy development
Transport	Road	BEVs (and possibly FCEVs) are the cheapest decarbonization options, even for heavy trucks. Countries with ambitious blending policies continue to support biofuels but probably not beyond 2050
	Aviation & Shipping	Hydrogen based fuels (synfuels or ammonia) become the preferred option in the long-term but are not yet widely available. Bioenergy has a role to play because it can be used from today, especially in aviation
Buildings	Space heating[1]	Almost all modern bioenergy used in buildings (excluding traditional biomass) is wood pellets which will likely be replaced by heat pumps. Renewable natural gas could play a minor role
Industry	Low T process heating	Electrification is the greenest and cheapest option in most low temperature heating processes. Biomass continues to competitive in the pulp and paper, and sugar, industries which use cheap self-supplied residues (e.g., bark)
	High T process heating	Hydrogen and CCS are usually the greenest options (CCS in cement to capture process emissions). CCS could be combined with bioenergy if there is a strong incentive for removals. Iron and steel will likely switch to scrap and H2DRI EAF
Power	Power generation	Bioenergy likely only makes sense if it is combined with CCS: BECCS. Without an incentive for carbon removals, it probably cannot compete with intermittent renewables or with dispatchable technologies such as Gas CCS

% of energy demand by fuel in 2050

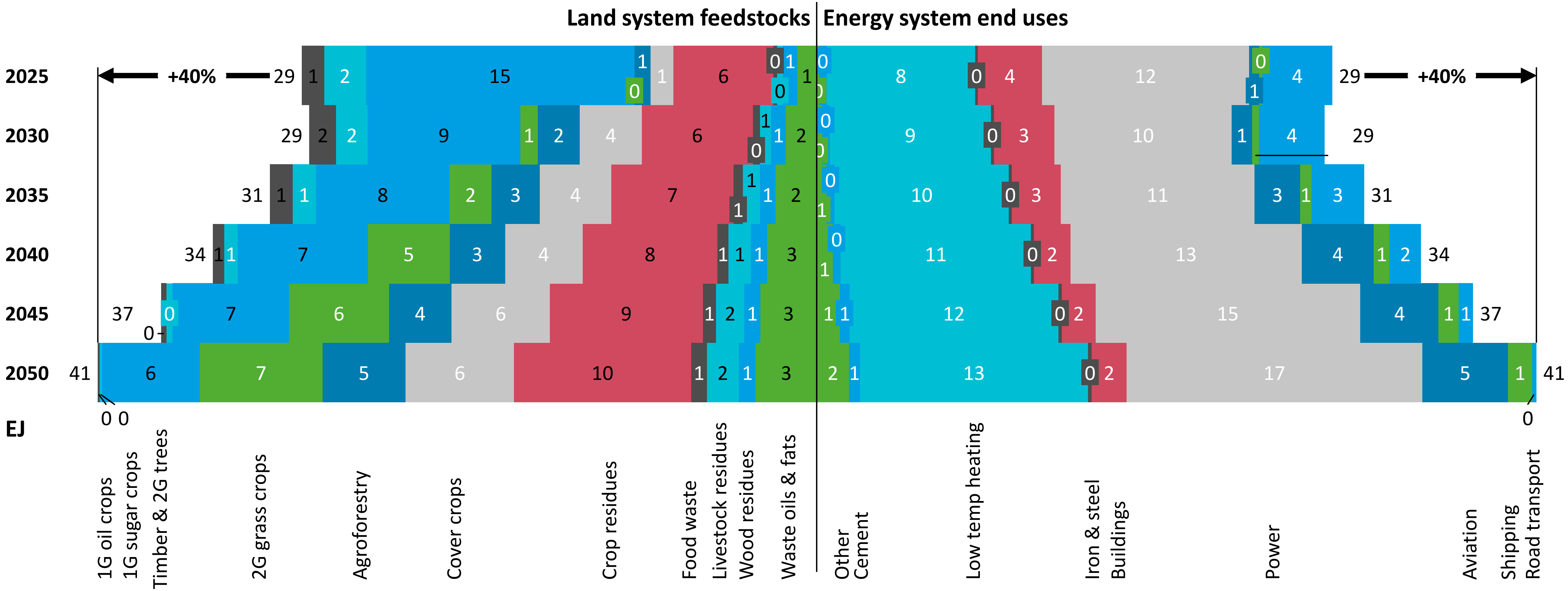


1. Converted to thermal output to account for the increased efficiency of heat pumps compared to other technologies

INEVITABLE POLICY RESPONSE

SUPPLY: DEMAND FOR MODERN BIOMASS INCREASES ONLY MODESTLY THROUGH 2050

Power, aviation, and low temperature heating require additional biomass by 2050

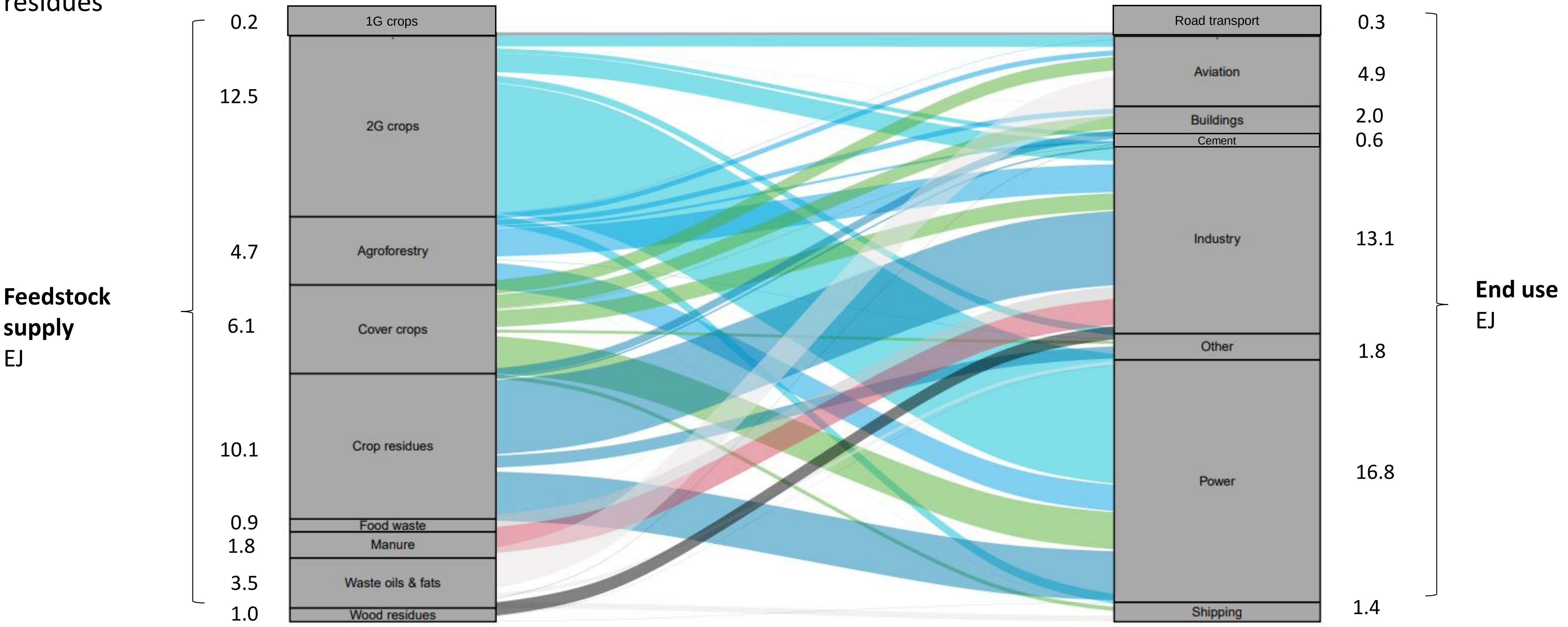


Note: To develop this trajectory, regional supply of feedstocks was matched with regional demand; most regions can use regionally produced low carbon cost feedstocks to meet regional demand for bioenergy; a few notable exceptions include Brazil importing from other Central & South American countries and the EU importing from Eastern Europe & non-EU European countries. On this chart, the power sector demand includes demand from energy transformation that does not use CCS (~4.3 EJ in 2050). This trajectory is integrated into both the energy and land systems modeling. The demand for dedicated land for bioenergy crops is applied as a constraint in the land system modeling.

INEVITABLE POLICY RESPONSE

SUPPLY: BY 2050 FEEDSTOCKS SHIFTS DECIDEDLY TOWARD NON-EDIBLE CROPS AND WASTES

By 2050, bioenergy feedstocks shift away from edible crops toward non-edible crops and wastes, including agricultural residues



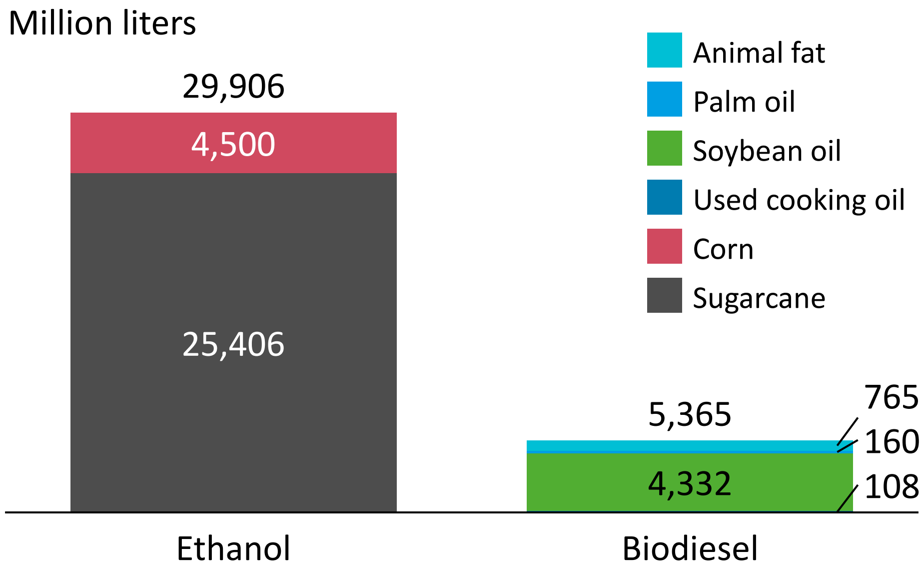
Note: Industry is mainly low-temperature heating with a small contribution (1.6%) from iron & steel. Waste oils and fats include tall oil, used cooking oil, palm oil mill effluent, and animal fats/tallow. 2G crops include both tree & grassy crop types. 1G crops include both oil crops and sugar crops. Agroforestry crops & cover crops likewise can include both oily or lignocellulosic crops.

