Biomass to energy

Developing sustainable carbon circularity

Looking at advanced applications and business models

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Biomass to energy - Developing sustainable carbon circularity

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Their review does not imply that they endorse this FactBook or agree with any specific statements herein.

About the FactBook: Biomass to energy - Developing sustainable carbon circularity
This FactBook seeks to provide an overview of biomass related technologies, emerging applications, and new business models, covering the entire value chain and analyzing the environmental benefits and economics of this space along with key insights.

About the Kearney Energy Transition Institute
The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Bioenergy, or biomass-to-energy, remains the main contributor to the renewable energy mix (1/2)

Bioenergy role in energy transition

(Introduction: pages 13–31)

Biomass has played a predominant role in the energy mix and provides multiple decarbonization solutions

Biomass refers to any organic matter, from vegetal or animal origin (including waste), which can be used to produce energy. It is the first and largest renewable energy source used by mankind (about **68% of global renewable energy demand** in 2017).

Biomass (for example, wood) has been used for heating and cooking for centuries. It corresponds to **“traditional” bioenergy**, where the biomass is directly combusted, generally for heating or cooking purposes. Biomass is also used to produce **“advanced” bioenergy**, where it is converted into bioproducts (for example, bioethanol, biogas) through modern conversion methods.

In principle, use of bioenergy would be carbon neutral if there were no emissions from its industrial value chain. Bioenergy could theoretically **decarbonize sectors representing about 50% of global GHG emissions**. Biomass can be used directly in transports and buildings or used to generate heat and power. It can also be used in the industrial sector, either to cover its energy needs or as a feedstock in various industrial processes.

Advanced bioenergy solutions emerged in the ’90s and has been followed by the emergence of a different generation of biofuels relying on different feedstocks

In the 90s, the so-called **first generation** of bioenergy emerged, using mostly food crops (for example, sugarcane) as a feedstock to process the molecular transformation into liquid and gaseous bioenergies at industrial scale. Although these first-gen bioenergy solutions benefited from carbon emissions reduction, using the natural carbon cycle, these solutions suffer from the competition with the food value chain. A **second then third generation** of bioenergy emerged, using non-food-competing sources—such as wood and forestry residues, crops and agricultural residues, algae and human and animal waste—as feedstocks.

This heterogeneity is also visible in the chemical composition of biomass. Indeed, biomass from vegetal origin is mainly composed from lignin and cellulose, whereas biomass from animal origin combines proteins, lipids, and carbohydrates.

Source: Kearney Energy Transition Institute

Bioenergy, or biomass-to-energy, remains the main contributor to the renewable energy mix (2/2)

Bioenergy role in energy transition

(Introduction: pages 13–31)

Executive summary (1/8)

Bioenergy development faces three main challenges: sustainability constraints, value chain complexity, and maturity of technologies

From a sustainability perspective, bioenergy production can be carbon neutral and even negative when combined with CCS. However, bioenergy use also comes with sustainability concerns, notably regarding possible **competition with food production**, but also to potential land-use change or to high resource requirements for feedstock cultivation. Bioenergy solutions rely on **complex value chains**, characterized by multiple feedstocks and energy transformation pathways with **emerging technology applications**.

Advanced bioenergy development decelerated in the late 2000s. But between 2018 and 2040, **bioenergy contribution is expected to stay steady at about 10% of the world energy mix**, with an average annual growth rate of +2.5% per year for advanced biomass demand (vs. 1% per year world energy demand). This latency actually hides an increase in the share of advanced bioenergy solutions (+500 Mtoe) vs. traditional use of biomass (-75 Mtoe), showing that the biomass-to-bioenergy value chain has an increasing role to play in energy transition.

The sustainable fraction of the feedstocks could fuel up to 25% of the total energy demand by 2060. It represents enough energy to cover the needs of the transport sector. Identifying the optimal transformation pathways and competitive applications and markets are the first priorities of these technology solutions.

This factbook aims to assess biomass-to-energy value chain attractiveness (vs. fossil and renewable alternatives) and its ability to contribute to climate change mitigation.

Source: Kearney Energy Transition Institute

The goal is to find optimal pathways from feedstock to biofuels

Biomass to bioenergy conversion pathways

(Section 1: pages 32–68)

Executive summary (2/8)

Advanced bioenergy solutions rely on six main categories of feedstocks and complex value chains

Six main feedstock types potentially provide carbon emissions reduction solutions not competing with the food value chain: **animal waste, agricultural residues, forestry residues, municipal solid waste, algae, and energy crops**. Their transformation into bioenergies generally occurs in three main steps: collection and conditioning, pretreatment, and conversion. Multiple options exist at each main step, making the bioenergy value chain an almost endless combination of processes and chemical transformation.

The biomass transformation process into bioenergy is composed of three main steps: conditioning, pretreatment, and conversion

When processed, biomass is refined through one or more sub-steps: **conditioning** which aims to reduce feedstock size and moisture content and increase its energy density, **pretreatment and conversion** which convert the carbon stored in the organic matter into a refined biofuel. Depending on the **feedstock qualities** (for example, high content in starch or oil) and **composition** (C,H,O,N ratio) some processing methods can be preferred and the intermediate (for example, syngas, pyrolysis oil) or final product (for example, alcohol, liquid hydrocarbon) created will differ. Overall, most conversion processes are specific to a biofuel while most feedstocks can be used for a given conversion process. **Optimizing the conversion pathway for a given biofuel is crucial to get the most of biomass supply.** Decisions may include several criteria: cost, energy efficiency, maturity, scalability, GHG emissions, energy consumption, and nature of the by-products.

For instance, analyses show that hydrothermal liquefaction and hydrothermal upgrading is the optimal way toward liquid hydrocarbons (renewable diesel, biogasoline, bio jet fuel), carbohydrates or syngas fermentation is the best way to produce alcohols (ethanol, methanol, butanol), and anaerobic digestion is the preferred route toward biogas and biomethane.

Source: Kearney Energy Transition Institute

In 2060, the overall sustainable potential of bioenergy could cover 15% to 30% of total energy demand

Biomass feedstock potential
(Section 1.1: pages 33–53)

Executive summary (3/8)

Feedstock potential can be regrouped in three stock types: theoretical, technical, and sustainable

This factbook scopes the following feedstocks: animal waste, agricultural residues, forestry residues, municipal solid waste, algae, and energy crops.

In total, one-third of the theoretical potential is sustainably exploitable in 2060.

Municipal solid waste and **animal waste** are revalorized as biomass feedstock but they are available in limited amount (each account for 5% of the global sustainable potential). For municipal solid waste, waste-to-energy pathways are attractive and policies are expected to make recycling more compelling in the long term. Animal waste scalability for bioenergy is limited because of pretreatment requirement, low collection rates, distributed supply, and popular alternative usage (for example, fertilizer).

Agricultural residues, as by-products of food crops, are various and abundant (one-third of the global sustainable potential) with low sustainability risks (except for GHG emissions).

Forestry residues supply is distributed and limited by collection issues and sustainable forest management requirements (for example, preserve local biodiversity). Only 15% of forestry theoretical potential is sustainable (highly dependent on local characteristics).

Algae are promising (best energy content in MJ/kg) but their conversion process is still immature and strict regulations are required to ensure sustainability.

Energy crops are specifically grown for bioenergy uses from non-edible crops but can have a detrimental impact on food supply by changing land allocation (about 40% of the global sustainable potential).

Agricultural residues and energy crops are expected to be the two major sources of sustainable biomass

They also have the **highest production-related GHG emissions** (after algae, cultivation of which is still energy- and nutrients-intensive). A sustainable feedstock must **not compete with other usage** to avoid additional pressure/depletion of resources (especially for feedstock competing directly with food chain) and **respect environmental constraints** (soil quality for animal waste, biodiversity for forestry, air quality for MSW, water use for algae). Identifying the optimal pathways in biomass-to-bioenergy value chains and sectors where biofuels applications are competitive vs. sustainable alternatives becomes the first-order priority to maximize bioenergy generated and optimize its usage.

Source: Kearney Energy Transition Institute

The feedstock and transformation pathways need to be optimized for the targeted biofuel

Biomass to bioenergy transformation process
(Section 1.2: pages 54-68)

Executive summary (4/8)

Modern biomass transformation processes were developed at the end on the 20th century

To be transformed, biomass is refined through one or more of these sub-steps: **conditioning** (aims to reduce feedstock size and increase its energy density) or **pretreatment and conversion** (to access and convert the carbon stored in the organic matter into refined biofuel suitable for use).

During pretreatment and conversion **biomass is decomposed into several building blocks** using mechanical, thermal, chemical, or biological reactions.

Processing technologies are various, from petroleum industry practices to natural processes

A lot of **processes** for **biomass come from the petroleum industry** and are adapted to this “new” carbon source (for example, Fischer-Tropsch, hydrocracking). On the other hand, **biological processes** are also important and inspired from natural processes of this resource (anaerobic digestion, fermentation).

Processing technologies can require energy input (gasification), produce energy (incineration), produce and consume energy (self sustained pyrolysis), or be autonomous (fermentation, anaerobic digestion).

The output depends on both the feedstock composition and the transformation pathway

Depending on the pretreatment technology used, the output can be an intermediate (in other words, input for conversion process, for example syngas, pyrolysis oil) or **a final product** (for example, biofuel) which can be further upgraded and refined in solid, liquid, or gaseous fuel later on.

Depending on **the feedstock properties and composition** (C,H,O,N ratio) the intermediate properties will vary (for example, high content of sugar/starch gives carbohydrates, high lipid fraction gives vegetable oil).

Most conversion **processes are specific to targeted biofuels** while most feedstock can be used for any conversion process.

Identifying the optimal feedstock and pathway for each biofuel is crucial for bioenergy penetration and relies on multiple criteria such as energy efficiency, GHG emission, energy consumption, nature of the by-products, cost, maturity, and scalability

Examples of optimal pathways—for **renewable diesel**: agricultural residues x hydrothermal liquefaction x hydrotreatment; for **biomethane**: animal waste or agricultural residues x anaerobic digestion

Source: Kearney Energy Transition Institute

Biomass is currently used in the heat and power and industry sectors, but the most promising future applications are for transport

Bioenergy market opportunities

(Section 2: pages 69–115)

Executive summary (5/8)

Current advanced bioenergy demand is concentrated in the heat and power and industry sectors

They each represent **34% of the advanced bioenergy demand**, followed by the buildings sector with 18% and the transport sector with 14%. The economic diagnosis performed in this factbook **revealed two types of market segments** for advanced biofuels, each with specific dynamics. The first ones are **“pivot markets”** where advanced biofuels are already established and characterized by a high contribution to bioenergy growth in absolute value but a low annual growth rate. The second ones are **“end-game markets”** where advanced biofuels should still be early stage by 2040 and characterized by a low contribution to bioenergy growth in absolute value but a high annual growth rate. Power and combined heat and power sectors (50% contribution and 4%/yr growth) as well as fuel for trucks (14% contribution with 6.5%/yr growth) appear to be “pivot markets,” whereas the aviation (6% contribution and 22%/yr growth) and shipping sectors (2% contribution and 12%/yr growth) are “end-game markets.”

Biomass-to-bioenergy value chain economic development relies on five interconnected drivers

The five drivers are often defined at country or even local scale, for instance the **feedstock supply** determines the energetic potential of the bioenergy (volume effect), shapes the biomass-to-bioenergy value chain (mix effect), and is a key driver for biofuel quality/cost competitiveness (price effect). The **infrastructure maturity** determines feasibility and risks associated with bioenergy projects, while **regulation** drives the biomass market supply and the bioenergy demand (volume and price effect), the **process economics** drive bioenergy cost competitiveness (price effect), and **substitutability** drives market positioning for biofuels and depends on the penetration of alternative renewable energies (for example, trucks, aviation, and shipping are the sectors where the uptake of alternative renewable solutions is forecasted to be the most limited).

The value chain assessment and determination of market opportunities led to the study of several business models in detail

- Municipal solid waste x sorting x incineration x CHP in the UK
- Forestry residues x hydrothermal liquefaction x hydrotreatment x bio jet fuels for aviation in the US
- Energy crops x anaerobic digestion x biomethane x power generation in China
- Agricultural residues x hydrothermal liquefaction x hydrotreatment x renewable diesel in the US

Source: Kearney Energy Transition Institute

Advanced biofuel has competitive advantages in hard-to-decarbonize sectors such as aviation

Bioenergy market dynamic
(Section 2.1: pages 69–97)

Executive summary (6/8)

The combination of the biofuel produced and the market segment can also be optimized

In order to do so, the technical characteristics of **12 of the most common biofuels** (solid, liquid, and gaseous) were compared and their competitive advantages in each market segment where they are applicable were assessed. In total, biofuels have been assessed on **nine criteria and three dimensions**: technical, economic, and sustainable, with equivalent weight in total ranking.

Technical diagnosis shows that biomass for power (biomethane) and liquid hydrocarbons (for example, renewable diesel, gasoline, and jet fuel) are the most attractive

The latter are attractive because of their low substitutability and high potential in the transport sector. They could play a significant role in the energy transition; however, they are **not sufficiently mature and need to be supported by regulations** and policies to be able to **compete economically** with their fossil counterparts. **Bio jet fuel** is not competitive yet and lacks policy supports but **looks to be a viable way to decarbonize aviation**. **Renewable diesel** (chemically similar to diesel) and biogasoline (chemically similar to gasoline) have higher **potential in road transport and shipping**. **Biomethane** is a promising alternative to decarbonize **heat and power supply** potentially at a lower cost than natural gas. For other processed biofuels (liquid and gaseous), they are more mature but limited by blending requirements or renewable alternative competition.

Source: Kearney Energy Transition Institute

Local conditions such as regulations and existing infrastructures are key to successful bioenergy development

Bioenergy market opportunities
(Section 2.2: pages 98–114)

Executive summary (7/8)

Biomass-to-bioenergy value chain economic development relies on five interconnected drivers

Five drivers are often defined at country or even local scale and can act as levers to activate in order to improve market environment.

Feedstock supply determines the energetic potential of the bioenergy (volume effect); shapes the biomass-to-bioenergy value chain, in other words the pathway for processing biomass (mix effect); and is a key driver for biofuel quality/cost competitiveness (price effect). Bioenergy supply is genuinely linked to primary land demand since it relies on food and wood consumption patterns (biomass residues collected as by-product throughout food or wood supply-consumption chain). It is also linked with land utilization (primary biomass is directly grown from farmland or forest). Besides, each feedstock has its own drivers, linked to local and sustainable constraints that can affect price and volume of supply available and alternative uses of feedstocks act as competition for supply and will drive prices up.

Infrastructure maturity determines feasibility and risks associated with bioenergy projects which affects the entire value chain (barrier to entry) as well as its rentability (price effects).

Regulation drives the biomass market supply and the bioenergy demand (volume and price effect) through five dimensions that are unequally advanced between countries: waste management regulations, decarbonization targets and blending mandates, land use and planning regulations, fiscal incentives and government subsidies, and other sustainability policies.

Process economics drive bioenergy cost competitiveness (price effect) with sustainable options (biomass-to-power is competitive with fossil fuels in some regions, but wind and solar prices are expected to reduce further and biomass-to-biofuel/gas is likely to remain more expensive than fossil fuels)—opportunity driven by country regulation.

Substitutability drives market positioning for biofuels and depends on the penetration of alternative renewable energies. Biomass usage should focus on market segments without other sustainable alternatives and where storable energies are valued in order to get the most of its competitive advantage. As such, it should avoid substitution with competitive energies: renewable diesel in truck and shipping industries, bio jet fuel in aviation, biomethane in power generation.

Source: Kearney Energy Transition Institute

Biomass to energy has successful applications in buildings and hard-to-decarbonize transport industries

Bioenergy successful business models
(Section 3: pages 115-133)

Executive summary (8/8)

In the UK, waste to energy emerged as a waste management solution to replace landfill disposal

This solution, combined with recycling, is an efficient way to revalorize waste and minimize the environmental impact of its disposal. Its share of the waste market is increasing (by 3% between 2018 and 2019) and large new projects are in development in the UK. Energy from waste consists of thermal treatments such as incineration or pyrolysis to reduce waste volume and produce sustainable energy from the organic fraction of MSW.

Bio jet fuels, chemically like conventional jet fuels, are promising and developed in the US

Bio jet fuels are heavy liquid hydrocarbons produced from biomass. They are advanced liquid biofuels which have not reached maturity yet and require technically challenging production processes. Thus they are mostly investigated in developed countries such as the US with the target of decarbonizing the aviation and shipping sector in a long-term perspective. Their production is mostly based on hydrotreatment of waste fats or vegetables or gasification and upgrading with a very wide range of possible feedstocks. Overall, these biomass applications are not cost-competitive yet and need policy support.

In China, biomass is used to produce heat and power in rural areas to replace natural gas

Biomethane production through biomass upgrading or biomass gasification is forecasted to play a rising role in the decarbonization of the power and transport sectors. This small-scale application with low investment cost is rapidly growing in developing countries or rural areas such as seen in China. The use of biomethane significantly reduces the GHG emissions compared to fossil fuels and its development is facilitated by its compatibility with existing natural gas infrastructures.

Renewable diesel is produced in the US to decarbonize the transport sector in the short term

Renewable diesel is a liquid hydrocarbon chemically equivalent to its petroleum counterpart. It can be produced from biomass through oil upgrading (similar to petrochemistry processes) or gasification and upgrading. Its production is not competitive yet but has better penetration as a blend than bio jet fuels.