INEVITABLE POLICY RESPONSE

CASE STUDY - BRAZIL: THE TRANSITION AWAY FROM 1G CROPS TO LOW CARBON COST FEEDSTOCKS REQUIRES TRADE AND INFRASTRUCTURE UPGRADES

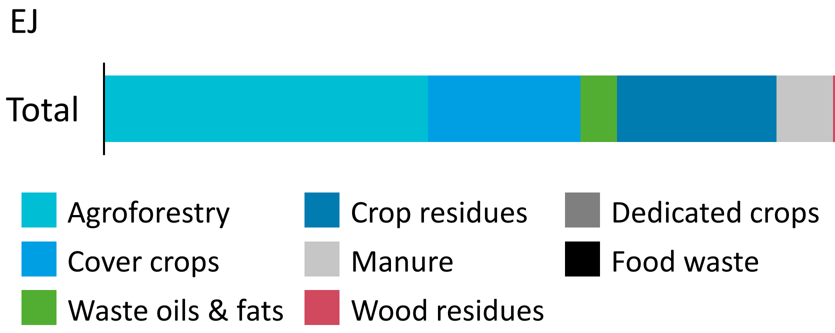
- Today, Brazil's liquid biofuel sector is dominated by 1G crops (sugarcane, corn, soy, and palm), requiring around 30 Mha of land. Additional land is required to produce solid biofuels for power
- However, much of this land used today does not satisfy potential future criteria for sustainable production

Current liquid biofuel production



- By 2050, Brazil satisfies its 4 EJ of annual bioenergy demand using low carbon cost feedstocks produced.
- This transition requires investments to modify existing plants to process 2G feedstocks to avoid stranding assets
- It also requires a shift in the location of feedstocks toward more sustainable land (e.g. with lower carbon payback period
- This means a shift from dedicated crops to those connected to agroforestry, cover crops and agricultural waste

Brazil sustainable feedstock mix in 2050

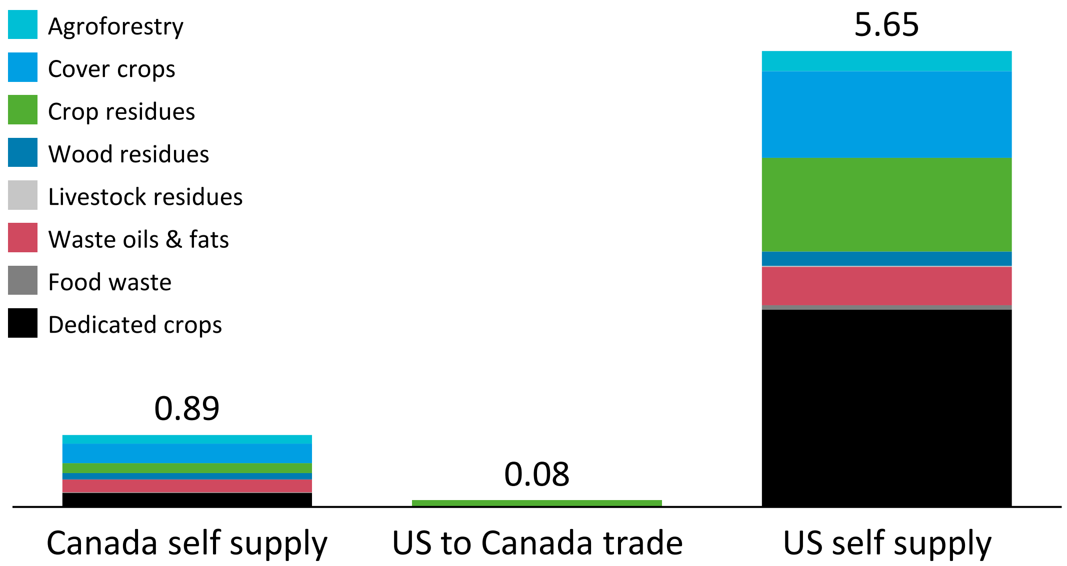


1. Area that meets the sustainability guardrails for no nature displacement, no deforestation, no food competition, and no irrigation.
2. Source: Global Power Plant Database. Map indicates locations of power plants that use biomass feedstocks and is non-exhaustive for infrastructure associated with the bioenergy industry (e.g., biofuel refineries).

INEVITABLE POLICY RESPONSE

CASE STUDY – CANADA & NORTHERN US: JOBS AND EXPORT OPPORTUNITIES

Low carbon cost feedstock use in 2050, EJ



Bioenergy crops suitable for this region[3]:

- Camelina – Oil crop used for biodiesel and SAF
- Switchgrass – Grassy crop used for power or cellulosic ethanol
- Willow – Fast-growing tree used for power or cellulosic ethanol

- Canada and the US, respectively, account for 2.3% (0.97 EJ) and 13.9% (5.65 EJ) of global bioenergy demand in 2050
- In Canada, dedicated area that meets the sustainability guardrails is relatively small (c.3.5 Mha)
- Imports from the US can be limited to < 10% of the Canadian bioenergy basket if the entire 0.2 EJ available from dedicated crops can be used to meet domestic bioenergy demand
- Saskatchewan and neighboring Alberta together account for 9% of North American onshore CCS capacity, and limited transport would be needed between fields & biomass plants
- Mining & petroleum account for 26% of GDP in Saskatchewan; growth in bioenergy provides an opportunity for employment transition within the energy sector
- In the US, only 35% of the available bioenergy supply from dedicated cropland is required to meet domestic bioenergy demand, and excess supply suggests export opportunities for the US

1. Area that meets the sustainability guardrails for no nature displacement, no deforestation, no food competition, and no irrigation.
2. Source: Global Power Plant Database. Map indicates locations of power plants that use biomass feedstocks and is non-exhaustive for infrastructure associated with the bioenergy industry (e.g., biofuel refineries).
3. Not exhaustive.

INEVITABLE POLICY RESPONSE

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INEVITABLE POLICY RESPONSE

METHODS OVERVIEW – PAGE 1/2

Derivation of the bioenergy trajectory

Feedstock supply

- The feasible supply of energy – by region and over time – from biomass feedstocks including wastes, residues, and energy crops that are integrated into existing agricultural systems are modeled by applying growth rates to estimates of present-day availability.
- The feasible supply of energy from the remaining category of bioenergy feedstocks – energy crops that are grown on dedicated land – is constrained by filtering the global land surface to include only those areas that pass four sustainability safeguards of: no deforestation, no biodiversity loss, no competition with food, and no irrigation. 567 Mha of land meets these four safeguards.
- The dedicated land available for bioenergy crops is further subset according to the carbon payback period of the land; that is, using geospatially explicit estimates of carbon accumulation rates from natural forest regrowth, we estimate the number of years that a parcel of land would need to grow bioenergy crops (and apply CCS) in order for the net CO_2 removal to be equivalent to that which would occur from re/afforestation of that parcel of land.

Bioenergy demand

- End uses in the energy sector were divided into those for which CCS can reasonably be applied (power & cement) and those for which CCS is not applicable (road transport, aviation, shipping, and buildings).
- For those end uses for which CCS is not applicable, the cost of bioenergy was compared with the cost for the next best available alternative to estimate future demand. Except for aviation, bioenergy is more expensive than the next best alternative, indicating that bioenergy is a transition fuel.
- Sensitivity runs with an energy system model were performed to determine demand for BECCS in the power & cement sectors. The amount of CO_2 removal per unit of energy production in the modeling varies by process and feedstock, but a rough approximation is 1 $GtCO_2$ per 10 EJ. The carbon payback period of land was translated into an opportunity cost for BECCS plants, such that BECCS uptake is limited by costs in both the energy & land systems.

METHODS OVERVIEW – PAGE 2/2

Bioenergy trajectory

- The supply & demand outlooks were combined with the policy landscape to derive the FPS23 trajectory.
- Most regions are able to use regionally produced low carbon cost feedstocks to meet regional demand for bioenergy; a few notable exceptions include Brazil importing from other Central & South American countries and the EU importing from Eastern Europe & non-EU European countries.
- This trajectory is integrated into both the energy and land systems modeling. The demand for dedicated land for bioenergy crops is applied as a constraint in the land system modeling.

INEVITABLE POLICY RESPONSE

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INEVITABLE POLICY RESPONSE

BIOENERGY PRODUCTION FROM DEDICATED CROPS INDUCES SUBSTANTIAL EMISSIONS AND LAND USE CHANGE

Conversion of natural ecosystems, such as primary tropical forest, has detrimental impacts to biodiversity

	Feedstock category[1]	Change in forest cover, Mha per EJ: Primary	Change in forest cover, Mha per EJ: Secondary	Deforestation emissions, $MtCO_2e$ per EJ	N_2O emissions, $MtCO_2e$ per EJ	CH_4 emissions, $MtCO_2e$ per EJ	Primary land-sector impact	
Residues & wastes	Crop residues				34		Fertilizer N_2O emissions	These waste streams are **low cost** and the most sustainable feedstocks available
	Livestock residues				-363	-525	Decreased CH_4, N_2O emissions	
	Food and industry waste[2]						No land cover change	
Dedicated non-edible crops & trees[3]	2G woody crops	-0.1	-0.7	200	202		Deforestation	2G crops are costly but may have a long-term role in some locations for some end uses
	2G grassy crops	0	-0.5	100	114		Deforestation, fertilizer N_2O emissions	
Dedicated edible crops	1G sugar crops (corn)	-4.5	-13.1	4900	16		Tropical deforestation	1G crops are extremely high cost – sustainable futures require limiting their long-term use
	1G oil crops (soy)	-1.4	-16.5	4300	15		Tropical deforestation, temperate peat degradation	

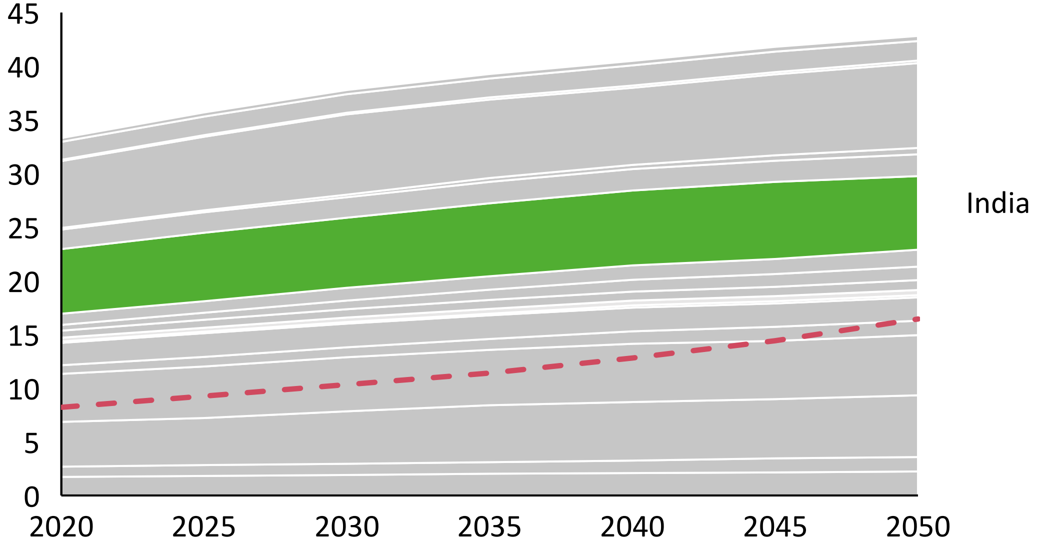
1. For all categories except food and industry waste, estimates of the impact of bioenergy feedstocks on the land system were derived using sensitivity simulations of the MAgPIE integrated assessment model, whereby bioenergy demand shocks (i.e., doubled demand, from 2025 onward) by individual feedstock were applied to a baseline scenario. Unless otherwise specified, all reported values are for 2050. Per-joule values for a specified year are estimated as the difference (shock minus baseline) in the variable of interest for that year at the specified geographic level divided by the global difference in bioenergy demand for that year. Since differences in land use area in 2050 between the shock and baseline simulations may have occurred in any year after or including 2025 (the first year of the shock), per-joule deforestation emissions for 2050 indicate the total deforestation emissions for the full period 2025-2050. In contrast, reported changes in agriculture-driven N2O emissions refer to differences between the shock and baseline scenario for 2050. For all variables, the quantified impacts are dependent on the underlying baseline scenario and modeling protocol and were derived from single representative simulations for each feedstock. Quantitative estimates should therefore be treated as indicative.
2. Includes food waste, wood residues, and waste oils and fats, such as tall oil, palm oil mill effluent (POME), used cooking oils (UCO), and animal fats/tallow.
3. Impact estimates refer to non-edible crops or trees that require dedicated land, as opposed to non-edible crops that are integrated into existing agricultural systems, such as through cover cropping or agroforestry.

INEVITABLE POLICY RESPONSE

AGRICULTURAL RESIDUES: CROP RESIDUES PROVIDE THE DOMINANT SOURCE OF POTENTIAL BIOENERGY FEEDSTOCK

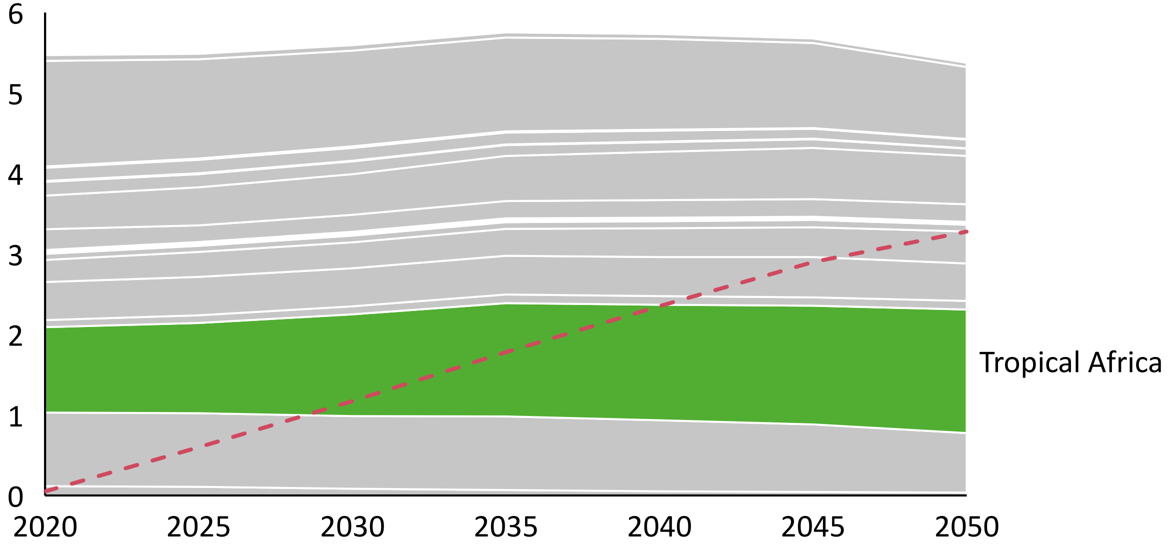
Feasible

Crop residues, EJ per year



- Increasing crop production increases availability of residues
- Crop residues provide an important source of soil organic matter, meaning only a fraction of the residues can be sustainably recovered
- Current residue use is primarily for livestock bedding and feed
- India has a high potential for crop residues but around 20% of residues are currently burned

Manure, EJ per year



- Manure production stays relatively constant, with rising population and consumption in developing regions counteracting declines in developed regions, with the largest potential in Tropical Africa
- Currently manure primarily provides fertilization to pasture and is collected for cropland fertilizer
- Biogas from manure needs scale to be commercially viable

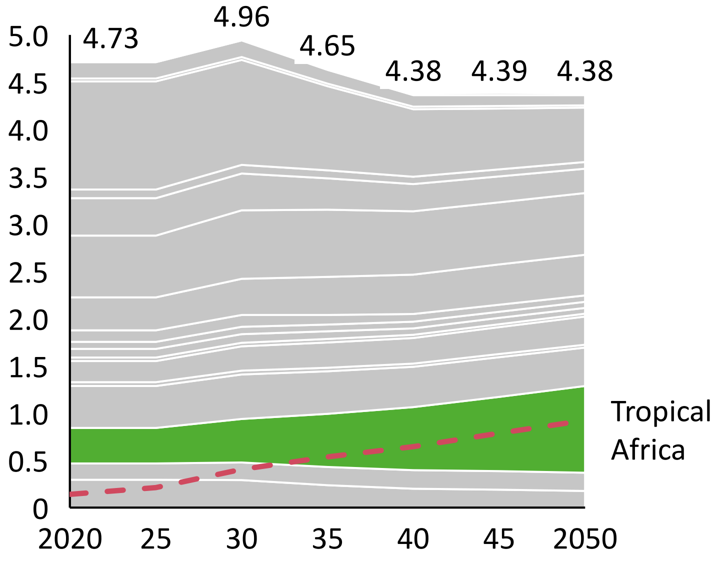
Source: Bhuvaneshwari et al. (2019), US EPA

INEVITABLE POLICY RESPONSE

FOOD AND INDUSTRY WASTE: FOOD WASTES ARE LOW EMISSIONS COST BUT HAVE VERY LIMITED AVAILABILITY

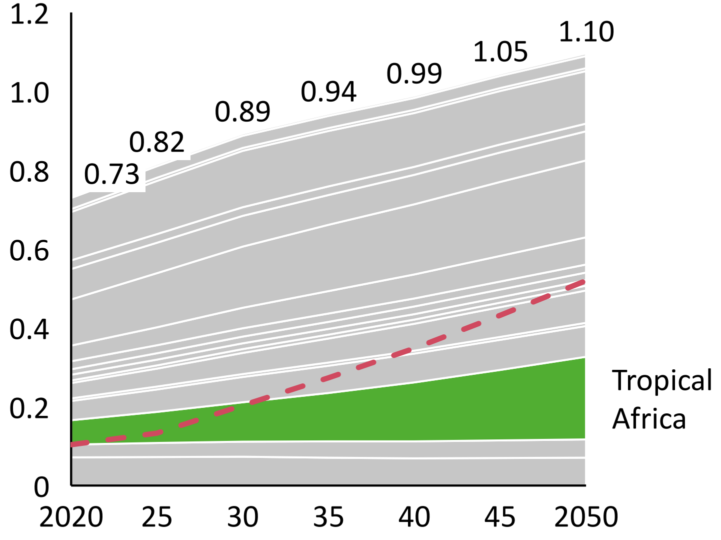
Feasible

Household food waste, EJ per year



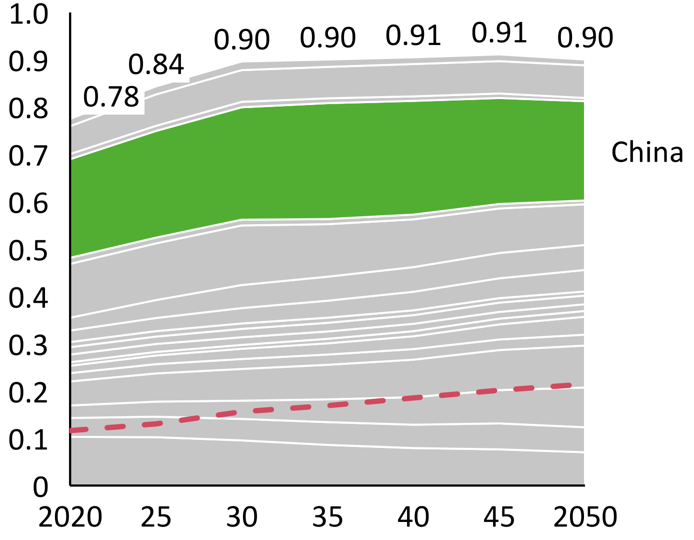
- Actions to reduce consumer food waste in the FPS scenario reduce the availability of feedstock despite a rising population
- Rising population and incomes in Tropical Africa drives increases food waste and available feedstock

Used cooking oil, EJ per year



- Rising oil consumption across regions increases availability of feedstock by ~50% by 2050
- Tropical Africa has highest potential growth due to increasing income and its influence on diet preferences

Animal fat, EJ per year



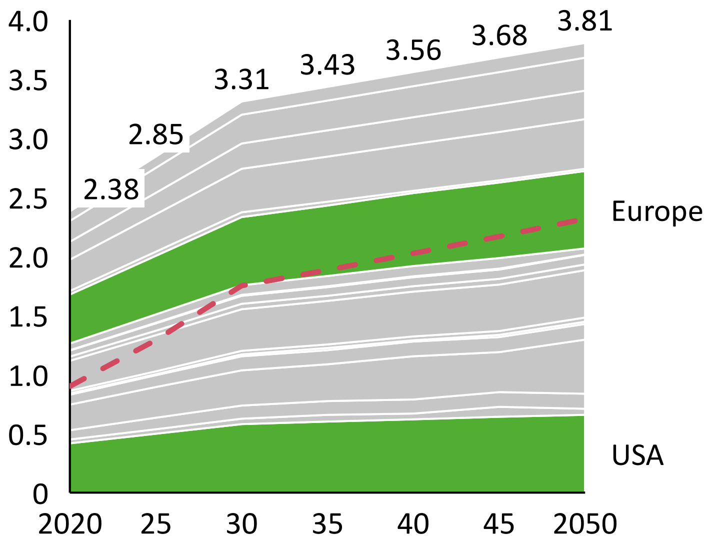
- Falling per capita meat consumption curtails feedstock growth, with rising population keeping availability roughly constant
- Existing uses, for example pet feed and cosmetics, are expected to compete with demand for biofuels, primarily from sustainable aviation fuel