Co-firing biomass in cement kilns to decarbonize cement industry

Source: Kearney Energy Transition Institute

AGENDA

Bioenergy role in energy transition

There are two types of bioenergy: traditional (direct combustion) vs. advanced (indirect combustion and conversion)

Traditional bioenergy

- **Direct combustion** of untransformed solid biofuel (wood, charcoal, and animal waste)
- Mostly used in **developing countries**
- **Low efficiency**
- **Heat production** applications
  - Vital and affordable energy for **cooking and space heating**

Advanced bioenergy

- **Indirect combustion** and **conversion** of biomass energy to advanced fuels
- Used in **developing and industrialized countries**
  - Sustainable source of **electricity** and **heat** as well as **liquid and gaseous fuel**

Introduction – definition

Sources: Traditional Biomass Energy, Bonn 2004, IRENA; Kearney Energy Transition Institute

So far, advanced bioenergy can be produced from four different biomass generations, characterized by different sources

This factbook focuses on generations 2 and 3 since generation 1 competes directly with the food chain and generation 4 is too early stage.

Overview of the four “advanced bioenergy” generations

1st generation

Definition

- Bioenergy produced from edible crops (for example, oil crops, sugar and starch crops) on arable land

Advantages

- Easy to harvest

Drawbacks

- Competition with food cultures
- Poor yields
- Limited resources

2nd generation

Definition

- Bioenergy produced from non-edible crops and waste to have a limited impact on food security

Advantages

- No direct competition with food (except for land use)

Drawbacks

- Possible adverse effects on local biodiversity
- Land use change

3rd generation

Definition

- Bioenergy produced from micro or macro algae, which have high yields and limited land use impacts

Advantages

- No competition with food
- High yields

Drawbacks

- Expensive/early stage resource
- Water intensive

4th generation

Definition

- Bioenergy produced from genetically modified crops to maximize yield

Advantages

- High yields
- Carbon neutral or negative (with CCS)

Drawbacks

- High engineering requirements and cost

Note: CCS is carbon capture and storage.
Sources: Green Prophet (Picture), Exeter University (Picture), Biomass Magazine (Picture), Chain Reaction Research (Picture); Kearney Energy Transition Institute

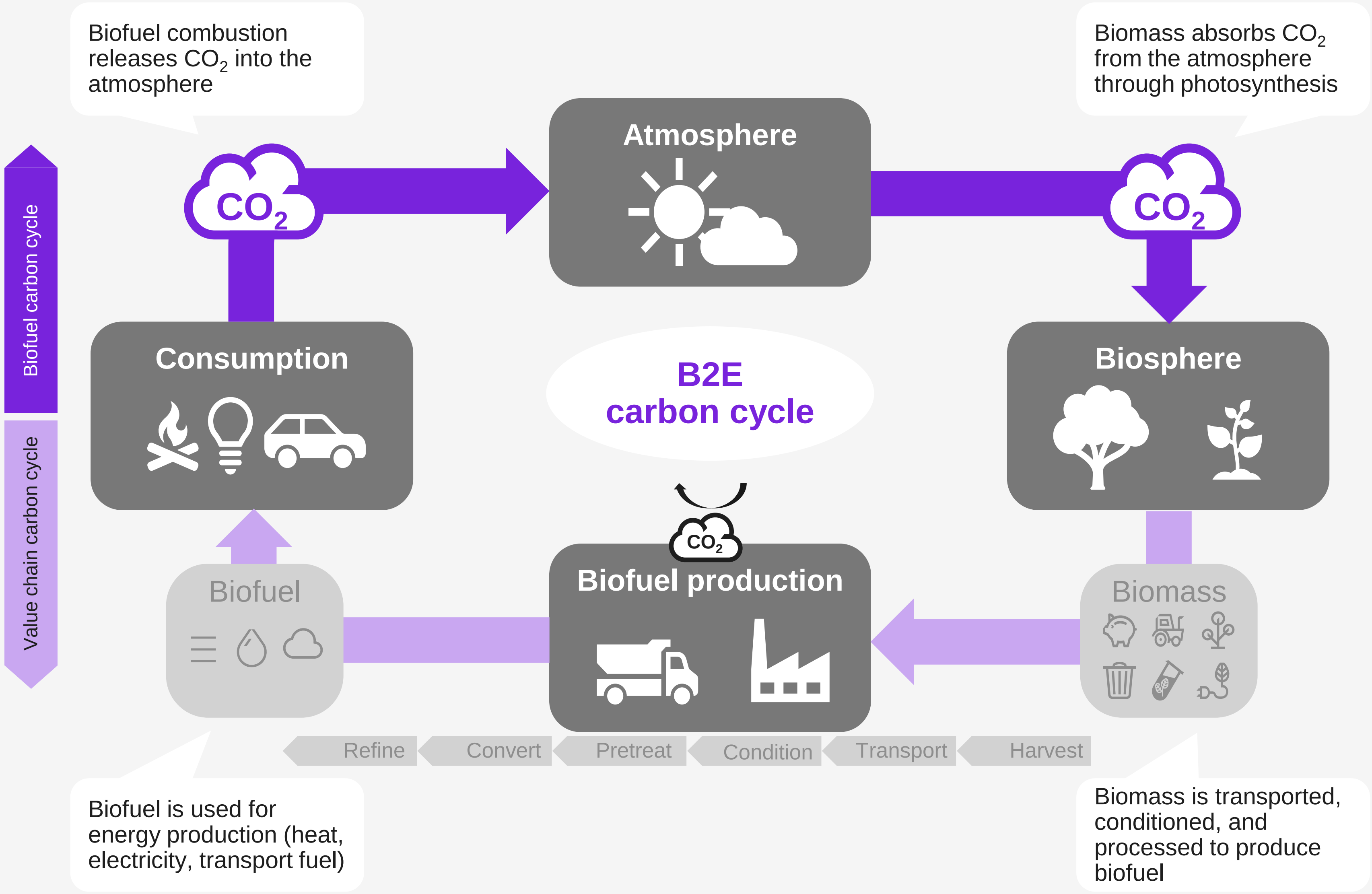
In principle, use of bioenergy would be carbon neutral if there were no emission from non renewable sources in its industrial value chain

Carbon neutrality of bioenergy uses the natural carbon cycle of biomass

CO_2	CO_2 emissions from biofuel consumption
CO_2	CO_2 emissions from biofuels value chain

Introduction – biomass role in carbon cycle

Biomass-to-energy carbon cycle



Biofuel combustion releases CO_2 into the atmosphere

Biomass absorbs CO_2 from the atmosphere through photosynthesis

Biofuel is used for energy production (heat, electricity, transport fuel)

Biomass is transported, conditioned, and processed to produce biofuel

Source: Kearney Energy Transition Institute

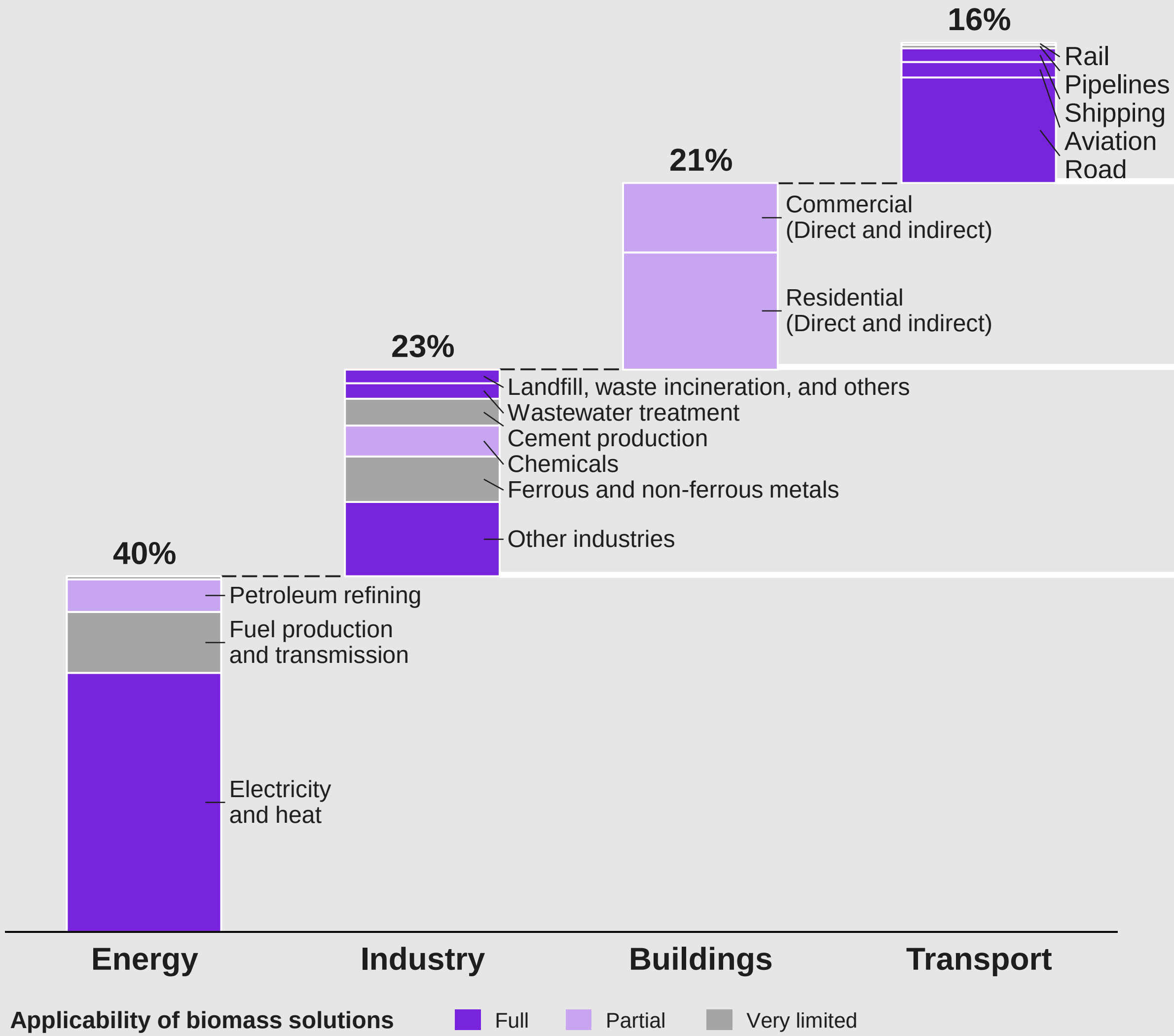
Bioenergy is highly applicable; theoretically it could decarbonize sectors representing about 50% of global GHG emissions[1]

Bioenergy is highly applicable thanks to the versatility of its products, which range from liquid biofuels (storable, transportable) to pilotable electricity

Introduction – biomass applicability per sector

Global GHG emissions per sector and bioenergies applicability

2010, GtCO2eq/year, without AFOLU[2]



1. 15% in Transport, 29% in Energy, 11% in Industry GHG emissions could be avoided by using biomass.
2. AFOLU is agriculture, forestry, and other land use.

Sources: IPCC (https://www.ipcc.ch/report/ar5/wg3/); Kearney Energy Transition Institute

Biomass alternatives for corresponding sector

- Jet fuels
- Biogasoline
- Biodiesel
- Bioethanol

- Heat and power from municipal solid waste
- CHP from gasification

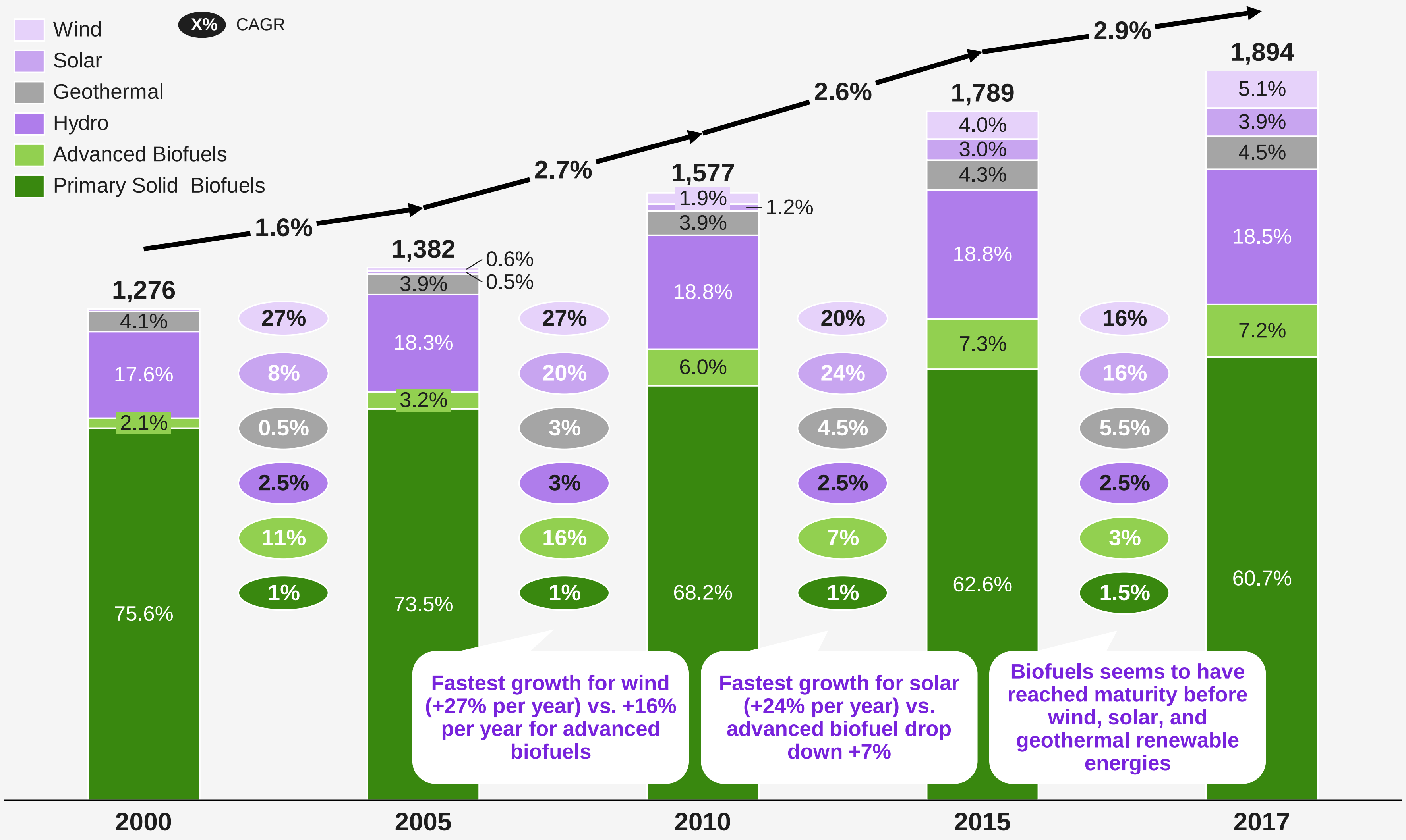
- Heat and power from solid biofuels
- CHP from biogases

- Heat and power from biogases
- Energy from waste

Bioenergy is historically the first contributor to the renewable mix; however its share is now decreasing vs. wind and solar energies

Renewable energies primary demand

2000–2017, Mtoe, world



Fastest growth for wind (+27% per year) vs. +16% per year for advanced biofuels

Fastest growth for solar (+24% per year) vs. advanced biofuel drop down +7%

Biofuels seems to have reached maturity before wind, solar, and geothermal renewable energies

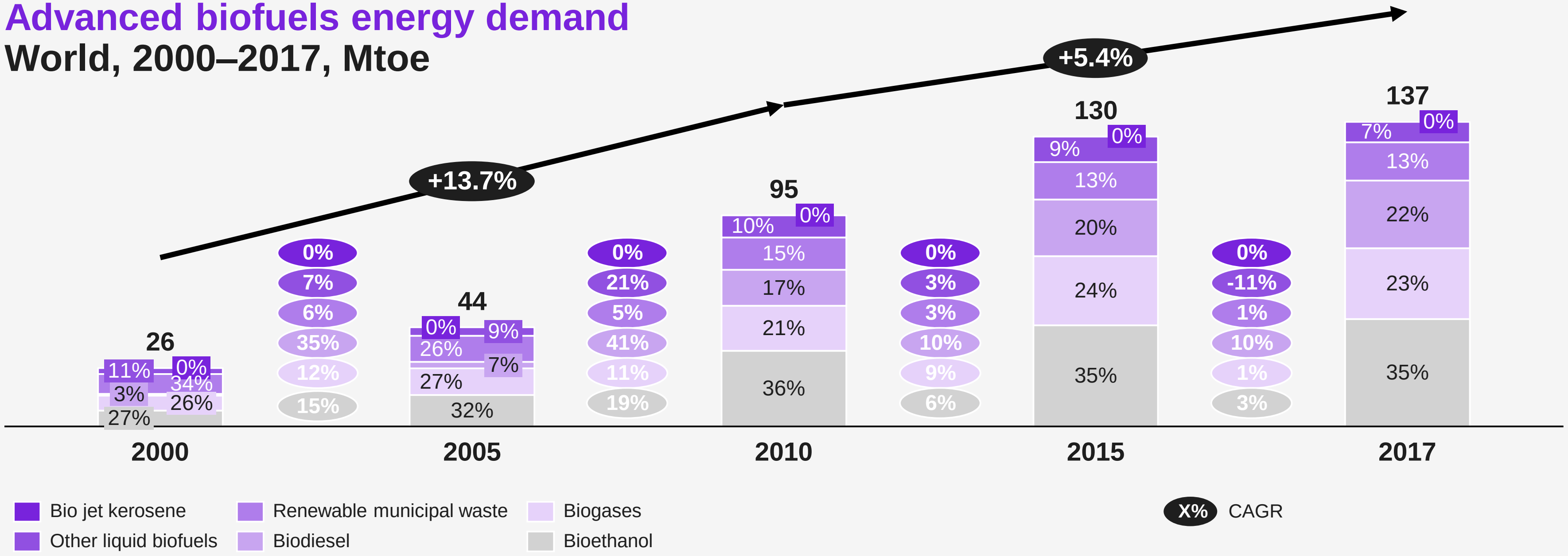
Sources: World Energy Outlook 2019 (IEA); Kearney Energy Transition Institute