INEVITABLE POLICY RESPONSE

FOOD AND INDUSTRY WASTE: THE PALM OIL AND FORESTRY INDUSTRIES REPRESENT THE LARGEST POTENTIAL SOURCES OF INDUSTRY WASTE

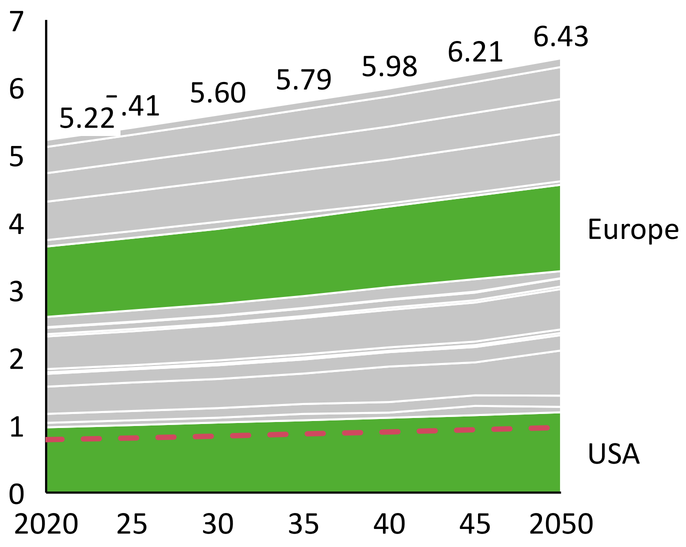
Feasible

Crude tall oil, EJ per year



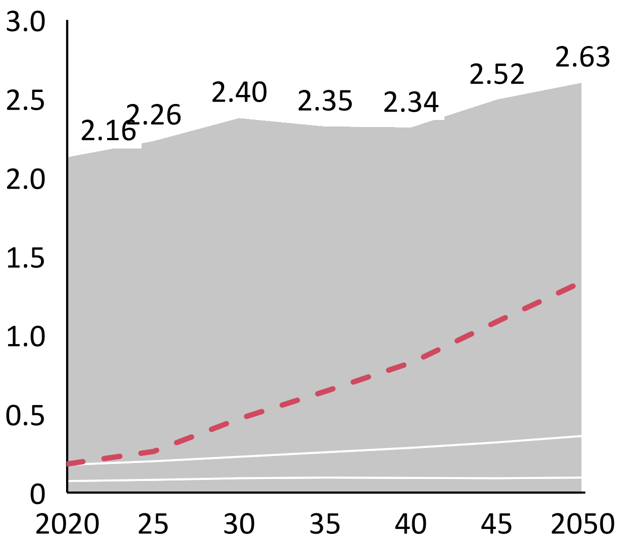
- Existing recovery and market for tall oil products are expanded in this scenario due to strong demand for end use products
- Major pulp producing regions are the US and Europe, with the largest processing capacity for tall oil

Wood residue, EJ per year



- Rising demand for timber increases availability of wood residues
- Wood residue recovery percentages and residue based products, for example particleboards, inhibit the share of residues that can be used for bioenergy

Palm oil mill effluent (POME), EJ per year



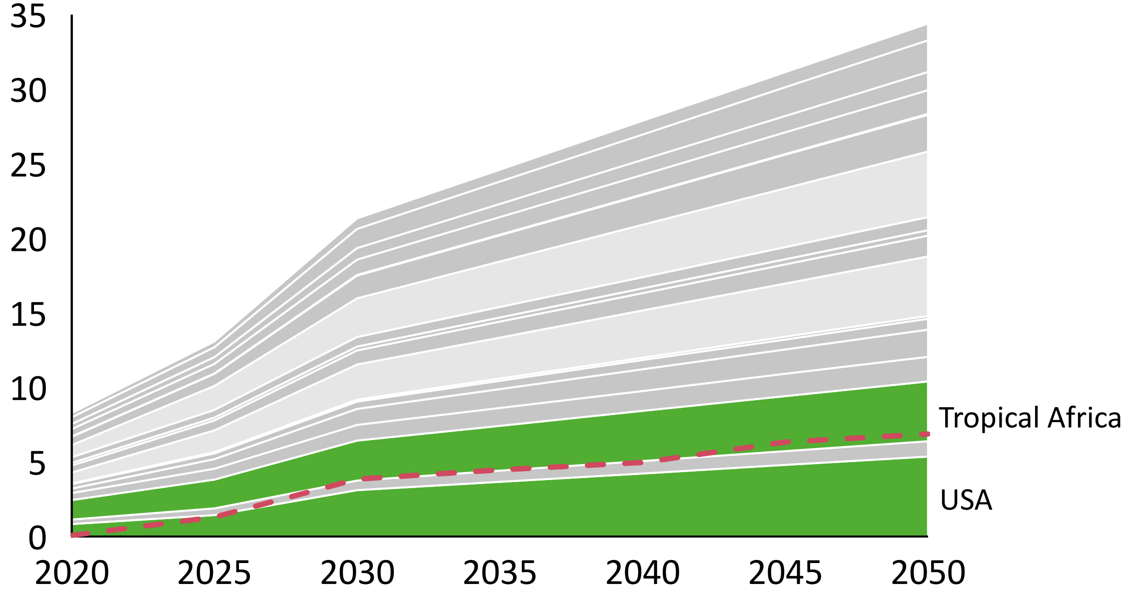
- Oil palm production increases ~21% in FPS by 2050
- POME is a major source of soil and water pollution in producing regions, converting waste from processing to biofuel could reduce the environmental impact

Source: Osman et al. (2020)

INEVITABLE POLICY RESPONSE

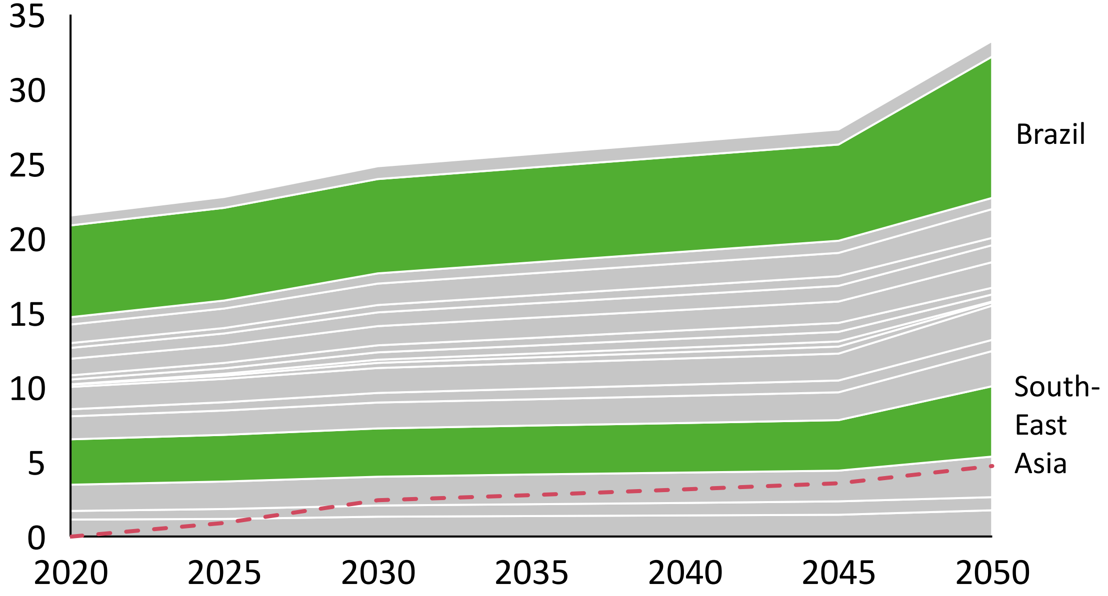
COVER CROPPING AND AGROFORESTRY: BIOMASS FROM THESE SOURCES IS LOW EMISSIONS COST, BUT HAS LIMITED AVAILABILITY

Cover crops, EJ per year



- Adoption of cover-cropping increases five-fold in FPS in part driven by policies that encourage **conservation agriculture practices**
- Bioenergy crops such as pennycress are expected to play an increasing role as a cover crop of choice as biomass markets become more mature and reach more farmers

Agroforestry and silvopasture, EJ per year



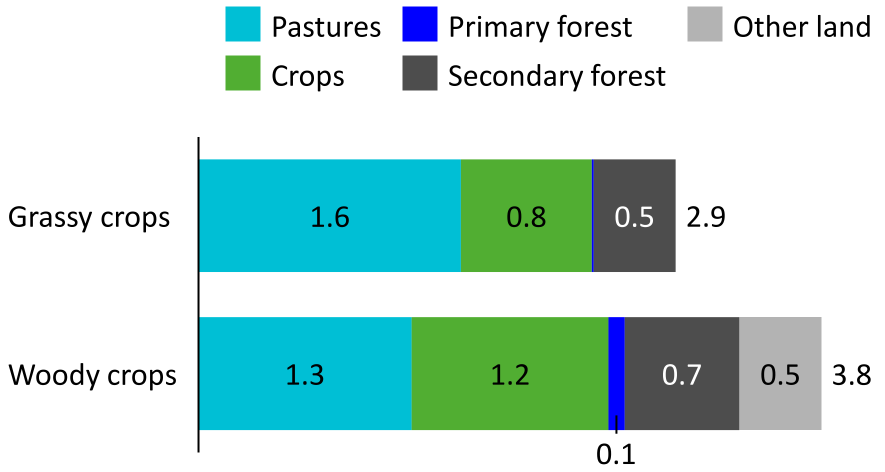
- Tree intercropping is expected to increase by more than 50% in the next thirty years encouraged by policy incentivizing improved nature outcomes and **increasing carbon sequestration** on agricultural land

INEVITABLE POLICY RESPONSE

NON-EDIBLE 2G CROPS: HAVE LIMITED IMPACT ON GLOBAL FOREST COVER

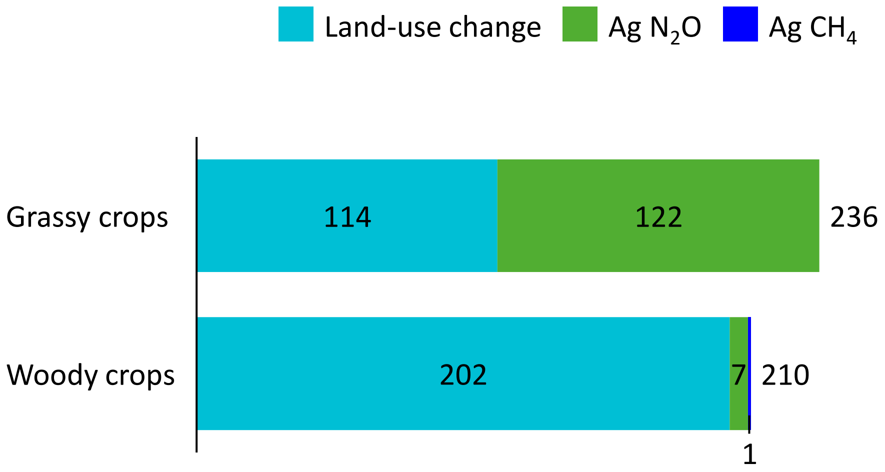
Compared to dedicated woody bioenergy crops, grassy bioenergy crops induce stronger N_2O emissions from fertilizer requirements

Area displaced[1] per additional unit of bioenergy demand from dedicated 2G crops, Mha per EJ



- Each additional EJ of bioenergy demand requires 3.0 Mha of land for grassy crops or 3.8 Mha for woody crops due to the higher yields of grasses
- The additional area largely displaces existing pasture and crop area globally
- Woody crops drive slightly higher deforestation than do grassy crops

Greenhouse gas emissions[1] per additional unit of bioenergy demand from indicated 2G dedicated feedstock category, $MtCO_2e$ per EJ



- Grassy crops have lower land-use change emissions per EJ of additional demand due to lower impacts on forest cover
- However, the additional fertilizer requirements of grassy crops induce higher N_2O emissions than for woody crops, contributing to the slightly stronger impact on cumulative GHG emissions

Example 2G feedstocks[2]

Grassy crops

Cellulosic cover crops
- Miscanthus
- Switchgrass
- Reed grass

Oil cover crops
- Camelina
- Pennycress

Woody crops

Oil trees
- Jatropha
- Pongamia

1. Quantitative estimates should be treated as indicative. See Section 2 for details about method and data uncertainties.
2. Dedicated non-edible bioenergy crops are represented in MAgPIE by two generic categories: grassy and woody crops.

INEVITABLE POLICY RESPONSE

1G SUGAR CROPS: GROWING CORN FOR ETHANOL DRIVES TROPICAL DEFORESTATION

Additional demand for corn ethanol shifts crop cultivation patterns, leading to forest and biodiversity loss in the tropics

USA

Accounts for 56% of corn expansion area, largely replacing other crops, with limited impact on national forest cover

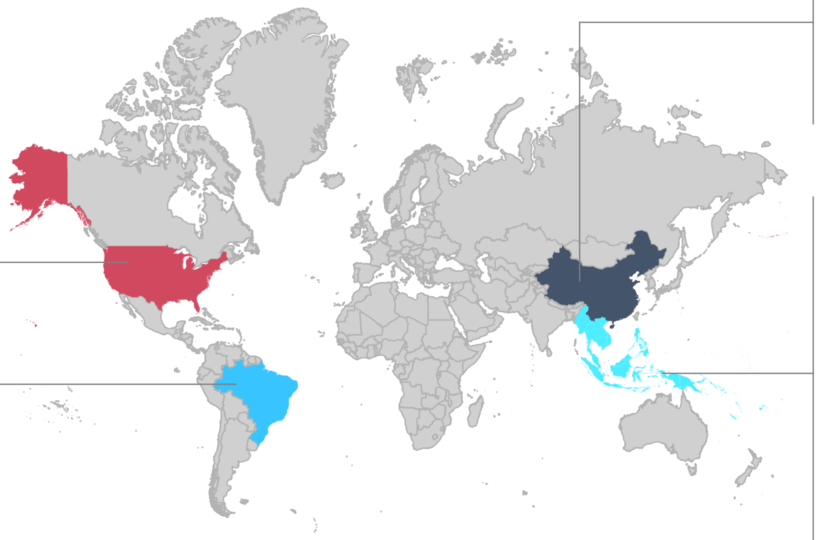
+19% ag-wide N_2O fertilizer emissions from doubling corn bioenergy demand (+11 $MtCO_2e$ per EJ)

Brazil

18% of global corn expansion area

12.4 Mha of deforestation per additional EJ of corn ethanol demand, 30% from primary forests

Deforestation emissions of 3,500 $MtCO_2e$ per EJ



China

16% of corn expansion area, largely replacing other crops

Limited impact on forests, with losses of 0.7 Mha per EJ

Southeast Asia

- 4% of global corn expansion area
- 1.2 Mha oil palm expansion per additional EJ of corn demand, as a replacement crop for food and feed
- 4.1 Mha per EJ forest loss, 95% of which is secondary forest

Estimate global impact of each additional EJ of corn ethanol demand[1]

21 Mha	Additional area of corn crops needed
18 Mha	Area deforested, mainly in the tropics
4,900 $MtCO_2e$	Deforestation emissions
16 $MtCO_2e$	N_2O emissions from additional fertilizer requirements

1. Quantitative estimates should be treated as indicative. See Section 2 for details about method and data uncertainties.

INEVITABLE POLICY RESPONSE

1G SUGAR CROPS: SIMILAR TO OTHER 1G FEEDSTOCKS, SUGARCANE DRIVES TROPICAL FOREST LOSS

Land-sector impacts from additional demand for sugarcane ethanol largely occur in sugarcane-producing regions

Tropical Latin America

10% of global sugarcane expansion area

1.2 Mha of primary forest loss per additional EJ of sugarcane ethanol demand, partially offset by secondary forest expansion of 1.1 Mha per EJ

Net deforestation emissions of 280 $MtCO_2e$ per EJ, which includes a partial offset from secondary forest regrowth of 230 $MtCO_2e$ per EJ

Brazil

Accounts for 90% of global sugarcane expansion area

10.6 Mha of deforestation per additional EJ of sugarcane ethanol, 35% from primary forests

Deforestation emissions of 3,200 $MtCO_2e$ per EJ

Limited increase in N_2O emissions from cropland fertilizer application: 5% increase from doubling global sugarcane ethanol demand

Estimated global impact of each additional EJ of sugarcane ethanol demand[1]

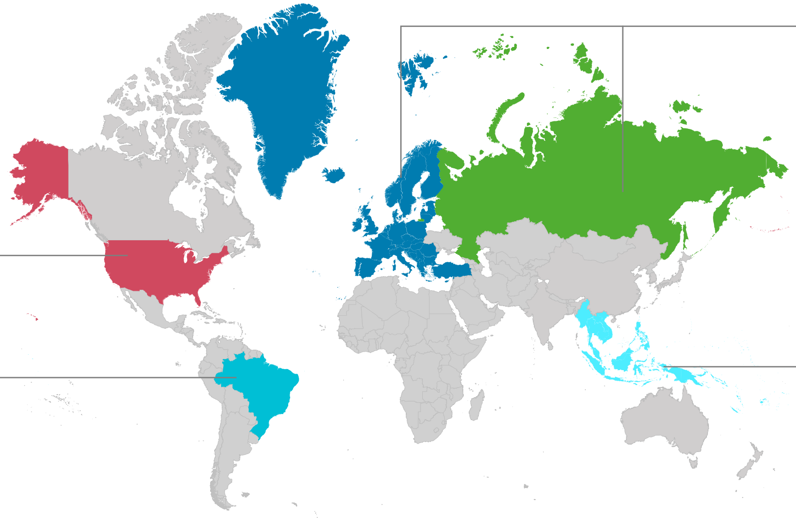
2 Mha	Additional area of sugarcane crops needed
4 Mha	Primary tropical forest loss, with impacts on biodiversity
1,600 $MtCO_2e$	Deforestation emissions
4 $MtCO_2e$	N_2O emissions from additional fertilizer requirements

1. Quantitative estimates should be treated as indicative. See Section 2 for details about method and data uncertainties.

INEVITABLE POLICY RESPONSE

1G OIL CROPS: USING SOYBEANS FOR BIOFUELS DRIVES HIGH LAND-USE CHANGE EMISSIONS

Additional demand for soybean oil for biofuels leads to tropical deforestation and temperate peat degradation



USA

Accounts for 18% of soybean expansion area, largely replacing other agricultural land, with limited impact on national forest cover

Brazil

70% of global soybean expansion area

16.5 Mha of deforestation per additional EJ of bioenergy demand from soy, largely secondary forests

Deforestation emissions of 3,700 $MtCO_2e$ per EJ

Europe and Russia

1.8 Mha per EJ of additional peat degradation, from shifting land-use changes

1.4 Mha in Europe due to degradation of intact peatland and 0.4 Mha in Russia due to avoided restoration

Southeast Asia

- <1% of global soybean expansion area
- 2.9 Mha oil palm expansion per additional EJ of bioenergy demand from soybeans, as a replacement crop for food and feed
- 3.9 Mha per EJ forest loss, mainly secondary forest

Estimated global impact of each additional EJ of soybean oil demand[1]

22 Mha	Additional area of soybean crops needed
18 Mha	Area deforested, mainly in the tropics
4,300 $MtCO_2e$	Deforestation emissions
15 $MtCO_2e$	N_2O emissions from additional fertilizer requirements

1. Quantitative estimates should be treated as indicative. See Section 2 for details about method and data uncertainties.

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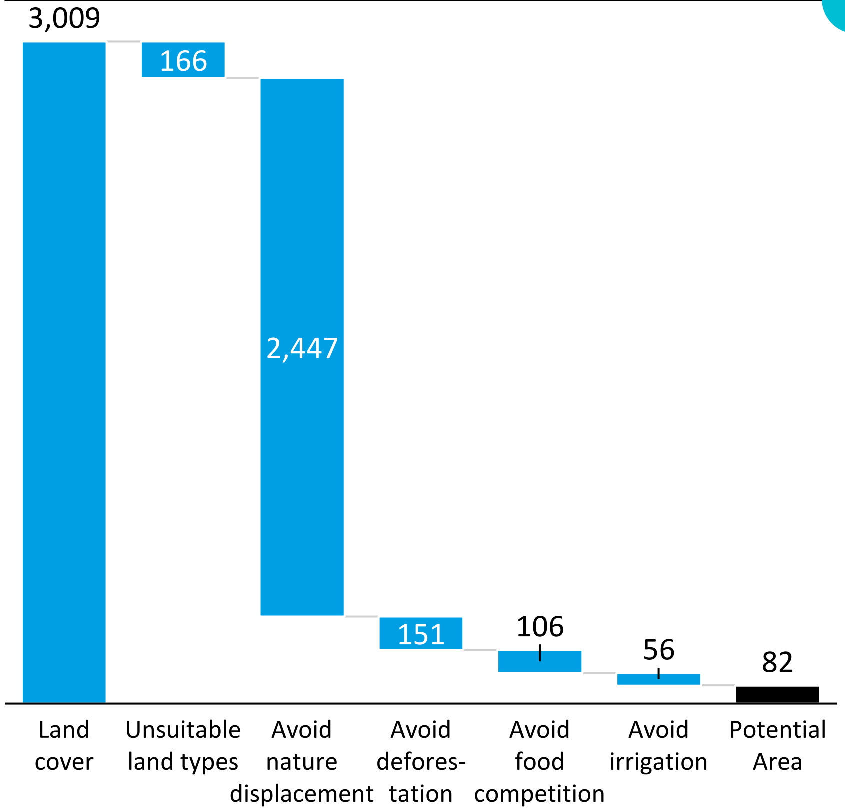
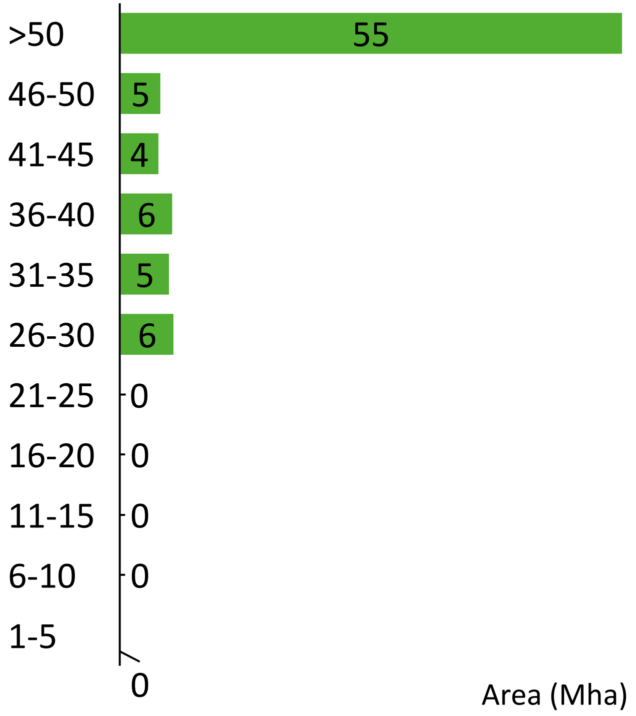
INEVITABLE POLICY RESPONSE