Introduction – biomass vs. other renewables demand

Advanced bioenergy has seen its growth slow down in the late 2000s

Advanced biofuels energy demand

World, 2000–2017, Mtoe



Technical drivers

2000–2010

- First renewable technology to reach maturity and commercial-scale deployment (sometimes even before 2000)
- High adaptability to existing infrastructure at low scale for biofuels (blending with gasoline or diesel) which facilitate early deployment

2010–2020

- Uptake limited by blending limits and low uptake of “flex-fuel” vehicles
- Increase in feedstock harvesting requirements to stick to sustainability concerns

Economic drivers

2000–2010

- Oil crisis leading high oil prices in 2008 (peak price above $160/barrel)
- Renewable solutions not cost competitive

2010–2020

- Increase in feedstock costs and slow overall decrease of bioenergy costs (-14% between 2010 and 2019)
- Low prices for oil over the decade ($70/barrel on average)
- Sharp decrease in wind and solar prices to become cost competitive with bioenergy (-78% for solar PV and -35% for wind between 2010 and 2018)

Sociopolitical drivers

2000–2010

- Interest rising for climate change and sustainable development leading to the uptake of low-carbon technologies

2010–2020

- Lagging policy framework in main biofuels markets
- Higher concerns about food competition and land use change induced by biofuels

Sources: Renewable Power Generation Costs 2018 (IRENA), IEA Renewables Information Database (2018); Kearney Energy Transition Institute

Introduction – advanced bioenergy demand

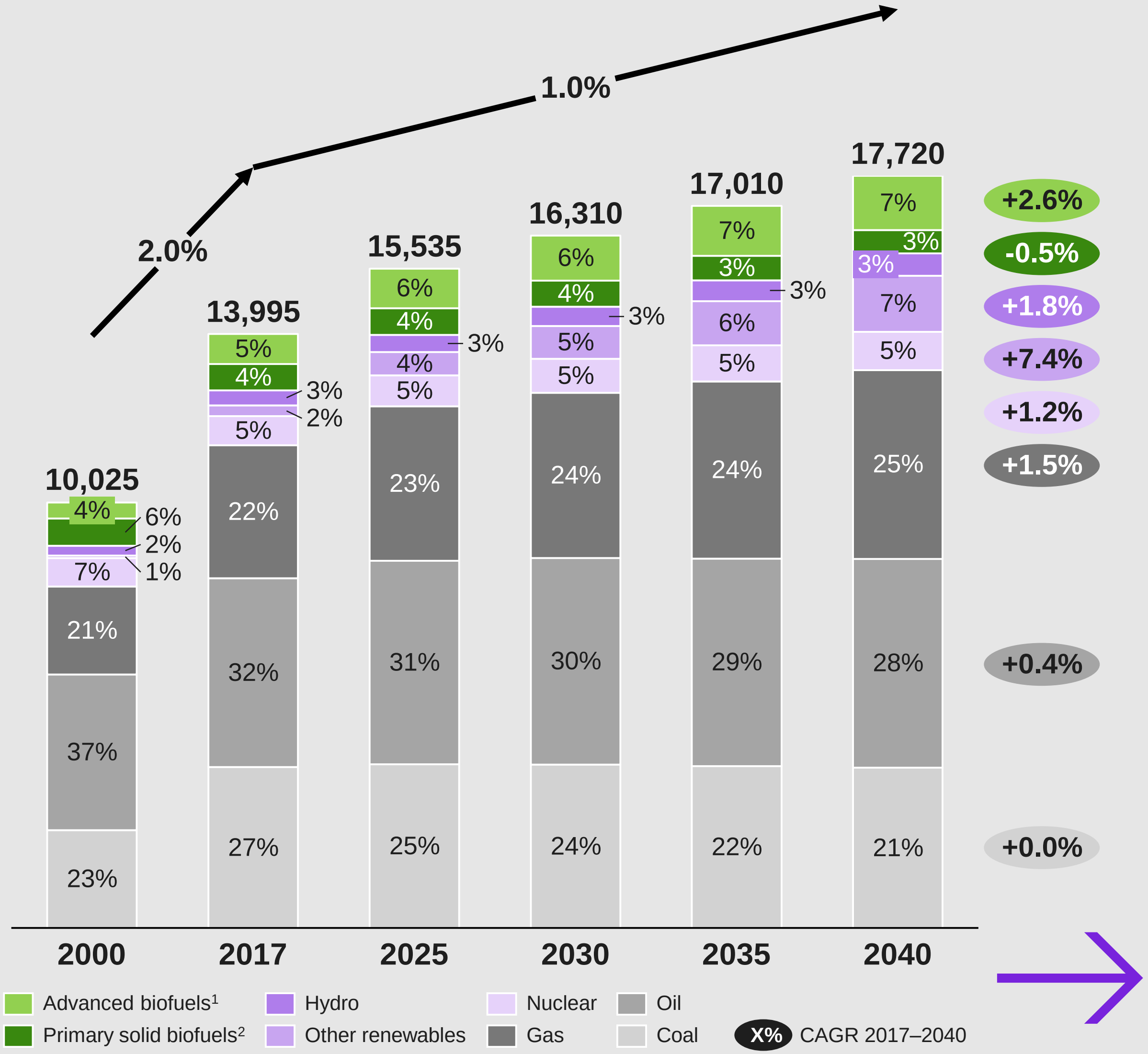
Wind and solar energies are expected to grow faster than advanced biomass by 2040 (+7% vs. +2,5%)

Overall, world energy demand will increase by ~1% per year till 2040

Introduction – biomass in primary energy demand

Primary energy demand by fuel

2000–2040, Mtoe, world, stated policies scenario



[1] Modern uses of biomass include advanced heat and power, biogas, biofuel

[2] Traditional uses of biomass include "fuelwood, charcoal, and organic waste" used as the main cooking fuel for 2.3 billion people

Sources: IEA WEO 2019 – Stated Policies Scenario; Kearney Energy Transition Institute

Macro trends

In 2040, carbon neutral energies will represent 25% of world mix (vs. 20% in 2017)

Bioenergies' share of global demand **will remain constant (~10% energy mix):**

- **Advanced biomass share will almost double** (in other words, the same CAGR as all carbon neutral energies)
- **Traditional biomass share will decrease by only 1%** relative to global demand

Other renewable energies' weight in the global mix will grow ~x4

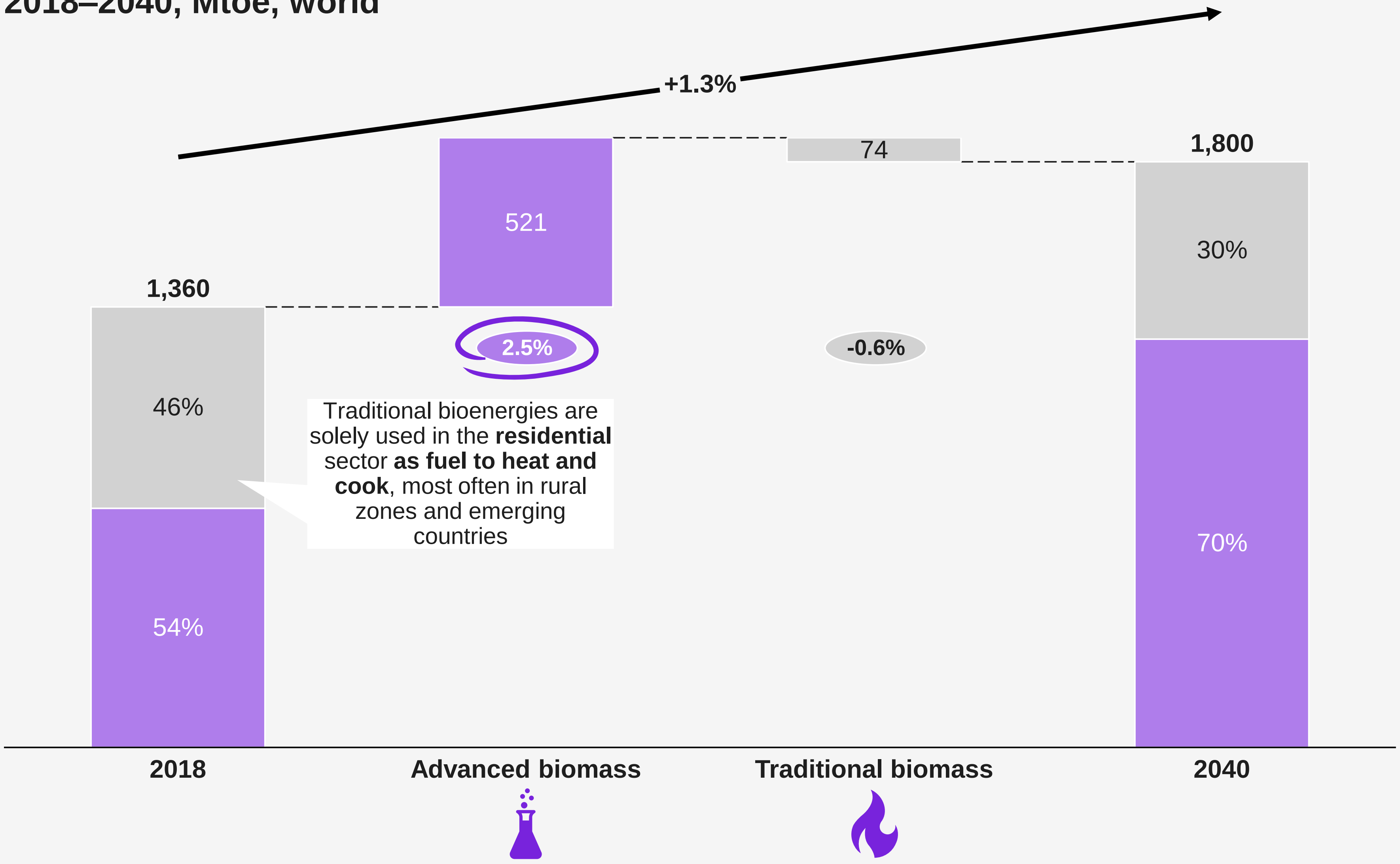
This factbook focuses on advanced bioenergy, the main growth driver of bioenergy (+2.5% per year)

Advanced bioenergies push forward primary biomass usage (in other words cultivated biomass—energy crops, algae, forests) to increase energy generation potential vs. biomass residues (animal, agriculture and municipal wastes)

Introduction – definition

Bioenergy demand forecast—stated policies scenario

2018–2040, Mtoe, world

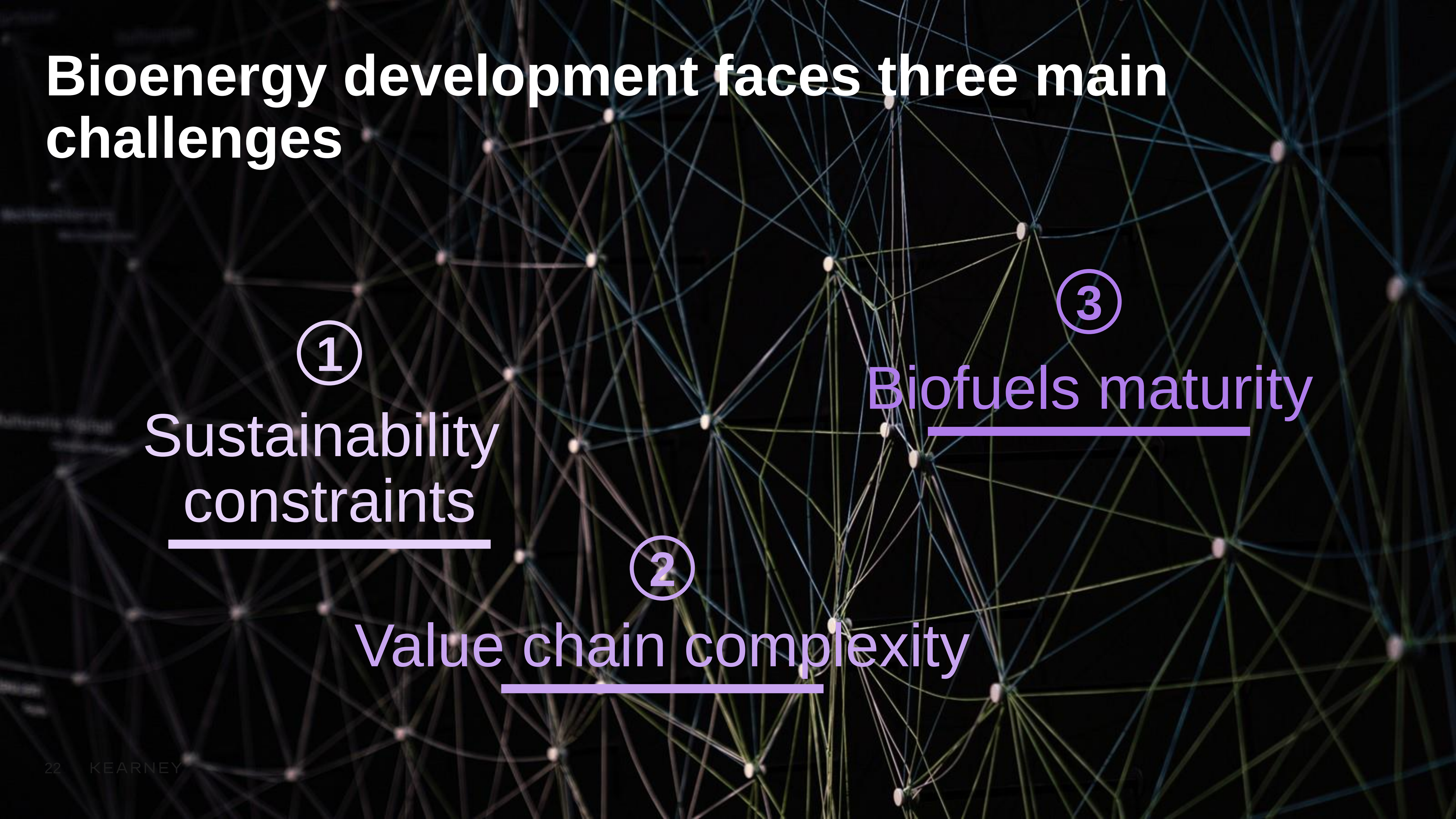


Traditional bioenergies are solely used in the **residential** sector **as fuel to heat and cook**, most often in rural zones and emerging countries

▨ Traditional biomass ■ Advanced biomass **X%** CAGR

Sources: World Energy Outlook 2019 (IEA); Kearney Energy Transition Institute

Bioenergy development faces three main challenges



①
Sustainability constraints

②
Value chain complexity

③
Biofuels maturity

Biomass harvesting and collection must meet standards to be sustainable

① Sustainability constraints

Direct consequence is that bioenergy production is intrinsically limited by the amount of sustainably collectable biomass

Sustainability constraints by advanced bioenergy generation

Generation	Year[1]	Description	Sustainability constraints			
			Direct competition with food	Land use change	Water use	Soil erosion
1st generation	~ 1990	– Bioenergy produced from edible crops (for example, oil crops, sugar and starch crops) on arable land	●	●	◑	◑
2nd generation	~ 2000	– Bioenergy produced from non-edible crops and waste to have a limited impact on food security	◔	●	◔	◔
3rd generation	~ 2015	– Bioenergy produced from micro or macro algae, which have high yields and limited land use impacts	○	◔	●	○
4th generation	Future	– Bioenergy produced from genetically modified crops to maximize yield and coupled with CCS technologies	○	◔	◔	◔