TROPICAL BIOME: FORESTS ARE A MUCH MORE EFFICIENT STORE OF CARBON THAN BIOMASS FOR THE VAST MAJORITY OF TROPICAL LAND

Potential area for dedicated biomass crops after applying sustainability guardrails, Mha



CPP for potential area assuming 2G yields, years



Example – planting of Populus varieties in India

Studies show an average annual yield of **9.9 t/ha** for Populus in India, which is higher than the global average yield for the crop

If 2G Populus is not commercially viable, or study yields do not scale, a 1G crop like maize with annual yields of **3.2 t/ha** might be used instead, **increasing the median payback period by 67%**

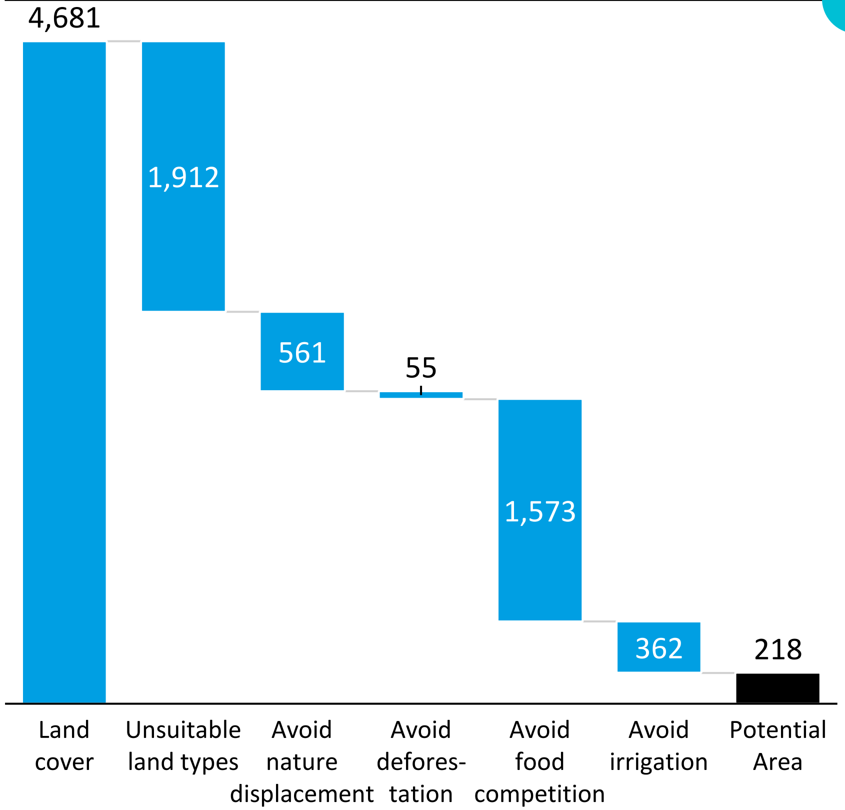
Note: Land categories may be overlapping, for example protected land is likely to be high carbon and biodiverse. The order of the land categories considered corresponds to the sequence of deductions for potential bioenergy land and therefore do not correspond to the total land area within each category. Unsuitable land refers to land area that cannot be used for crop production

Source: Gibbs et al. 2008, Li et al. (2018)

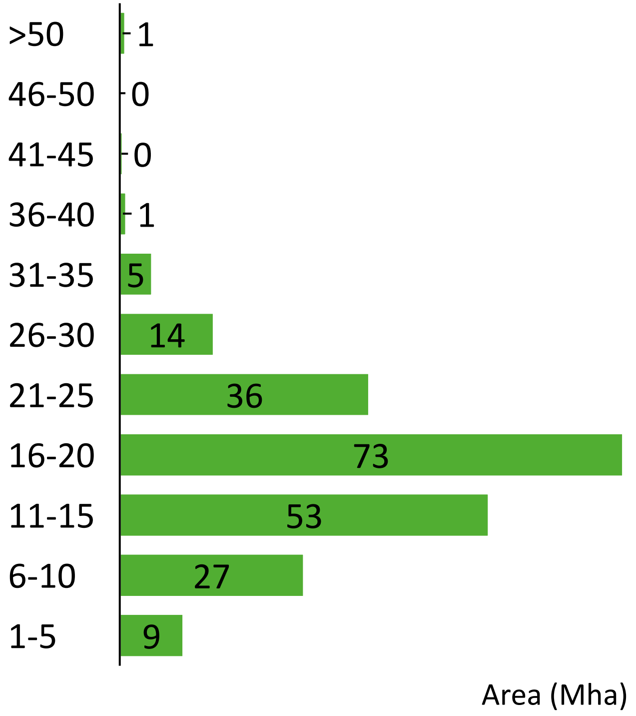
INEVITABLE POLICY RESPONSE

ARID BIOME: 218 MHA ARE FEASIBLE FOR BIOENERGY PRODUCTION WITH A RELATIVELY LOW PAYBACK PERIOD

Potential area for dedicated biomass crops after applying sustainability guardrails, Mha



CPP for potential area assuming 2G yields, years



Example – planting of eucalyptus varieties in South Africa

Studies show an average annual yield of **16.9 t/ha** for eucalyptus in South Africa, a higher yield compared even to other 2G bioenergy crops

If 2G eucalyptus is not commercially viable, or study yields do not scale, a 1G crop like maize with annual yields of **5.4 t/ha** might be used instead, **increasing the median payback period by 10 years**

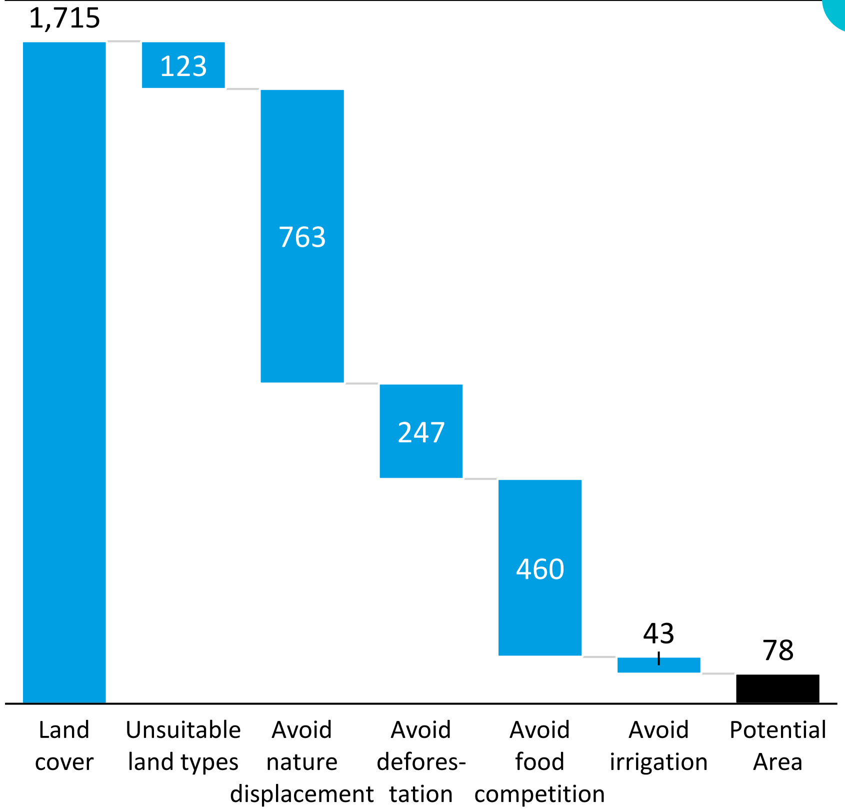
Note: Land categories may be overlapping, for example protected land is likely to be high carbon and biodiverse. The order of the land categories considered corresponds to the sequence of deductions for potential bioenergy land and therefore do not correspond to the total land area within each category. Unsuitable land refers to land area that can not be used for crop production

Source: Gibbs et al. 2008, Li et al. (2018)

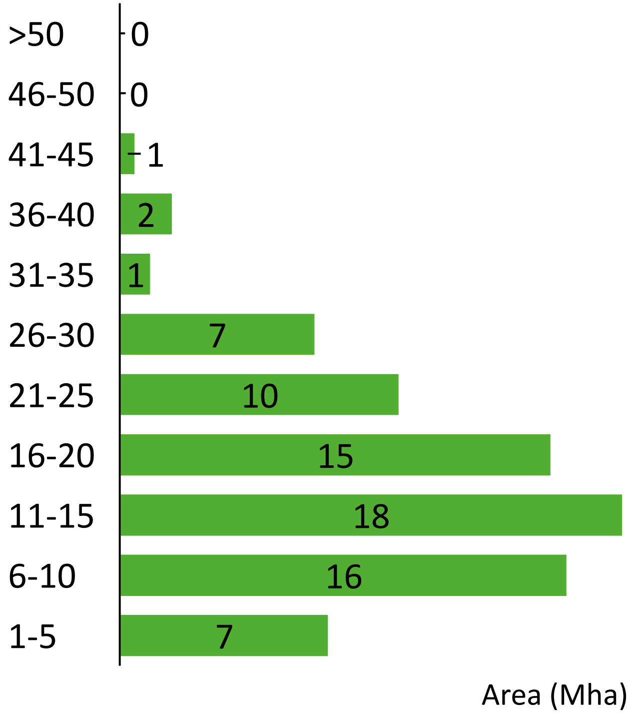
INEVITABLE POLICY RESPONSE

TEMPERATE BIOME: 78 MHA ARE FEASIBLE FOR BIOENERGY PRODUCTION

Potential area for dedicated biomass crops after applying sustainability guardrails, Mha



CPP for potential area assuming 2G yields, years



Example – planting of miscanthus varieties in Germany

Studies show an average annual yield of **11.62 t/ha** for miscanthus in Germany (neighbor France is shown), a yield close to that of some edible crops

If 2G miscanthus is not commercially viable, or study yields do not scale, a 1G crop like maize with annual yields of **10.4 t/ha** might be used instead, **increasing the median payback period by 5 years**