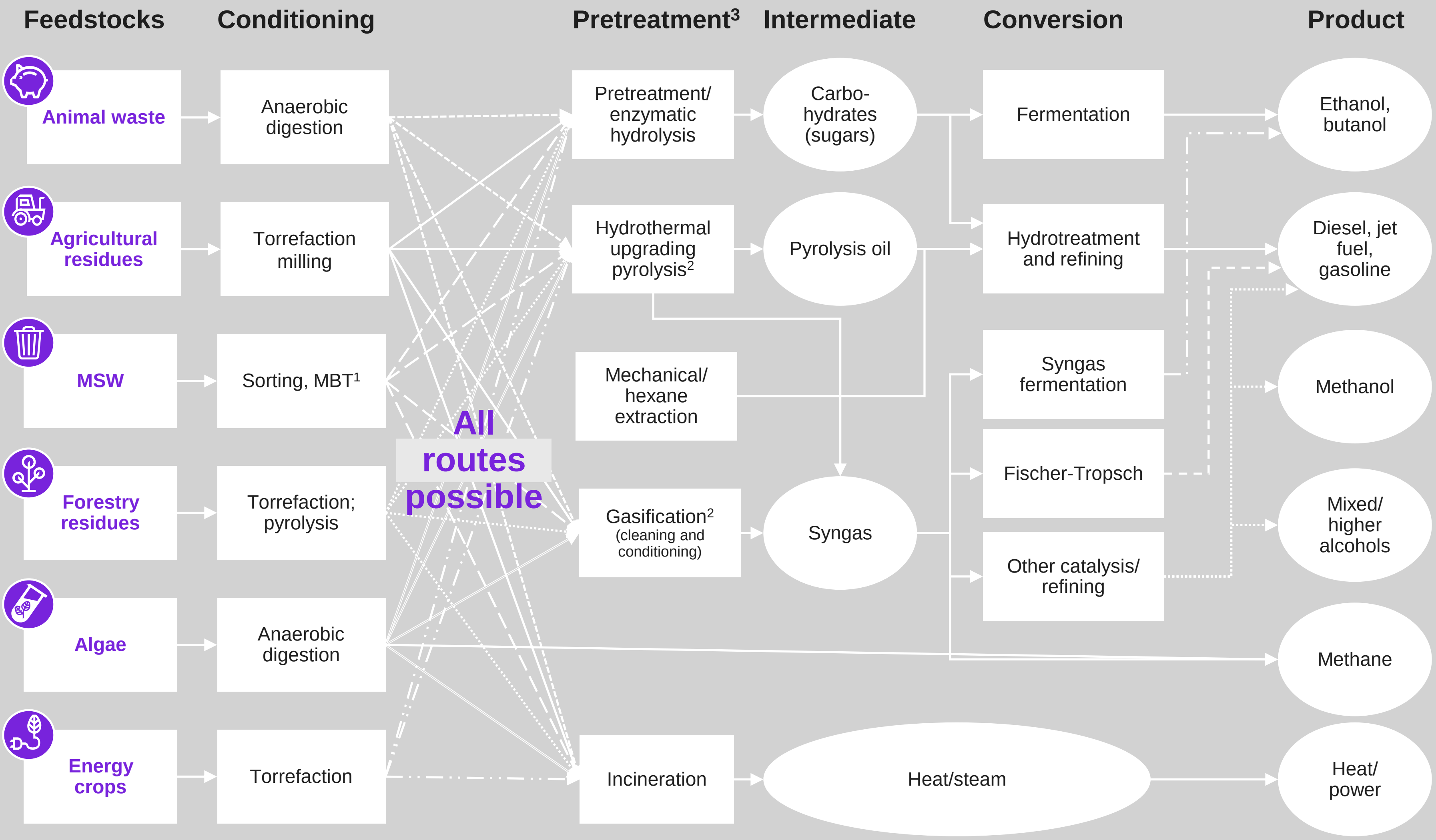
⬚ Scope of the factbook ● High constraint ◑ Medium constraint ◔ Low constraint ○ No constraint

[1] Year of maturity of the bioenergy production processes associated to the given feedstock generation
Source: Kearney Energy Transition Institute

Biomass processing has a wide diversity of possible routes which increases the complexity of bioenergy project development

2 Value chain complexity

Schematic representation of advanced feedstocks-to-energy pathways



Feedstocks

Animal waste

Agricultural residues

MSW

Forestry residues

Algae

Energy crops

Conditioning

Anaerobic digestion

Torrefaction milling

Sorting, MBT[1]

Torrefaction; pyrolysis

Anaerobic digestion

Torrefaction

All routes possible

Pretreatment[3]

Pretreatment/ enzymatic hydrolysis

Hydrothermal upgrading pyrolysis[2]

Mechanical/ hexane extraction

Gasification[2] (cleaning and conditioning)

Incineration

Intermediate

Carbo-hydrates (sugars)

Pyrolysis oil

Syngas

Heat/steam

Conversion

Fermentation

Hydrotreatment and refining

Syngas fermentation

Fischer-Tropsch

Other catalysis/ refining

Product

Ethanol, butanol

Diesel, jet fuel, gasoline

Methanol

Mixed/ higher alcohols

Methane

Heat/ power

[1] Mechanical biological treatment
[2] Thermochemical process
[3] Not included: anaerobic digestion leading to methane production and non-energy routes (for example, composting, landfill); specific additional processes between intermediate and conversion stage may be required (for example, separation of by-products)

Sources: IEA Bioenergy roadmap; Kearney Energy Transition Institute

Conversion of biomass to energy and consumption generally follows three main steps

② Value chain complexity

Ⓐ Harvesting/ collection

Feedstock collection on production site

- **Animal waste**
- **Municipal solid waste**
- **Agricultural residues**
- **Algae**
- **Forestry residues**
- **Energy crops**

→

Ⓑ Processing

Feedstock transformation in a final product

– **Mechanical** (for example, lipid extraction)

– **Thermal** (for example, torrefaction, gasification)

– **Chemical** (for example, Fischer-Tropsch)

– **Biochemical** (for example, anaerobic digestion, fermentation, and composting)

– **Electrochemical** conversion

→

Ⓒ Biofuel consumption

Use of the final product to generate energy

Solid biofuel (for example, wood chips, pellets)

Liquid biofuel (for example, bioethanol, biodiesel)

Gaseous biofuel (for example, biomethane, syngas)

〉 **Heat**
Power
Motion

→

Introduction – definition

Source: Kearney Energy Transition Institute

Harvest and collection of biomass, called “feedstock” in this factbook, is the first step to produce bioenergy

② Value chain complexity

Six categories of feedstocks are assessed in this report

X Deep-dived

Introduction – definition

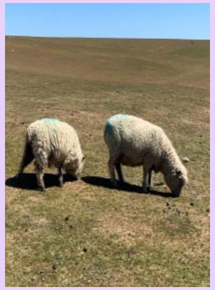
Overview of the different sources of biomass

Ⓐ

Harvesting/collection

Agricultural residues
Leftovers from crop harvests (for example, straw) or residues from conversion processes (for example, bagasse)

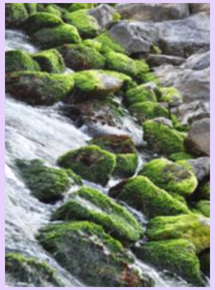
Forestry residues
Raw wood or wood residues resulting from forest management practices



Animal waste
Waste resulting from livestock farming (for example, manure) and also animal remains

Municipal solid waste
Set of everyday items discarded by the public after their initial use

Energy crops
Specific crops dedicated to bioenergy production in order to minimize competition with food supply



Algae
Micro and macroalgae grown for bioenergy production because of their high energy content

Processing

Conditioning
↓
Pretreatment
↓
Conversion

Biofuel consumption

Biofuel
Solid
Liquid
Gaseous
↓
Bioenergy
Heat
Power
Motion

Source: Kearney Energy Transition Institute

Feedstock processing toward biofuel includes three sub-steps: conditioning, pretreatment, and conversion

② Value chain complexity

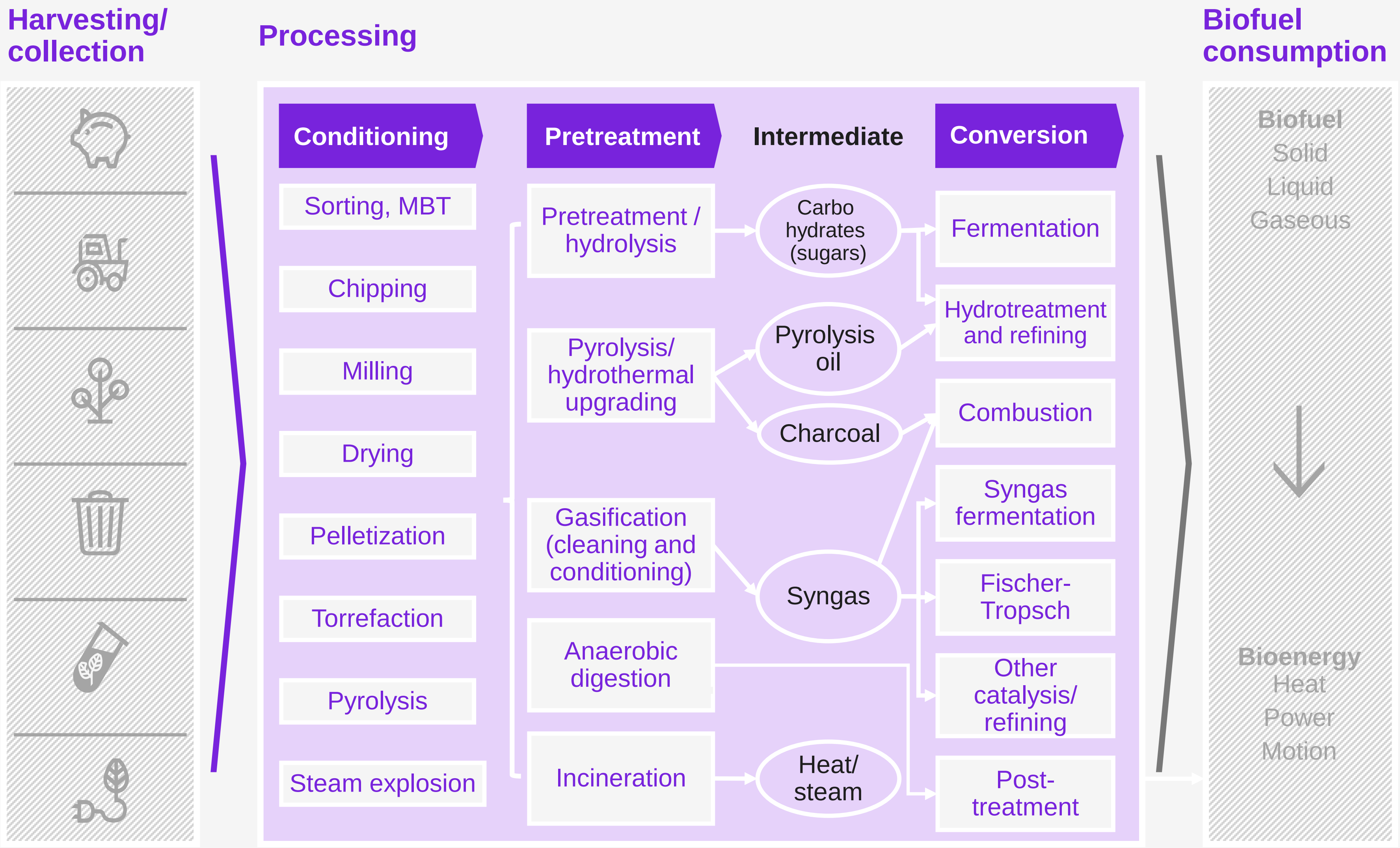
Not exhaustive

X Deep-dived

Introduction – definition

Processing methods general overview

Ⓑ



Harvesting/ collection

Processing

Conditioning
- Sorting, MBT
- Chipping
- Milling
- Drying
- Pelletization
- Torrefaction
- Pyrolysis
- Steam explosion

Pretreatment
- Pretreatment / hydrolysis
- Pyrolysis/ hydrothermal upgrading
- Gasification (cleaning and conditioning)
- Anaerobic digestion
- Incineration

Intermediate
- Carbo hydrates (sugars)
- Pyrolysis oil
- Charcoal
- Syngas
- Heat/ steam

Conversion
- Fermentation
- Hydrotreatment and refining
- Combustion
- Syngas fermentation
- Fischer-Tropsch
- Other catalysis/ refining
- Post-treatment

Biofuel consumption

Biofuel
Solid
Liquid
Gaseous

Bioenergy
Heat
Power
Motion

Note: MBT is mechanical biological treatment.
Sources: IEA Bioenergy roadmap; Kearney Energy Transition Institute

Eventually, biofuels are consumed to produce energy in the form of heat, power, or motion

② Value chain complexity

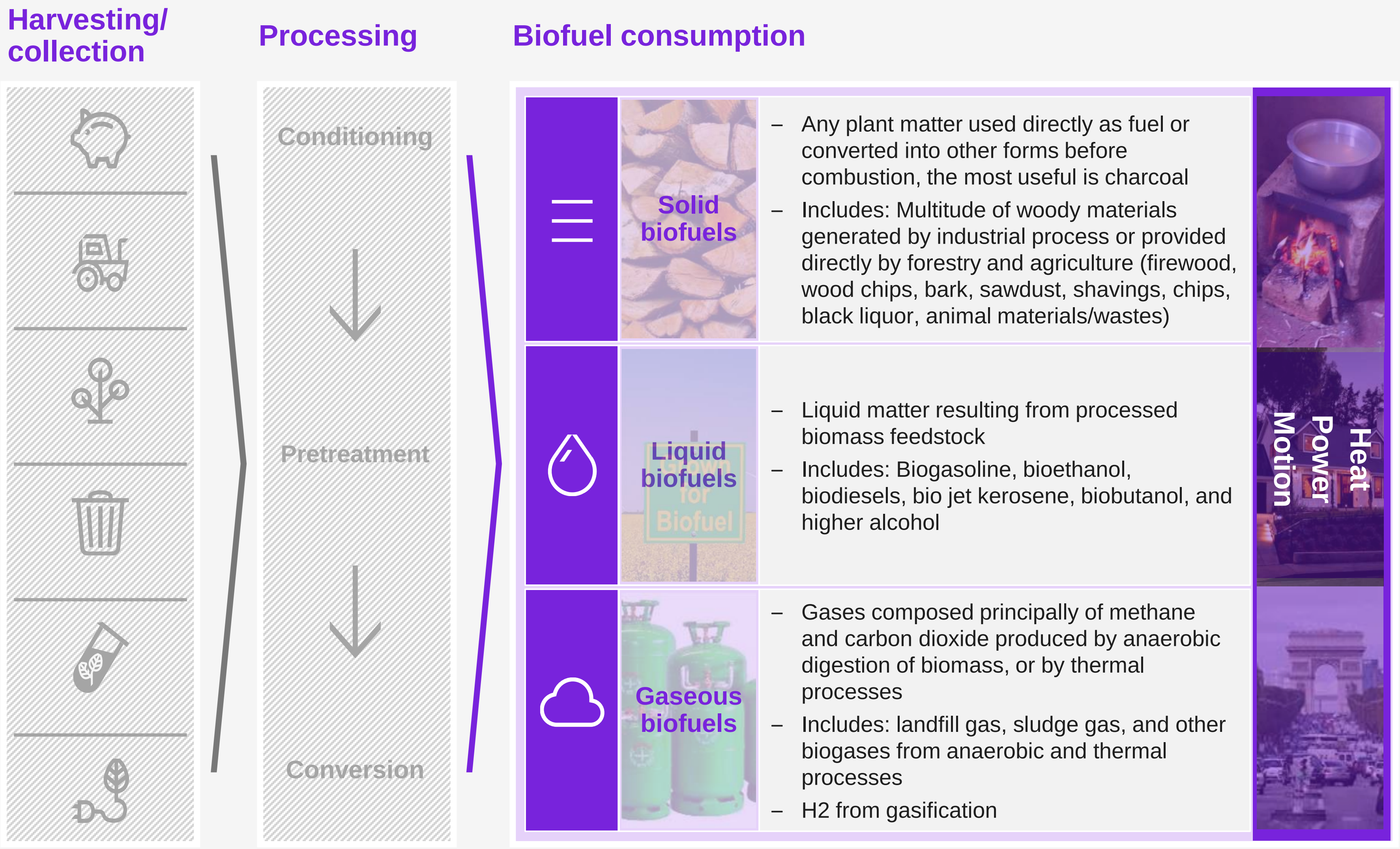
Three types of biofuels—solid, liquid, and gaseous—can be used to produce energy.
We define liquid and gaseous biofuels as "advanced biofuels."

X Deep-dived

Introduction – definition

Definition of the different biofuels

C



Harvesting/ collection

Processing

- Conditioning
- Pretreatment
- Conversion

Biofuel consumption

Solid biofuels	– Any plant matter used directly as fuel or converted into other forms before combustion, the most useful is charcoal – Includes: Multitude of woody materials generated by industrial process or provided directly by forestry and agriculture (firewood, wood chips, bark, sawdust, shavings, chips, black liquor, animal materials/wastes)
Liquid biofuels	– Liquid matter resulting from processed biomass feedstock – Includes: Biogasoline, bioethanol, biodiesels, bio jet kerosene, biobutanol, and higher alcohol
Gaseous biofuels	– Gases composed principally of methane and carbon dioxide produced by anaerobic digestion of biomass, or by thermal processes – Includes: landfill gas, sludge gas, and other biogases from anaerobic and thermal processes – H2 from gasification

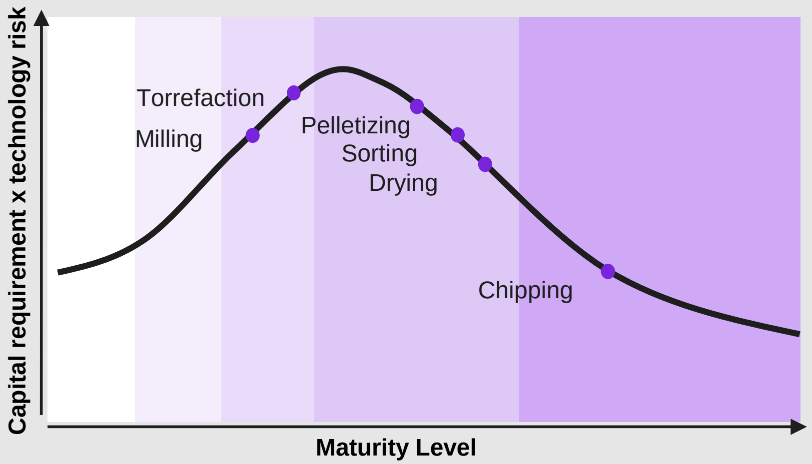
Heat
Power
Motion

Source: Kearney Energy Transition Institute

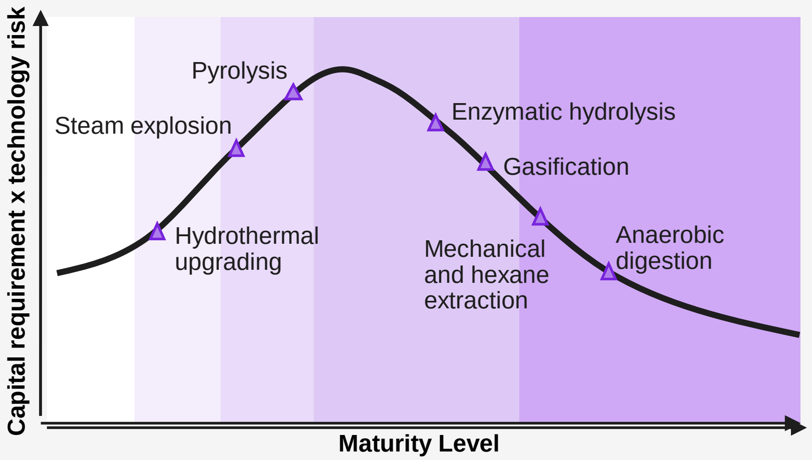
This diversity also comes with disparities in the processing technologies and biofuels maturity level

3 Biofuels maturity

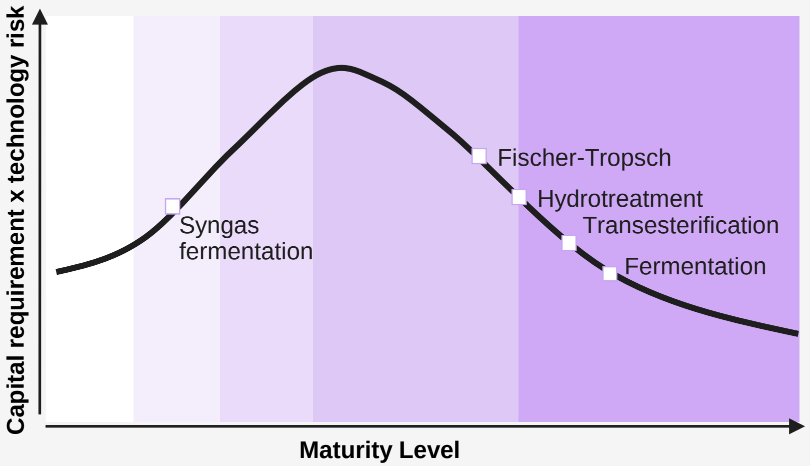
Conditioning technologies maturity curve



Pretreatment technologies maturity curve

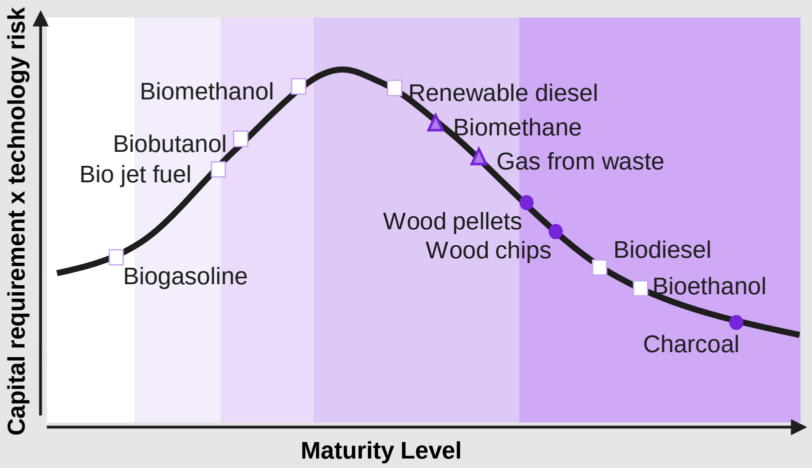


Conversion technologies maturity curve



Source: Kearney Energy Transition Institute

Biofuels maturity curve

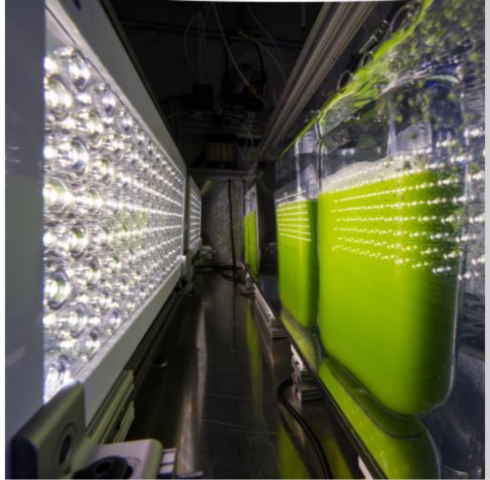


- Research
- Development
- Demonstration
- Deployment
- Mature technology

The attractiveness of bioenergy relies on three main groups of criteria: technical, economic, and environmental

The following opportunity assessment criteria will be used to evaluate the prioritized list of value chains

Introduction – biomass value chain assessment criteria



Technical

- Energy efficiency
- Compatibility
- Maturity
- Infrastructure adaptability

Economic

- Profitability
- Competitiveness
- Scalability
- Public incentives

Environmental

- Life cycle GHG emissions and air quality
- Biodiversity
- Circularity
- Water and soil quality and stress

Sources: US Department of Energy (Picture), US Department of Primary Industries and Regional Development (Picture), Mongabay (Picture); Kearney Energy Transition Institute

The objective of the factbook is to assess biomass-to-energy value chain attractiveness and ability to respond to climate change

Thanks to chapter 1 and 2, we will be able to obtain the top combination feedstock x processing methods x biofuels x market segments that we will then deep-dive in chapter 3

Introduction – objective of the factbook

Key questions to assess biomass-to-energy value chain attractiveness

1 Value chain assessment

1.1 Feedstock overview

What is the energy potential of biomass?

– What are the different feedstocks available?

– What are the conditions to ensure sustainable harvesting and collecting of biomass feedstocks?

1.2 Processing methods overview

What is the optimal feedstock x processing method x biofuels combination?

– What are the existing processing methods characteristics?

– What are their stage of maturity?

2 Biofuels market opportunities and enablers

2.1 Attractiveness and maturity assessment

What is the optimal biofuel x market segment combination?

– What are the technical and environmental characteristics of biofuels?

– What are the competitive advantages vs. fossil fuels or other renewable energy sources?

– Which market segment is the most promising?

2.2 Market drivers and corresponding enablers

What are the market conditions that ease biomass-to-bioenergy development?

– What are biomass-to-bioenergy market drivers?

– What are the corresponding levers to activate in order to increase attractiveness?

3 Conclusion: successful business models

Where and how successful business models exist?

Source: Kearney Energy Transition Institute

Section 1

Biomass-to-bioenergy value chain assessment

Key questions

What is the energy potential of biomass?

i. What are the main feedstocks available?

ii. What are their characteristics?

iii. How can those feedstocks be collected?

iv. What are the conditions to ensure sustainable harvest and collection of biomass feedstocks?

Source: Kearney Energy Transition Institute

Six feedstocks are assessed in this report: animal waste, forestry residues, agricultural residues, algae, MSW, and energy crops

Non-exhaustive

Feedstock – definition

Animal waste

Waste from keeping livestock (solid and liquid manure) such as horses, cattle, pigs, sheep, or poultry

Forestry residues

Primary residues from cultivation, harvesting, or logging activities (for example, thinnings) and secondary residues from wood processing (for example, sawdust, wood chips, black liquor)

Agricultural residues

Field residues including stalks, stubble, leaves, seed pods, and process residues such as husks, seeds, bagasse, molasses, and roots

Algae

Algae are chlorophyll-containing organisms, ranging from microscopic microalgae to larger macroalgae and distinguished from plants by the absence of true roots, stems, and leaves; the use of algae for bioenergy purposes is still at an early stage of maturity

Municipal solid waste

Waste collected and treated by or for municipalities (includes organic waste, paper and cardboard, plastic, metal, glass and textiles, wood) or any similar waste from commercial and industrial sources

Energy crops

Short rotation coppice (poplar, willow, eucalyptus, and locus), ley crops, energy cane, and perennial cultivation (miscanthus, switchgrass, reed canary grass, and other grasses)

Sources: USDOE Billion Ton Report; Kearney Energy Transition Institute

For each feedstock, three specific potentials are estimated: theoretical, technical, and sustainable

Each of these feedstocks is deep-dived below and their corresponding potential is assessed

X Deep-dived

Feedstock – methodology

Methodology for the chapter analysis

Feedstock	**Theoretical potential** The **physical theoretically usable energetic potential** of a feedstock	**Technical potential** **Fraction of the theoretical potential** that remains **after unavoidable losses** due to technical restrictions (such as harvesting and collection efficiency or processing issues)	**Sustainable potential** **Fraction of the technical potential intentionally limited** by consideration of environmental, social, and ecological aspects such as food security and competing resource uses
Animal waste Waste resulting from livestock farming (for example, manure) and also animal remains	Energy embedded in the total quantity of animal excrement and slaughter/processing facility waste	Fraction of theoretical potential that can be practically collected from fields and facilities	Fraction of technical potential after removing unethical sources or where fertilizer demand is not met
Agricultural residues Leftovers from crop harvests (for example, straw) or residues from conversion processes (for example, bagasse)	Energy embedded in the portion of agricultural biomass remaining after the primary product is harvested	Fraction of theoretical potential that can be practically collected from fields and facilities	Fraction of technical potential after removing sources that can be processed for the food value chain or degrade soil quality
Municipal solid waste Set of everyday items discarded by the public after their initial use	Energy embedded in the total quantity of forest residues produced	Fraction of theoretical potential that can effectively be collected	Fraction of technical potential that is new growth or waste from wood processes which can be sustainably reused
Forestry residues Raw wood or wood residues resulting from forest management practices	Energy embedded in the total amount of municipal solid waste produced	Fraction of theoretical potential that can effectively be collected	Fraction of technical potential after removal of recycled fraction (for example, paper, plastic)
Algae Specific crops dedicated to bioenergy production in order to maximize the yield	Energy embedded in the total amount of land and marine algae produced	Fraction of theoretical potential that can effectively be collected	Fraction of technical potential after removing sources that compete with other uses or do not meet sustainable water use requirements
Energy crops Specific crops dedicated to bioenergy production	Energy embedded in the total amount of biomass grown in the energy crop	Fraction of theoretical potential that can be effectively gathered	Fraction of technical potential after removing sources that compete with food and feed crops or which impact land use

Source: Kearney Energy Transition Institute

There are large disparities in energy potential and GHG emissions between feedstocks

These disparities are linked to their production conditions and requirements to ensure sustainability and can only be precisely assessed locally.

Feedstock – results

Biomass feedstocks overview

World, 2060, IEA Technology Roadmap

	Energy content (MJ/kg)	Technical challenges	Sustainability requirements	Theoretical, technical, and sustainable potentials (Mtoe)	GHG[1] (gCO2e/MJ)
Animal waste (liquid and solid)	6–8	– Difficult manure collection and lack of treatment facilities	– Interferences with competing uses (fertilizer)	100% 1,650–2,000 35% 575–725 7% 100–150	3–5
Agricultural residues	11–17	– Crop burning preventing residue collection	– Interference with competing uses (fertilizer, food or bedding for cattle)	100% 2,100–4,375 69% 1,450–3,050 52% 1,100–2,275	5–11
Forestry residues	10–16	– Highly distributed resource – Policies increasingly aiming to achieve zero deforestation	– Fragile and sensitive forests protection – Overtaking of trees growth pace	100% 2,275–4,710 45% 1,025–2,120 15% 350–725	3–6
Municipal solid waste	4–10	– Increase of recycling policies	– Interference with recycling – Processing facilities pollutants emissions	100% 450–700 83% 375–575 52% 225–375	0.5–1
Algae	18–19	– Early stage feedstock – Competing uses in the chemical and food industries	– High water and nutrients requirements	Data missing	18–40
Energy crops	10–16	– Good predictability and control of supply volume	– Potential for land use change	100% 2,950–4,950 70% 2,075–3,450 48% 1,425–2,400	13–14

■ Theoretical potential ■ Technical potential ■ Sustainable potential X% Share of theoretical potential

[1] GHG emissions gCO2eq/MJ of feedstock energy content. Only emissions related to feedstock production are accounted here. Direct (related to feedstock final use) and indirect emissions are not taken into account here. Production-related emissions are split in feedstock generation-related emissions and transport-related emissions, only generation accounted for animal waste and algae, only transport for MSW.

Sources: Kearney, Technology Roadmap - Delivering Sustainable Bioenergy (IEA), USDOE Billion Ton Report (2016), USDOE Billion Ton Report Volume 2 (2016), FAO Tackling Climate Change through livestock (2013), Xin et al. - An Empirical Study on Greenhouse Gas Emission Calculations Under Different Municipal Solid Waste Management Strategies (2020), Kearney Energy Transition Institute

Animal waste is waste generated by cattle and slaughterhouse

Illustrative

Animal waste – deep-dive

Animal waste examples: manure and renderings

Manure

- Manure is an organic matter
- Most manure consists of animal feces, other sources include compost and green manure
- Manure use for bioenergy is in competition with its traditional use as organic fertilizer in agriculture
- Manures contribute to the fertility of soil by adding organic matter and nutrients, such as nitrogen

Renderings

- Leftover animal products and grease that are turned into stable and usable tallow
- Tallow is a stable grease; it is high-quality biomass feedstock because of its high fat content that can be processed into biodiesel or refined liquid hydrocarbons

Sources: Kearney Energy Transition Institute

Based on pretreatment requirements, low collection rates, and distributed supply, scalability of animal waste is limited

Organic content (% Carbon)	50–95%
Ash content (%)	20–60%
Moisture content (% mass)	50–95% (undried)
Fixed carbon (%)	Data missing
Biogas yield (m3/t)	12–25 cattle/pig slurry 30–100 poultry
Bulk density (kg/m3)	513–1000
Energy content	6–8 MJ/kg

Animal waste – deep-dive

Overview

Supply characteristics:

- Directly linked to number of livestock units and collection rates
- Limited variability due to seasonality, weather, and so on
- Exposed to changes in demand of animal products such as meat, dairy, wool
- Challenging collection mechanisms and distributed supply network

Conversion technologies:

- Anaerobic digestion and incineration are the only viable solutions because of feedstock low energy density and high moisture
- No economically viable conversion or conditioning process to decrease the transport or storage costs of animal waste

Regulations:

- Anaerobic digestion has experienced regulatory support
- Carbon taxes have benefitted producers of animal waste but regulations vary across countries

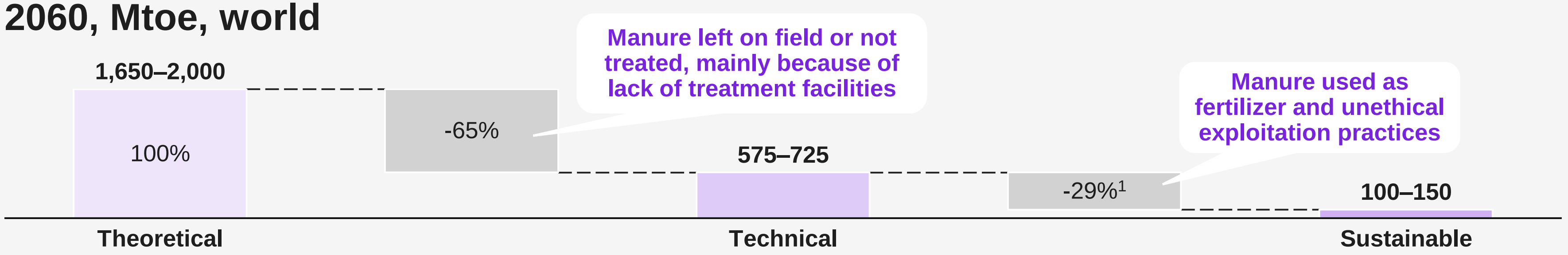
Sustainability constraints

Competing demand segments	– Use of animal waste as fertilizer, which is its most prevalent application
Soil quality	– Portion of manure applied to soil is necessary to maintain soil fertility
Water quality	– Nitrogen, phosphorus, and pathogen content of manure can affect water quality
Air quality	– Ammonia emissions of manure can volatilize and have an adverse impact on air quality – Emissions of manure used as household fuel (for example, dry dung cakes) can be hazardous to health
Land use change and food competition	– No risk for food competition and very limited risk for land use

XX Main sustainability criteria

Animal waste feedstock total potential

2060, Mtoe, world



Theoretical
- Total quantity of animal excrement and slaughter/processing facility waste
- Multiplied by corresponding energy content