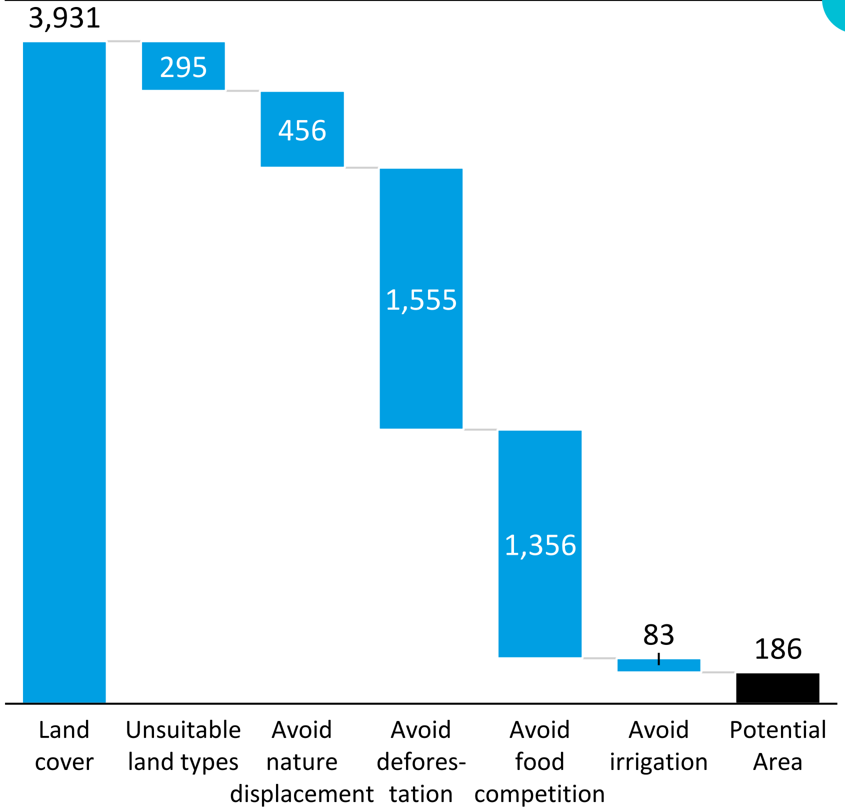
Note: Land categories may be overlapping, for example protected land is likely to be high carbon and biodiverse. The order of the land categories considered corresponds to the sequence of deductions for potential bioenergy land and therefore do not correspond to the total land area within each category. Unsuitable land refers to land area that can not be used for crop production

Source: Gibbs et al. 2008, Li et al. (2018)

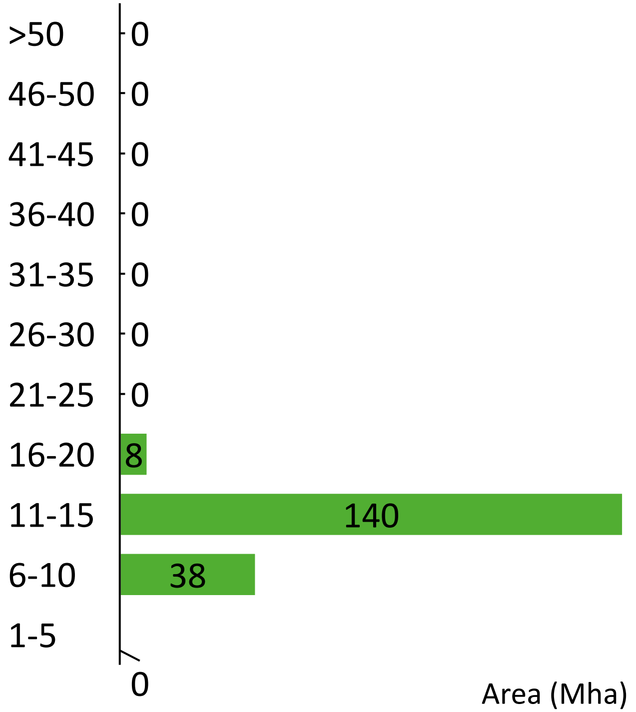
INEVITABLE POLICY RESPONSE

COLD BIOME: 186 MHA ARE FEASIBLE FOR BIOENERGY PRODUCTION WITH A RELATIVELY LOW PAYBACK PERIOD

Potential area for dedicated biomass crops after applying sustainability guardrails, Mha



CPP for potential area assuming 2G yields, years



Example – planting of Willow varieties in Canada

Studies show an average annual yield of **11.62 t/ha** for Willow in Canada, a yield close to that of some edible crops

If 2G Willow is not commercially viable, or study yields do not scale, a 1G crop like maize with annual yields of **10 t/ha** might be used instead, with little change in the median pay back period

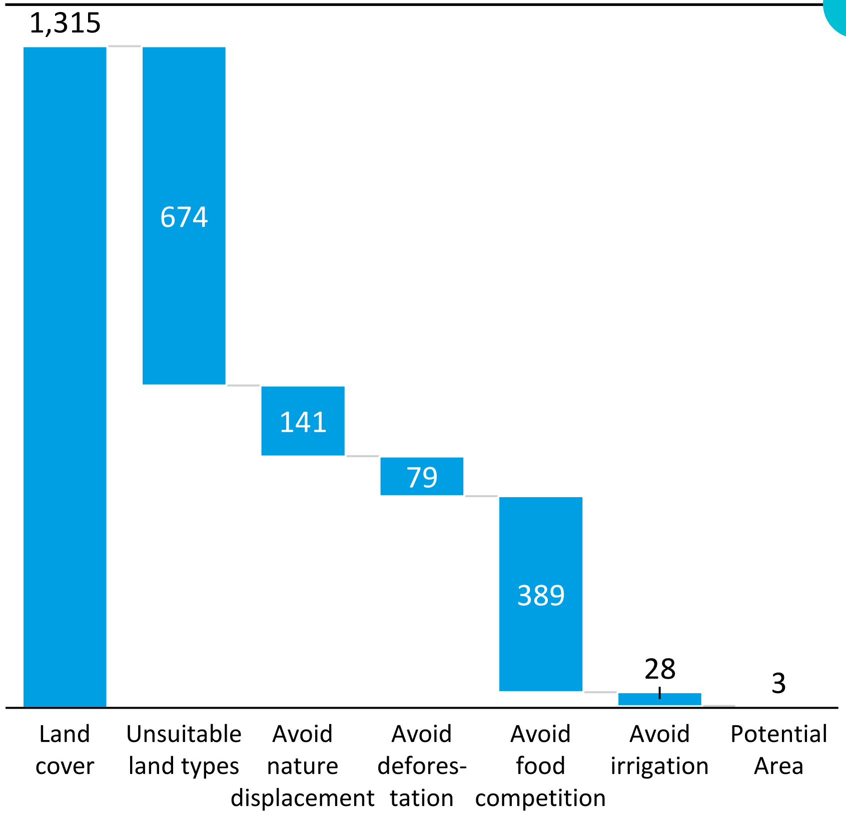
Note: Land categories may be overlapping, for example protected land is likely to be high carbon and biodiverse. The order of the land categories considered corresponds to the sequence of deductions for potential bioenergy land and therefore do not correspond to the total land area within each category. Unsuitable land refers to land area that can not be used for crop production

Source: Gibbs et al. 2008, Li et al. (2018)

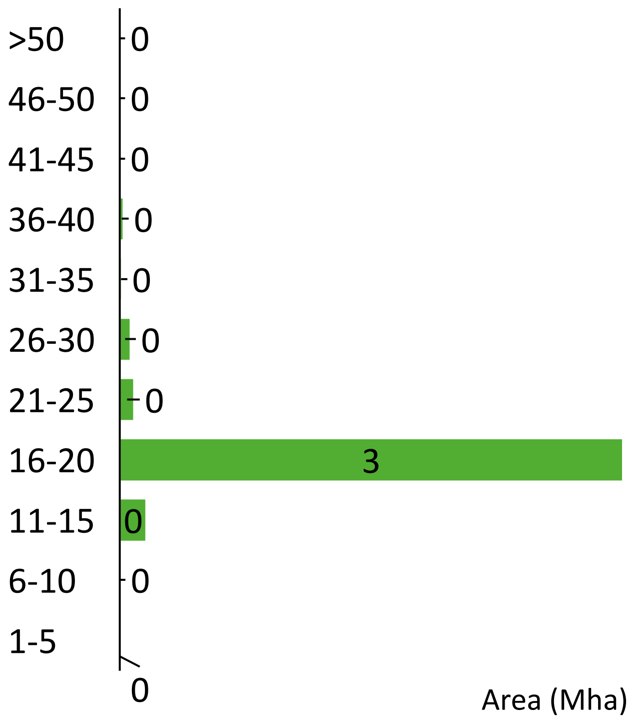
INEVITABLE POLICY RESPONSE

POLAR AND TUNDRA BIOME: 3 MHA ARE FEASIBLE FOR BIOENERGY PRODUCTION

Potential area for dedicated biomass crops after applying sustainability guardrails, Mha



CPP for potential area assuming 2G yields, years



Example – planting of prairie cordgrass varieties in polar regions

Studies on yields in polar and tundra regions are limited – cold biome results provide approximate yields. Tundra biomes shown are in the high Andes of Bolivia and Peru.

If 2G prairie cordgrass does not become commercially viable at scale, it is unlikely that there will be a suitable 1G alternative.

Note: Land categories may be overlapping, for example protected land is likely to be high carbon and biodiverse. The order of the land categories considered corresponds to the sequence of deductions for potential bioenergy land and therefore do not correspond to the total land area within each category. Unsuitable land refers to land area that can not be used for crop production

Source: Gibbs et al. 2008, Li et al. (2018)