Technical
- Manure can be treated through various management systems such as lagoons, dry lots, digesters, or solid storage tanks

Sustainable
- Current manure application rates as fertilizer are assumed to be in line with recommended rates for sustainability

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[1] Percentage based on the theoretical potential

Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), Food and Agriculture Organization – Environmental impact of manure, FAOSTAT, EPA; Kearney Energy Transition Institute

Agricultural residues include a wide variety of field and process residues

Illustrative

Agricultural residues – deep-dive

Agricultural residues examples: straw and rice husks

Straw

- Straw is an agricultural by-product consisting of the dry stalks of cereal plants after the grain has been removed
- Straw can be collected using machines transforming it into straw bales
- Straw is considered a field residue, a material left in an agricultural field or orchard after the crop has been harvested

Rice husks

- Rice husks are the hard protective coverings of rice grains
- Husks can be separated from rice manually using a technique called winnowing, or thanks to a hulling machine
- Rice husks are a kind of process residues

Sources: ETIP Bionergy, Global Wood Chip Trade for Energy (IEA Bioenergy), Woodchip Heating Fuel Specifications in the Northeastern United States (BERC), Rice Knowledge Bank; Kearney Energy Transition Institute

As by-products of food crops, agricultural residues are abundant with low sustainability risks

Organic content (% Carbon)	40–50%
Ash content (%)	8–21%
Moisture content (% mass)	5–30%
Fixed carbon (%)	9–21%
Biogas yield (m3/t)	160–600
Bulk density (kg/m3)	15–200
Energy content	11–17 MJ/kg

Agricultural residues – deep-dive

Overview

Supply characteristics:

- Distributed supply limited by high equipment cost, traditional crop burning practices, and competing uses
- By-product of a necessary commodity lowering sustainability risks
- US, China, and Brazil are current supply hotspots with markets such as India pushing regulations to reduce crop burning and encourage bioenergy

Conversion technologies:

- High lignin content requires conditioning or pretreatment
- Fermentation to ethanol or thermochemical conversion to other energy biofuels products such as biodiesel and bio jet fuel

Regulations:

- Regulations impacting land use change—including restrictions on agricultural land—may impact future feedstock supply potential
- Decarbonization targets, net carbon impact policies, and carbon credit incentives may support crop growth and wider production of biofuels as substitutes for fossil alternatives

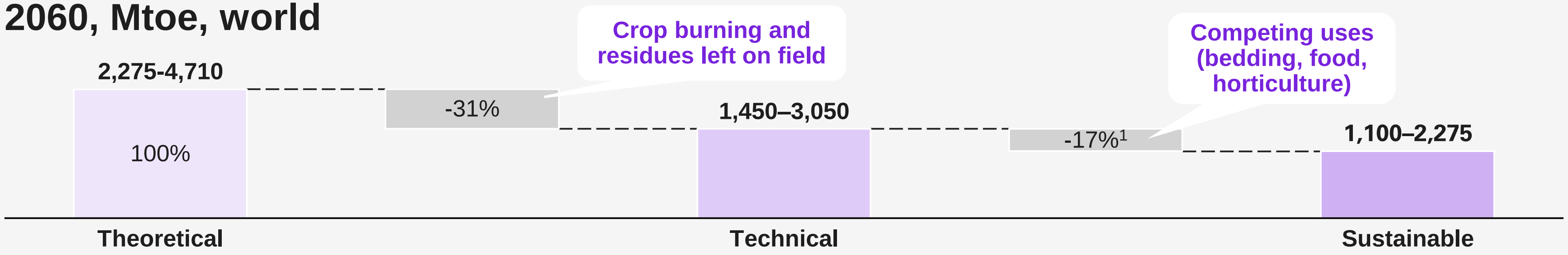
Sustainability constraints

Competing demand segments	– Food or bedding for cattle which has a low environmental impact and is coherent with circularity principles – Use for horticultural purposes or as compost
Soil quality	– Residue removal required to protect the soil and water and ensure long-term productivity
Water and air quality	– Agricultural residues limit the use of fertilizers and other pollutants when used as compost – Neutral impact on freshwater resources and access
Land use change and food competition	– No direct competition with food security but possible impact on land use rights and usage, directly and indirectly

XX Main sustainability criteria

Agricultural residues feedstock total potential

2060, Mtoe, world



- Portion of agricultural biomass remaining after primary product harvesting

- Crop burning is one of the main barriers to residue collection; its use is widespread for its low cost and ability to eliminate weed and pests
- FAO recommends 25% of residues to be left on field

- Fraction of technical potential after removing competing uses and sources that can't be processed for the food value chain or degrade soil quality

---

[1] Percentage based on the theoretical potential

Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), Ramboll, IEA, EPA, FAOSTAT; Kearney Energy Transition Institute

Forestry residues come from wood harvesting and transformation processes

Illustrative

Forestry residues examples: thinnings, sawdust, and wood chips

Thinnings

- Thinning refers to the selective removal of trees, which is undertaken notably to improve the growth rate or health of the trees remaining in the forests
- Several thinning methods can be applied in function of the objective sought (thinning from below or above to trees selected on their size, diameter-based thinning, and so on)

Sawdust

- Sawdust is composed of fine particles of wood
- It is a by-product or waste product of woodworking operations such as sawing, milling, planing, routing, drilling, or sanding
- Sawdust can be produced by woodworking machineries or tools

Wood chips

- Wood chips are wood pieces (between 5 and 50 mm) produced by mechanical treatment
- They can be split into forest chips, wood residue chips, sawing residue chips, and short rotation forestry chips

Forestry residues – deep-dive

Sources: Northern Arizona University, Wood Dust and Formaldehyde (World Health Organization IARC), Forest Research UK; Kearney Energy Transition Institute

Forestry residues supply is highly distributed and exposed to severe sustainability risks—especially in terms of biodiversity

Organic content (% Carbon)	40–50%
Ash content (%)	1–12%
Moisture content (% mass)	30–45%
Fixed carbon (%)	12–19%
Biogas yield (m3/t)	150–450
Bulk density (kg/m3)	150–265
Energy content	10–16 MJ/kg

Forestry residues – deep-dive

Overview

Supply characteristics:
- Highly distributed supply with low collection rate and high transport costs especially for primary residues
- Complex sustainability considerations (see sustainability constraints)
- Supply, although abundant, is exposed to natural disasters, weather, seasonality, and other long-term climate changes

Conversion technologies:
- Conditioning methods such as chipping, pelletization, torrefaction
- Pathways to power (for example, incineration) are the most widely performed because of their low cost
- Advanced conversion to fuels also achieved scalability in limited cases

Regulations:
- Heterogeneity of policies resulting from multiple forestry protection regulations at federal, state, and municipal levels
- Increase of regulations mandating higher residues collection rates
- Forestry policies increasingly aim to achieve zero deforestation and increase carbon sequestration detrimental to forest exploitation

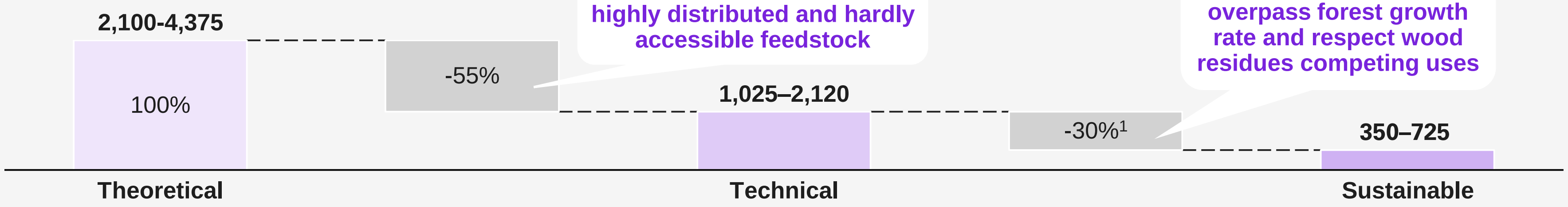
Sustainability constraints

Competing demand segments	– Secondary wood products: wood manufactured products, construction materials, and so on
Soil quality	– Residues removal (either from clear cuts or thinnings) can alter soil quality and habitat longevity and reduce soil carbon levels
Biodiversity	– Forests are home to abundant biodiversity – Protected, and environmentally sensitive forest lands to be excluded from exploitation – Production and harvest systems need to be adapted to wood species, timber size, and land condition to minimize impacts – Necessity to restrict harvest levels to ensure that tree growth exceeds harvest
Land use change	– Higher residues and wood use can induce land use change detrimental to carbon sequestration and forest biodiversity protection

XX Main sustainability criteria

Forestry residues feedstock total potential

2060, Mtoe, world



Low collection rates since highly distributed and hardly accessible feedstock

Limited collection to not overpass forest growth rate and respect wood residues competing uses

Theoretical
- Total quantity of forest residues produced in the world

Technical
- Wood residues collection conditioned by road access, topographical constraints, and forest density
- Process residues collection limited to non-hazardous wood residues

Sustainable
- Average rotation cycle of forest wood is 15 years
- Uniform distribution of tree implies one-fifteenth of total biomass to be new growth every year making use of only that portion sustainable
- Very few competing uses for wood residues

[1] Percentage based on the theoretical potential

Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), Biomass and Bioenergy Journal, FAO, IRENA, USDOE Billion Ton Report (2016); Kearney Energy Transition Institute

Kearney XX/ID

Municipal solid waste is waste collected from final product consumption (excluding commercial and industrial waste)

Illustrative

MSW – deep-dive

Municipal solid waste example: food and paper waste

Food waste

- Food waste is an organic fraction of municipal solid waste coming from discarded food items because they are spoiled or in excess
- Food waste can be collected at any step of the food supply chain: production, processing, retail, and consumption

Paper

- Paper and cardboard waste can be used as biomass feedstock; they have high carbon content and low moisture
- Their use as biomass feedstock is competing with recycling application and is usually preferred regarding the circularity principle

Source: Kearney Energy Transition Institute

Waste-to-energy pathways are attractive but policies are expected to make recycling more compelling in the long term

Overview

Supply characteristics:
- Negative feedstock cost coming from treatment/disposal social function
- Increase of total waste per capita, notably in developing countries
- Centralized waste management (for example, city councils) easing its collection

Conversion technologies:
- Anaerobic digestion and industrial composting
- Incineration, which has low feedstock quality requirements and can be an attractive disposal solution, particularly if combined with CCS
- Other technologies like gasification or Fischer-Tropsch process having stricter feedstock quality and pre-processing requirements

Regulations:
- Stricter regulation diverting waste away from landfill and ambitious targets to increase recycling rates
- Policies enforcement to improve health and sanitation in developing countries

Sustainability constraints

Competing demand segments	– Increasing conversion of waste recycling into reusable materials receiving growing policy support – Open/unmanaged landfills: causing environmental and health hazard – Biogas recovery: use of landfill to capture biogas from natural decomposition of waste
GHG emissions	– Limits landfill-related methane emissions (for example, landfills are the third-largest source of human-related methane emissions in the US)
Soil and water quality	– Recycling limits issues associated with waste disposal such as ground water contamination
Air quality	– Gases and ashes from incineration may contain heavy metals and other toxins causing air pollution and contributing to acid rain – Impact of processing facilities on air quality in proximity of inhabited areas

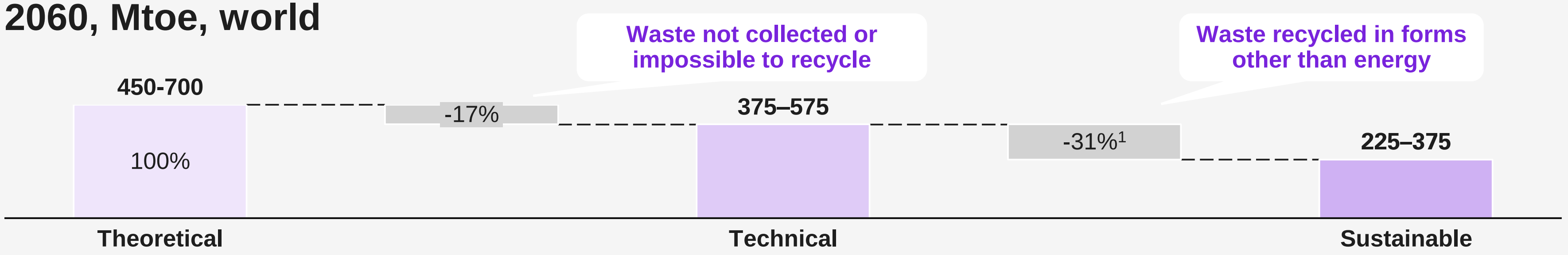
XX Main sustainability criteria

Organic content (% Carbon)	9–57%
Ash content (%)	4–28%
Moisture content (% mass)	37–61%
Fixed carbon (%)	Data missing
Biogas yield (m3/t)	100– 50
Bulk density (kg/m3)	180–260
Energy content	4–10 MJ/kg

MSW – deep-dive

Municipal solid waste feedstock total potential

2060, Mtoe, world



Theoretical
- Total amount of municipal solid waste produced in the world
- Waste generated per person per day averages 0.74kg but varies from 0.11kg to 4.54kg

Technical
- Fraction of theoretical potential that can effectively be collected within a specific region
- % of waste collected is notably linked to GDP per capita and government focus

Sustainable
- Fraction of technical potential after removal of fraction recycled in forms other than energy (for example, paper, plastic)

[1] Percentage based on the theoretical potential

Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), World bank, United Nations, World Energy Council, Ramboll; Kearney Energy Transition Institute

Algae are micro and macro organisms that rapidly grow in water from photosynthesis

Illustrative

Algae cultivation for bioenergy production

Open systems photobioreactors

- Cultivation design of choice for the vast majority of commercial algae biomass production globally
- Less expensive to build and operate than closed photobioreactors and have demonstrated commercial scale-up capability

Closed systems photobioreactors

- Objective to limit waste of water and nutrients by opting for a closed system
- Theoretical higher process efficiency allowing energy-efficient downstream processing
- Viable solution only for high-value markets (for example, food supplements, cosmetics) because of high costs

Sources: USDOE Billion Ton Report; Kearney Energy Transition Institute

Algae – deep-dive

Algae are promising but still immature and require strict regulations because of high water requirements

Organic content (% Carbon)	45–50%
Ash content (%)	< 10%
Moisture content (% mass)	80–90% (undried)
Fixed carbon (%)	Data missing
Biogas yield (m3/t)	287–611
Bulk density (kg/m3)	250–550 (macroalgae)
Energy content	18–19 MJ/kg

Algae – deep-dive

Overview

Supply characteristics:

- Diversity of species from simple unicellular cyanobacteria to complex multicellular macroalgae (seaweeds)
- Early stage technology not mature and fully scalable yet

Conversion technologies:

- Algal lipid extraction and upgrading (ALU) or hydrothermal liquefaction (HTL)

Regulations:

- Grants and R&D support (Horizon 2020 and FP7 programs in the EU, various projects in the US, CO2-Microalgae-Fuels Project in China)
- Algae supported as part of general bioenergy policies in the most mature markets (for example, EU capping on agricultural crops-based biofuels production to foster advanced biofuels including algae)

Sustainability constraints

Competing demand segments	– Food industry: algae can be served as food or used as a soil fertilizer – Chemical industry: pigments produced by algae can be used as alternatives to chemical dyes and coloring agents
GHG emissions	– CO_2 is a key nutrients for algal growth (with nitrogen and phosphorus) but has to be mitigated by the production related emissions
Water use	– High volumes of water and nutrients required to ensure commercial production of algae – Effective water recycling essential to minimize water and chemical nutrients consumption
Land use change	– Importance of cultivation site choice (climate, slope, water and nutrient sources proximity)

XX Main sustainability criteria

Algae feedstock total potential

Algae extraction technologies still early stage
No theoretical, technical, and sustainable potential estimates are available at a world level

Sources: Kearney analysis, Technology Roadmap – Delivering Sustainable Bioenergy (IEA), IEA Bioenergy – State of Technology Review Algae Bioenergy (2017), Milledge et al., Macroalgae-Derived Biofuel: A Review of Methods of Energy Extraction from Seaweed Biomass, Kearney Energy Transition Institute

Energy crops are non-edible crops specifically grown for bioenergy uses

Illustrative

Energy crops examples

Miscanthus

- Miscanthus is a non-edible crop characterized by its high biomass yield and rapid growth (up to 4 meters by season)
- It is considered as one of the most promising options to provide bioenergy
- However, miscanthus appears as a potentially invasive species

Energy cane

- Energy cane is sugarcane genetically modified to become more productive for biofuel and energy production
- Ability to be planted in areas with low agricultural capability to limit its impact on food production
- It is also designed to require less water and less inputs to grow

Energy crops – deep-dive

Sources: USDOE Billion Ton Report, GranBio, Miscanthus France; Kearney Energy Transition Institute

Energy crops are promising but can have a detrimental impact on food by changing land allocation

Organic content (% Carbon)	40–50%
Ash content (%)	1–6%
Moisture content (% mass)	10–20%
Fixed carbon (%)	10–19%
Biogas yield (m3/t)	150–450
Bulk density (kg/m3)	50–264
Energy content	10–16 MJ/kg

Energy crops – deep-dive

Overview

Supply characteristics:

- Supply predictability and control in spite of exposure to natural hazards
- Yield of energy crops is highly reliant on specific crop, local weather, soil content and quality, and therefore on site selection
- Considerations around sustainability such as competition with food crops for land use are particular risks, especially in markets with a food production deficit
- Most commonly used energy crops are willow and miscanthus

Conversion technologies:

- High lignin content requires conditioning or pretreatment
- Fermentation to ethanol or thermochemical conversion to other energy biofuels products such as biodiesel and bio jet fuel

Regulations:

- Regulations on land use change—including restrictions on energy crop plantations and other sustainability factors—impact feedstock potential

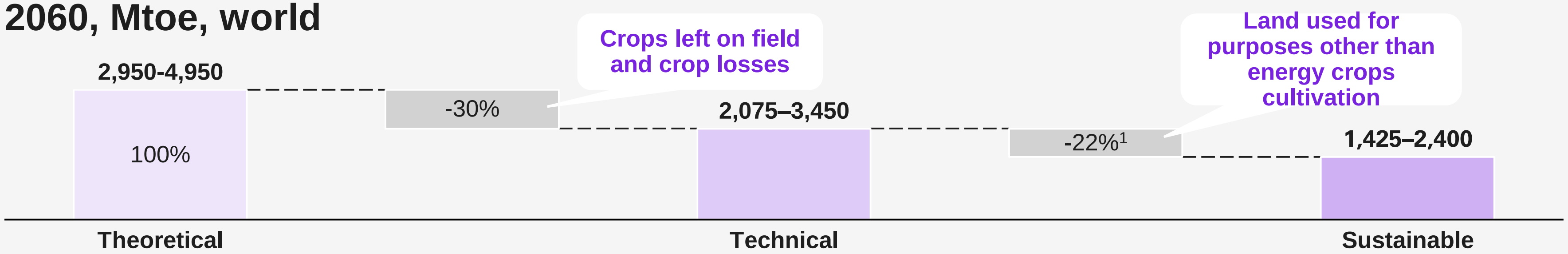
Sustainability constraints

Competing demand segments	– Use as food or feeding for animals is the only significant competing alternative – Specific energy crops are increasingly being used for other applications (for example, miscanthus as “green” building material) but adoption remains low
Soil quality	– Management of residue removal to protect the soil, maintain its carbon and nutrient content
Water and air quality	– Crops requires fertilizers and other pollutants – Possible impact on water resources
Land use change and food competition	– Limit energy crops to non-agricultural land (either arable, pasture) to avoid arable crops or livestock displacement – Strictly enforce Indirect Land Use Change (ILUC) mitigation measures to ensure the land grown on avoids food competition – High GHG emissions for production

XX Main sustainability criteria

Energy crops feedstock total potential

2060, Mtoe, world



Theoretical

- Energy crops include short rotation crops (for example, willow), as well as energy cane and perennial cultivation (for example, miscanthus)

Technical

- ~25% of feedstock left on field for crop renewal and ~5% losses
- Crops losses are biotic (weeds or pests) and abiotic (lack of water, inadequate temperature)

Sustainable

- Fraction of technical potential after removing sources that compete with food and feed crops or impact land use
- Elimination of land used for temporary or permanent meadows and pasture

---

[1] Percentage based on the theoretical potential

Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), FAO, Global Agro-Ecological Zones Portal, DEFRA UK; Kearney Energy Transition Institute

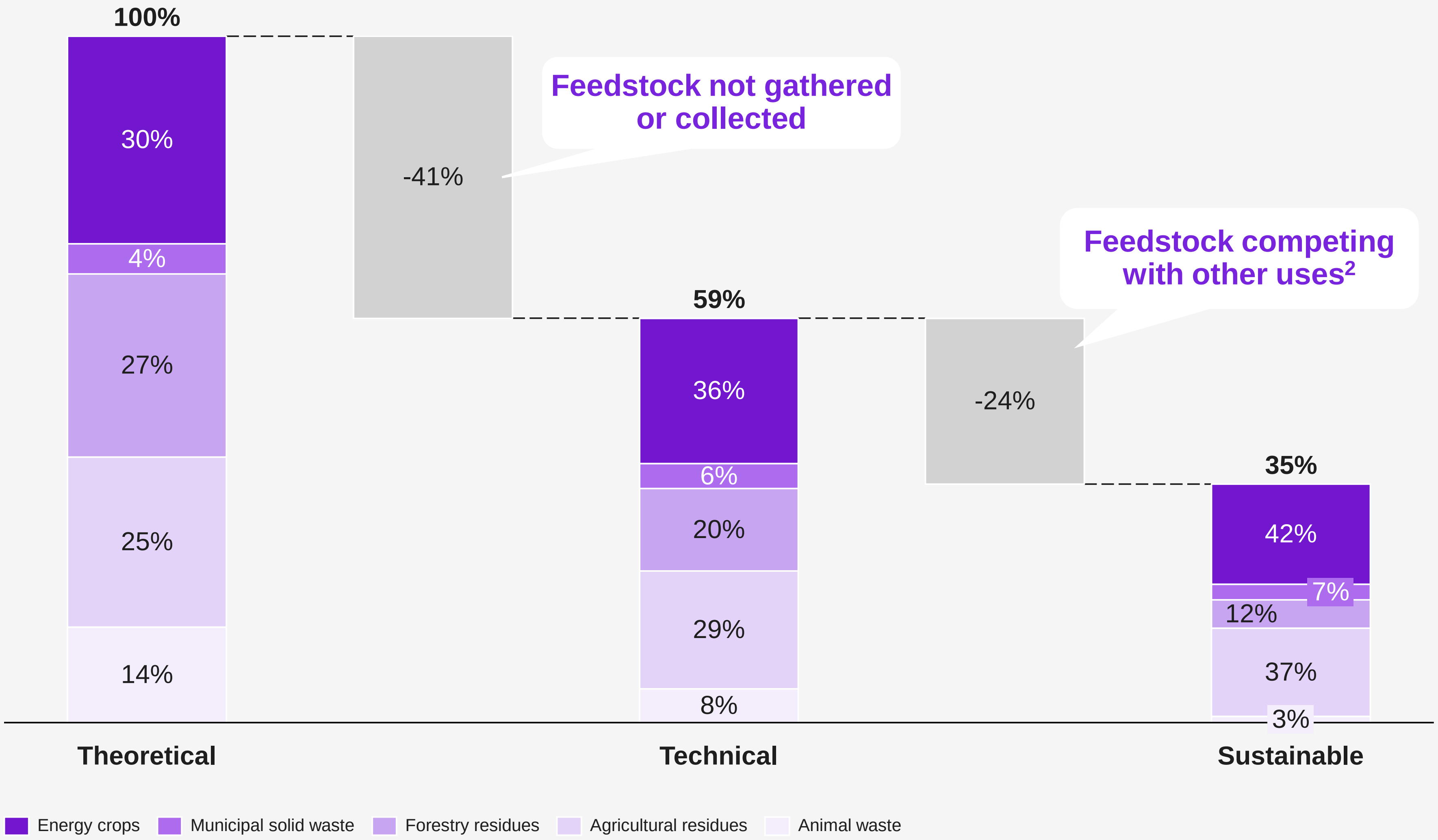
In total, one-third of the global theoretical biomass potential would be sustainably exploitable in 2060

Biomass feedstock supply is strongly linked to the food industry with about 70% of the sustainable supply coming from agricultural residues and energy crops

Feedstock – results

Feedstock energy potential by feedstock type

World, 2060, % of theoretical potential, Mtoe[1]



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[1] Algae are not taken into account because there exists no world estimate of their theoretical, technical, and sustainable potentials as it is still an early stage technology.

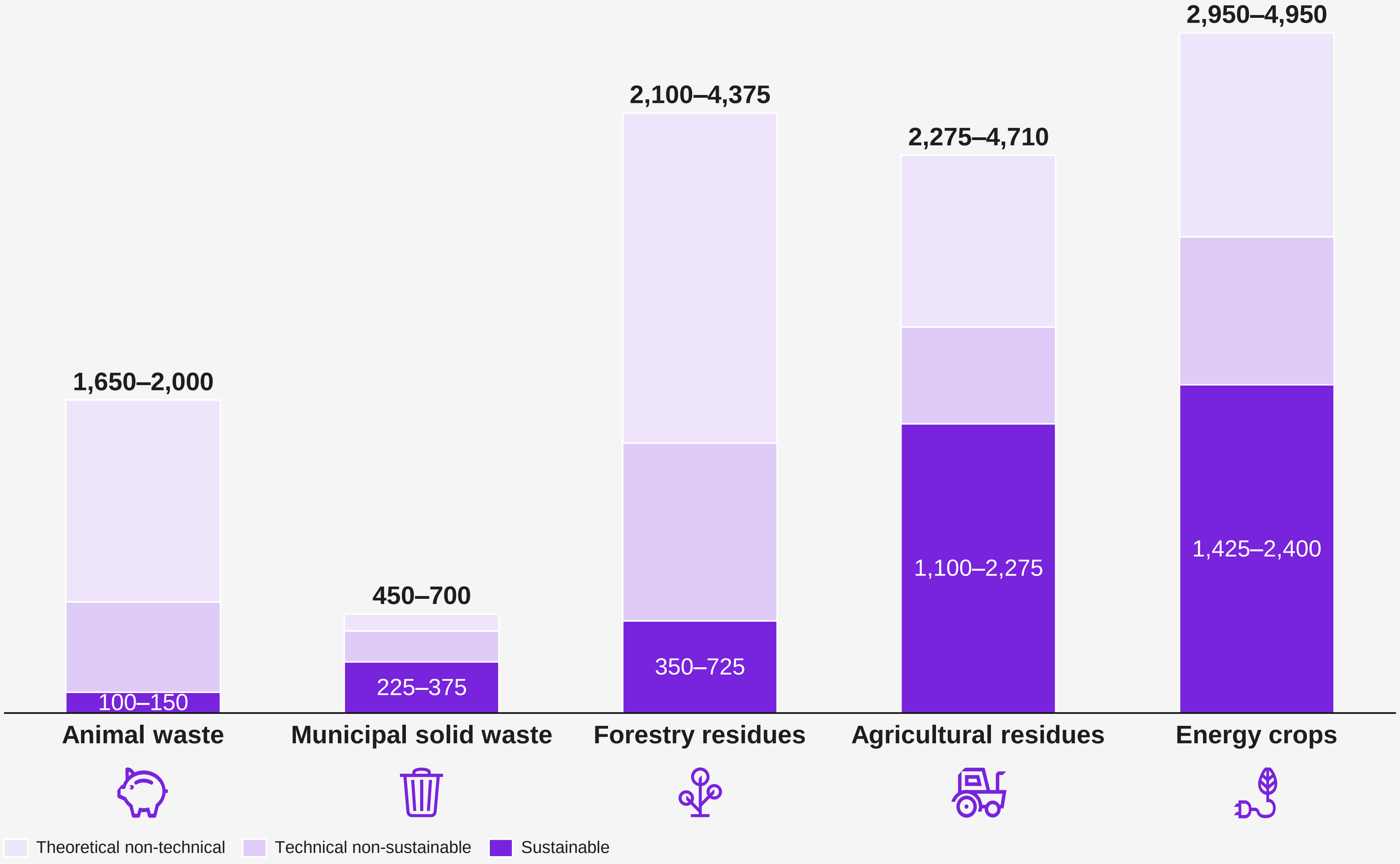
[2] Feedstock potential already used for other purposes is deducted from the technical potential to determine the sustainable potential because its use for bioenergy purposes would induce an additional pressure on the resource which could lead to feedstock depletion.

Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), USDOE Billion Ton Report (2016); Kearney Energy Transition Institute

Agricultural residues and energy crops will be the two main sources of biomass supply by 2060

Feedstock energy potential by feedstock type

World, 2060, Mtoe



Sources: Technology Roadmap – Delivering Sustainable Bioenergy (IEA), USDOE Billion Ton Report (2016); Kearney Energy Transition Institute

Feedstock – results

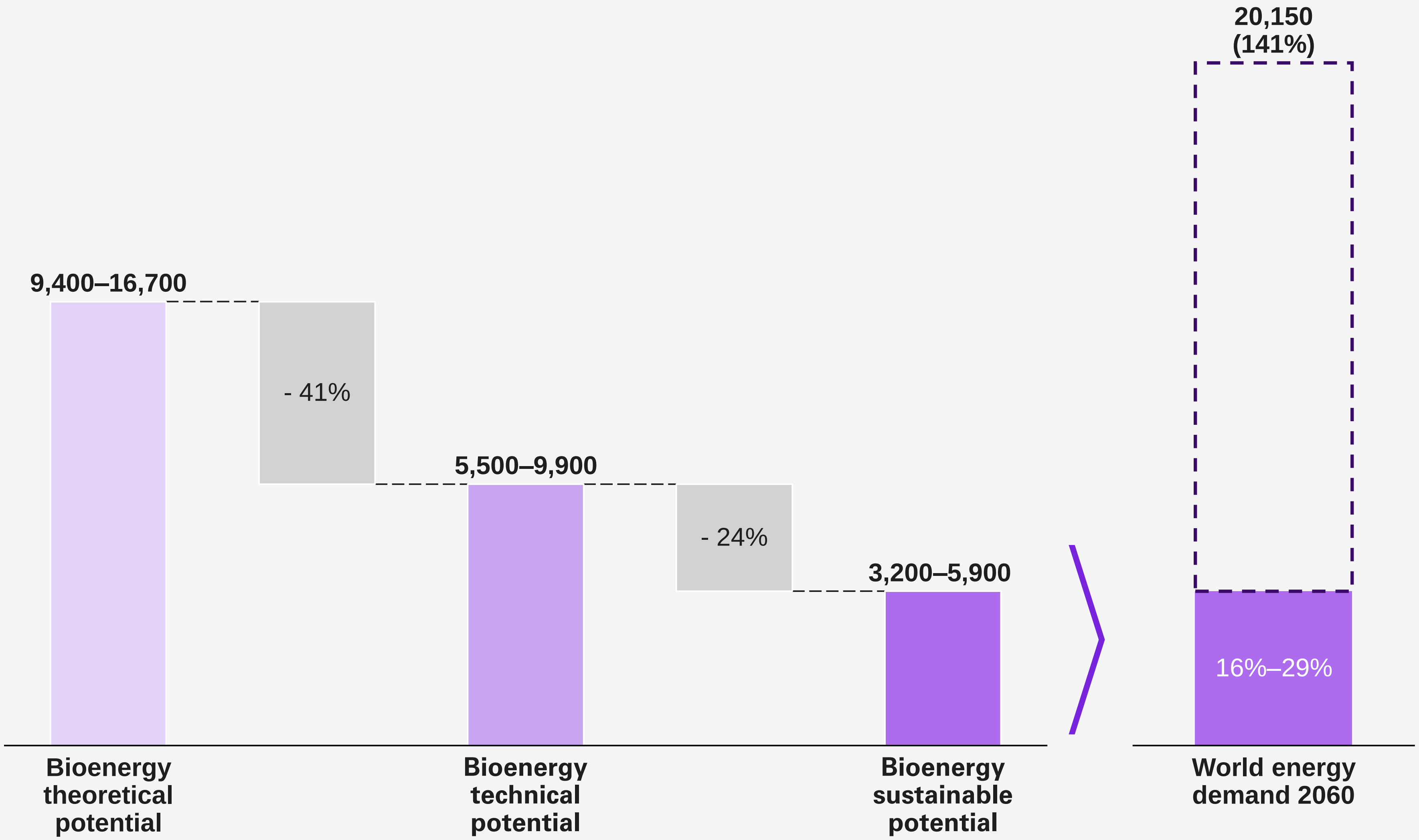
As a result, bioenergy could sustainably supply ~25% of the world energy demand in 2060

With feedstock supply being limited, their allocation in the biomass-to-bioenergy needs to be focused on decarbonizing sectors with no other renewable alternatives options.