INEVITABLE POLICY RESPONSE

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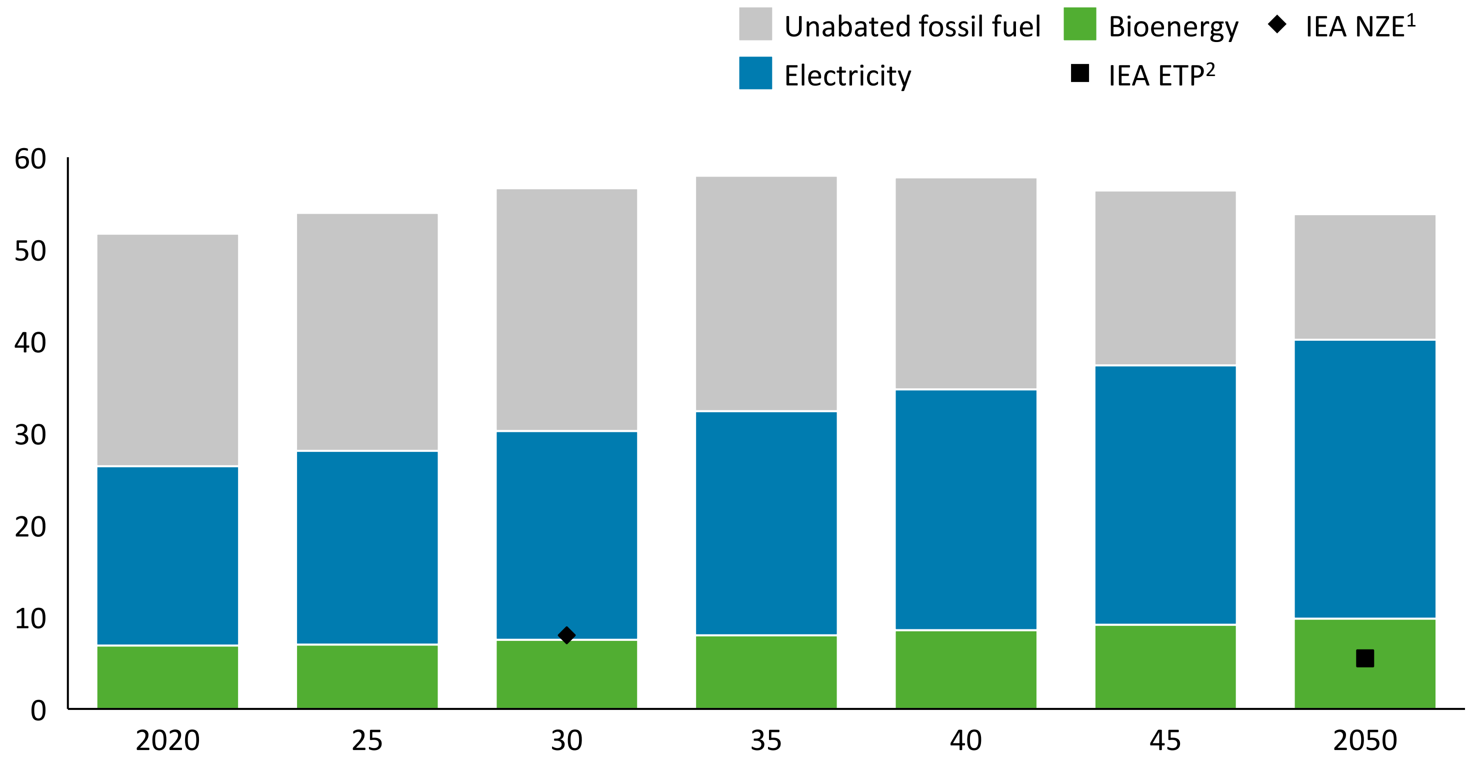
INEVITABLE POLICY RESPONSE

LOW TEMPERATURE HEATING – ELECTRIFICATION DOMINATES BUT BIOMASS USED IN PULP AND PAPER

FPS23 energy demand, EJ



1. Based on growth in pulp and paper bioenergy use. IEA, 2023, Pulp and paper; 2. IEA, 2017, Energy Technology Perspectives

Electrification is the cheapest low-carbon option for most low T processes

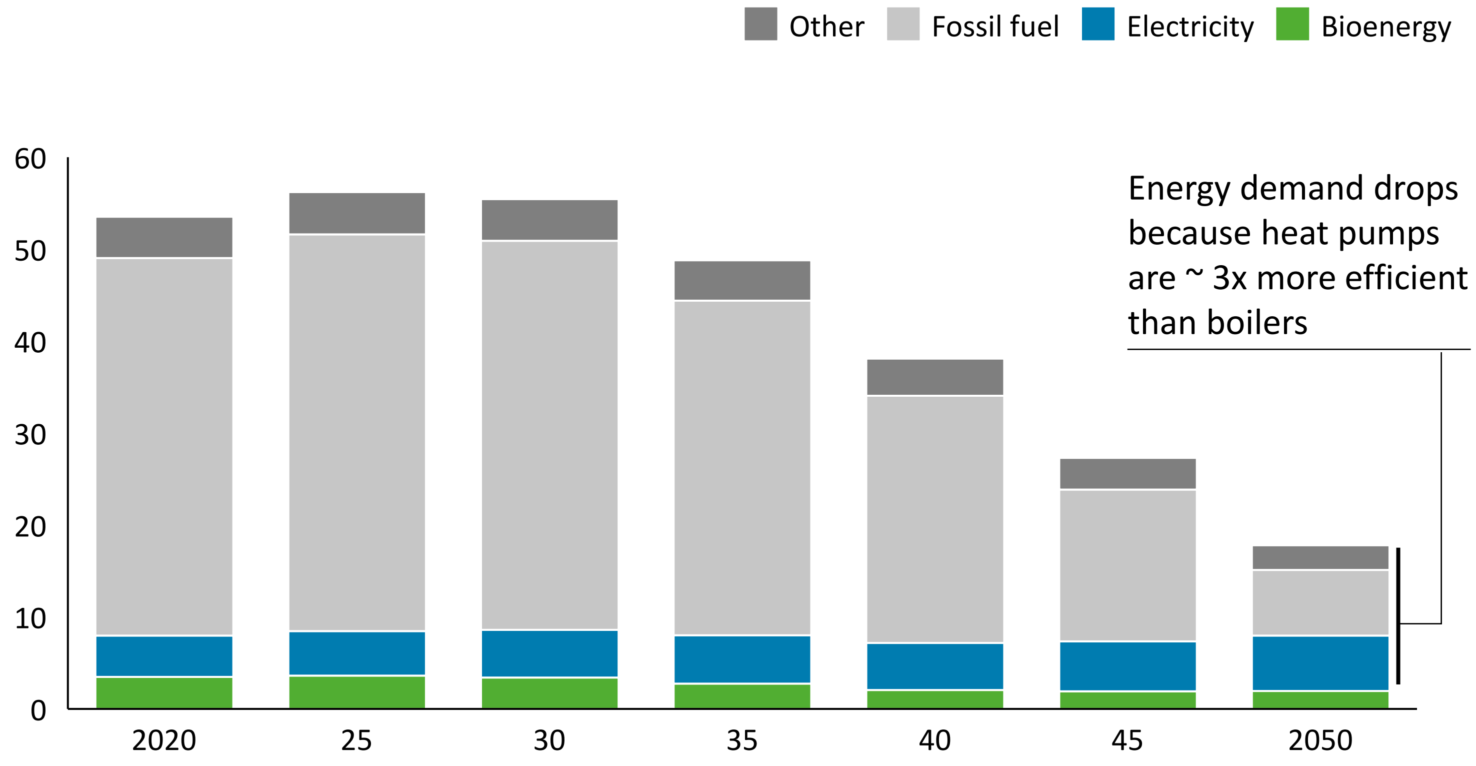
However, the pulp and paper, and sugar, industries use - and will likely continue to use - residues from industrial processes for heating (e.g. bark)

These should not place additional pressure on the land system so continue to be used in FPS23

INEVITABLE POLICY RESPONSE

SPACE HEATING – BIOENERGY SWITCHES TO RNG AND DEMAND DECLINES AS HEAT PUMPS BECOME CHEAP

FPS23 energy demand, EJ (excludes traditional biomass)



1. IEA, 2023, An introduction to biogas and biomethane
2. IRENA, 2022, Bioenergy for the energy transition

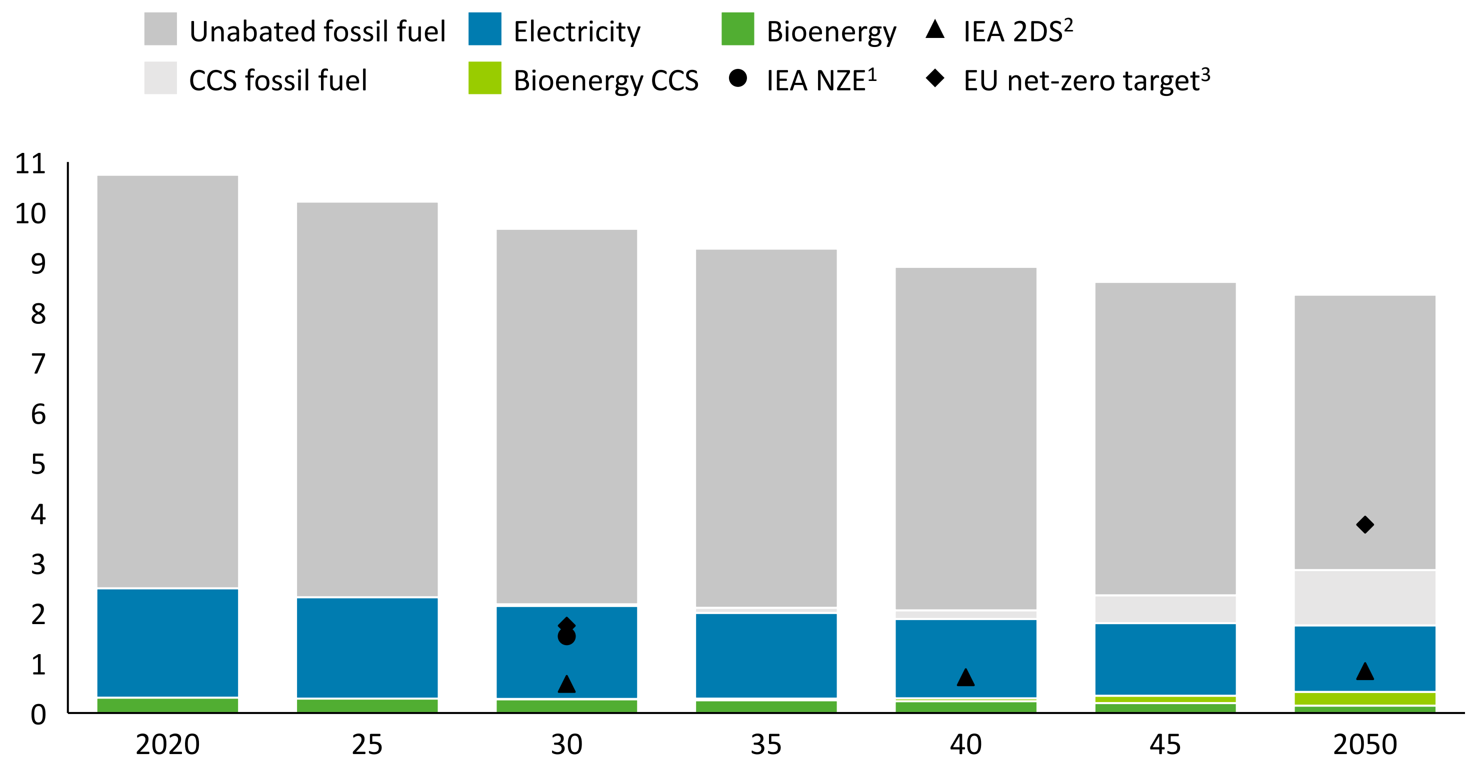
90% of modern bioenergy use in buildings (excluding traditional biomass) is wood pellets[1]. Europe accounts for more than 75% of global pellet demand, a lot of which is imported from NA[2]

In FPS23, regions which currently use pellets electrify, which is the cheapest low-carbon option. Biomass remains a small part of the mix, but as renewable natural gas (RNG) not pellets

INEVITABLE POLICY RESPONSE

CEMENT – DECARBONIZATION IS SLOW AND STARTS WITH CCS WHILE BECCS COMES IN FROM 2040

FPS23 energy demand, EJ



In FPS23, cement is slow to decarbonize due to lower policy ambition. The first choice for decarbonization is CCS which also captures process emissions

Plants currently using bioenergy increasingly switch to BECCS to take advantage of incentives for carbon removals

1. IEA, 2023, Cement; 2. IEA, 2018, Low-Carbon Transition in the Cement Industry; 3. Cembureau, 2020. Cementing the European Green Deal

Disclaimer

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