Feedstock – results

Bioenergy potential vs. world energy demand[1]

World, 2060, Mtoe



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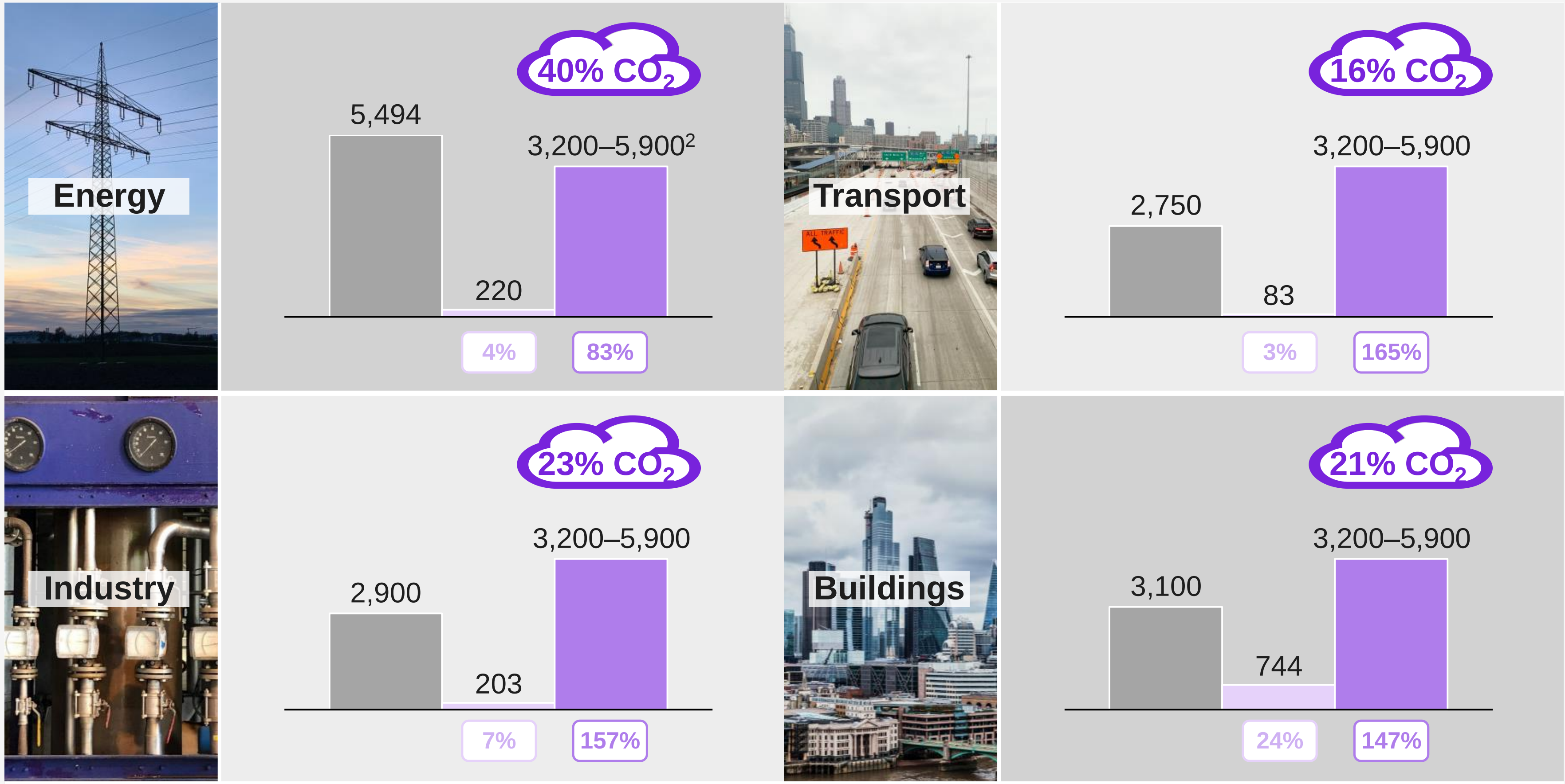
[1] Potentials calculated in this section account for the “raw” energy embedded in the feedstocks. A more accurate comparison would take into account the difference between the energy embedded in the different feedstocks and the energy content of the biomass-derived fuels.

Sources: IEA WEO 2019, IEA Energy Technology Perspectives 2017, Technology Roadmap – Delivering Sustainable Bioenergy (IEA), USDOE Billion Ton Report (2016); Kearney Energy Transition Institute

The future bioenergy potential is enough to power either the entire transport, buildings, or industry sector

Bioenergy sustainable potential vs. energy by sector

World, Mtoe, 2018[1]



%CO_2 GHG emissions reduction | % of current bioenergy | % of sustainable bioenergy

■ Current sector energy consumption ■ Current bioenergy share in sector consumption ■ Future sustainable potential bioenergy consumption

[1] The sum of energy demands in the different subsectors does not exactly match the total of the previous slide because this chart also considers the secondary products (heat, electricity) consumed in the transport, industry, and buildings sectors.

[2] The value of bioenergy potential in 2060 is based on the mean of the range displayed (3,200–5,900 Mtoe), 2060 figures were used because of the lack of consensus on today's bioenergy sustainable potential.

Sources: World Energy Outlook 2019 (IEA), Technology Roadmap – Delivering Sustainable Bioenergy (IEA); Kearney Energy Transition Institute

Feedstock – results

Key questions

Source: Kearney Energy Transition Institute

For each biofuel, what is the best combination of processing method and feedstock?

i. What are the technical and economic characteristics of the existing processing methods?

ii. What are their level of maturity and future potential?

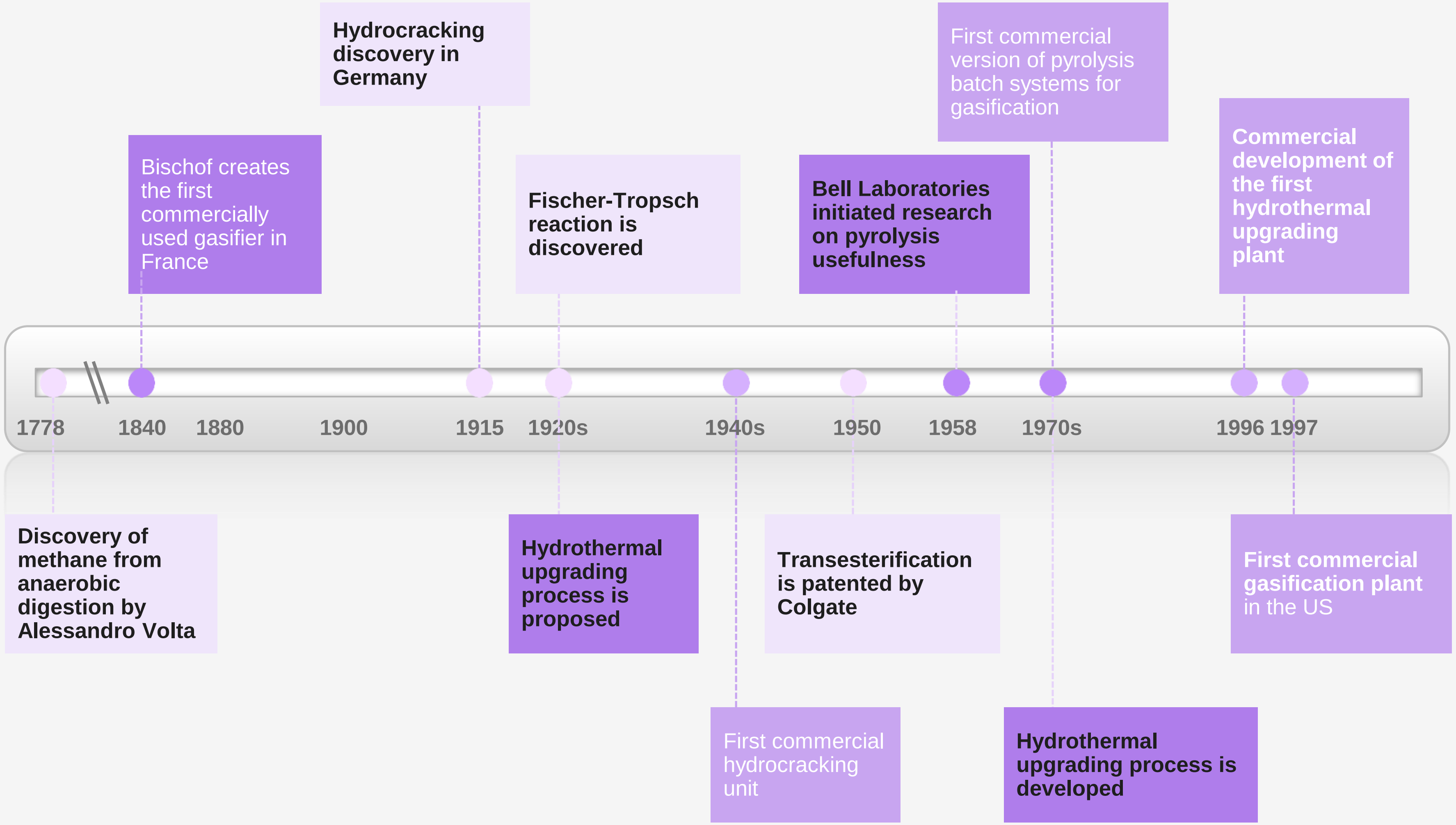
iii. What are the most suitable feedstocks for each existing processing method?

Processing technologies for advanced biomass were commercially developed during the 20th century

Non-exhaustive

Processing methods – introduction

History of biomass processing technologies



Hydrocracking discovery in Germany

First commercial version of pyrolysis batch systems for gasification

Bischof creates the first commercially used gasifier in France

Fischer-Tropsch reaction is discovered

Bell Laboratories initiated research on pyrolysis usefulness

Commercial development of the first hydrothermal upgrading plant

Discovery of methane from anaerobic digestion by Alessandro Volta

Hydrothermal upgrading process is proposed

Transesterification is patented by Colgate

First commercial gasification plant in the US

First commercial hydrocracking unit

Hydrothermal upgrading process is developed

▇ Technical achievement ▇ Commercial development ▇ Discoveries

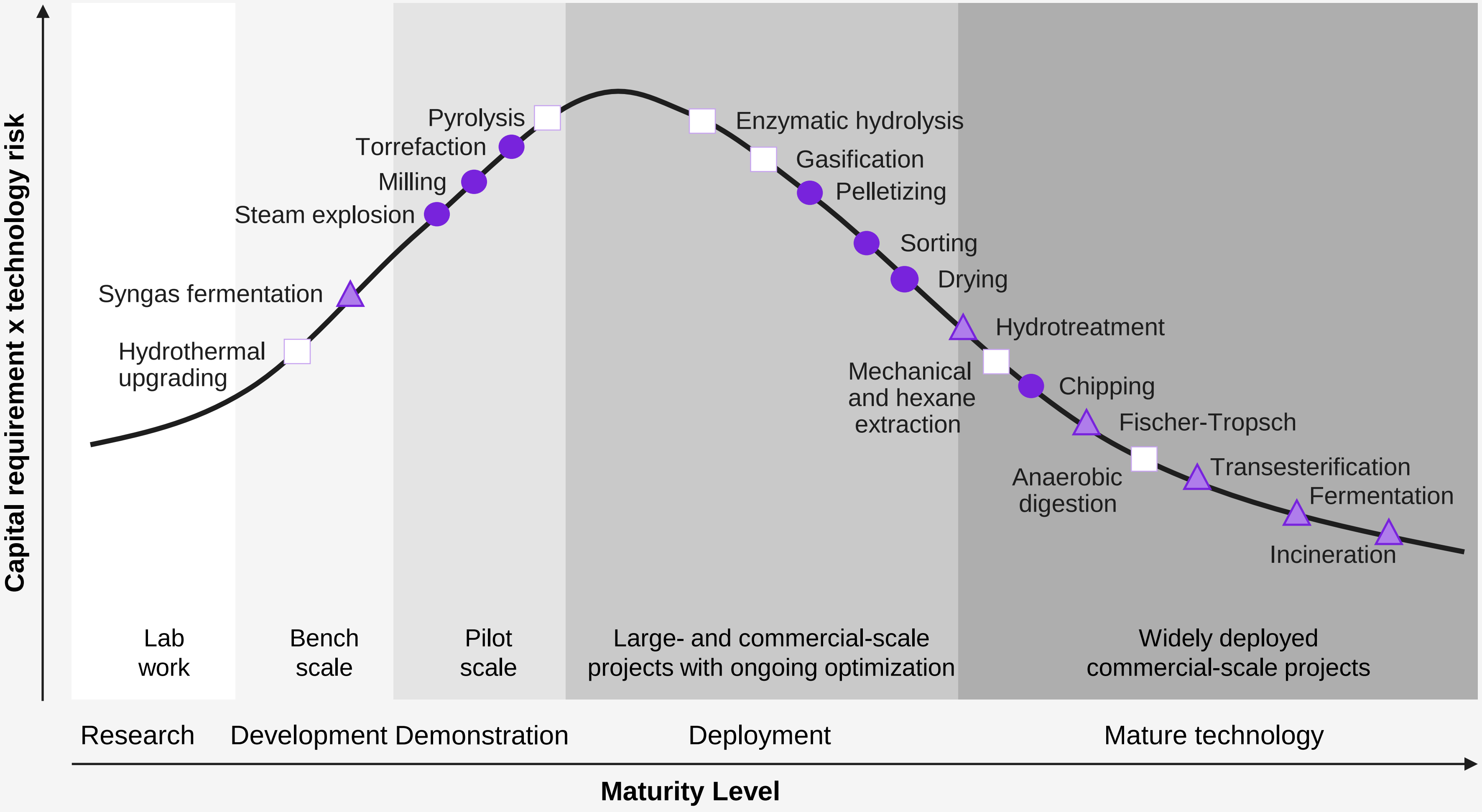
Source: Kearney Energy Transition Institute

Today, technologies also used to transform conventional resources are more mature than those mainly applicable to biomass

Those technologies' technical characteristics and economics are detailed in Appendix.

Processing methods – introduction

Technology maturity curve for bioenergy processing methods



● Conditioning ☐ pretreatment ▲ Conversion

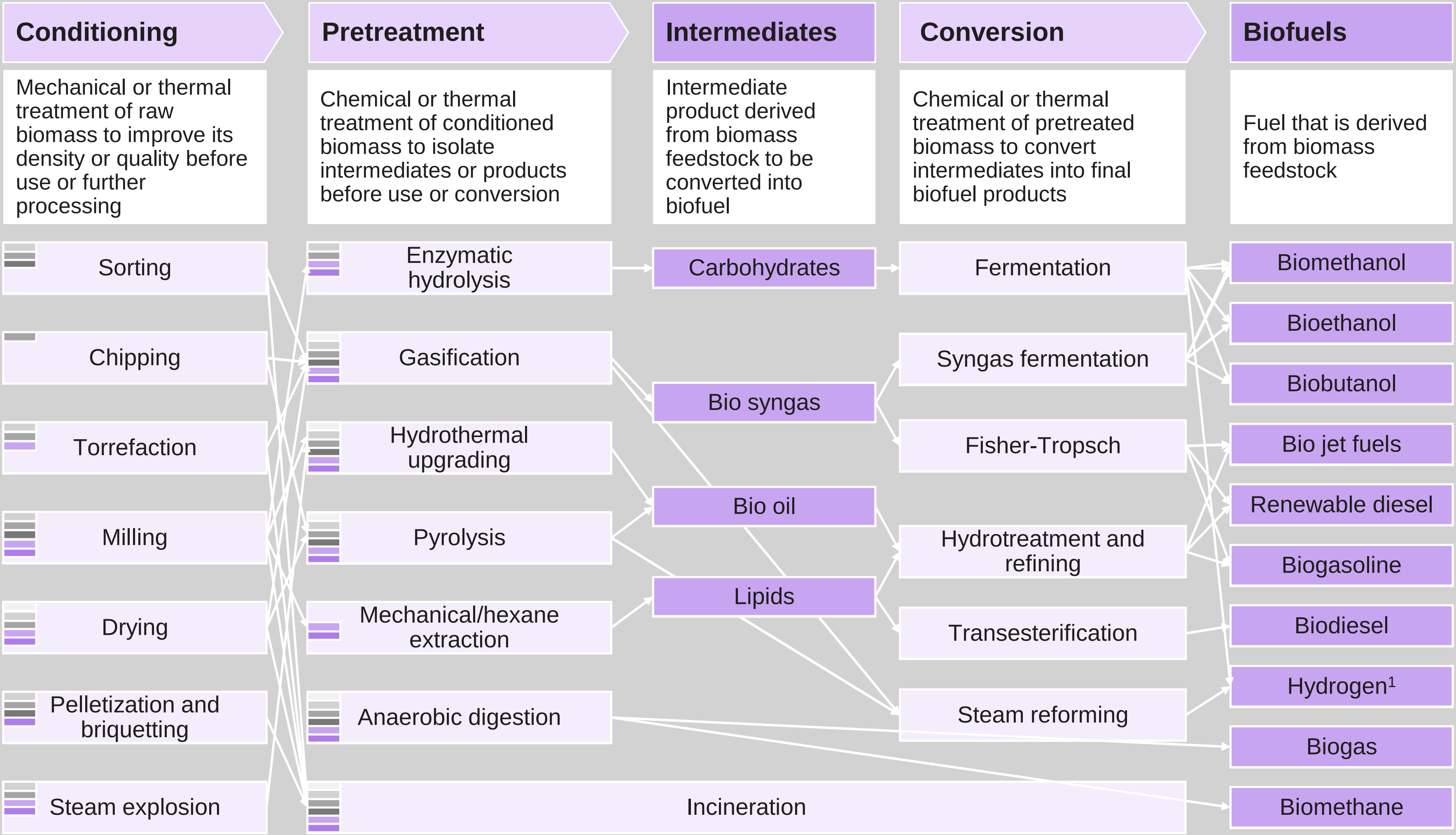
Sources: Advanced Biofuel Feedstocks – An Assessment of Sustainability (ARUP); Kearney Energy Transition Institute

Bioenergy relies on multiple possible combinations of feedstock and conversion pathways

Each one of those technologies and products is deep-dived in fact cards (see Appendix).

Processing methods – scope of analysis

From biomass to biofuels



Conditioning

Mechanical or thermal treatment of raw biomass to improve its density or quality before use or further processing

- Sorting
- Chipping
- Torrefaction
- Milling
- Drying
- Pelletization and briquetting
- Steam explosion

Pretreatment

Chemical or thermal treatment of conditioned biomass to isolate intermediates or products before use or conversion

- Enzymatic hydrolysis
- Gasification
- Hydrothermal upgrading
- Pyrolysis
- Mechanical/hexane extraction
- Anaerobic digestion
- Incineration

Intermediates

Intermediate product derived from biomass feedstock to be converted into biofuel

- Carbohydrates
- Bio syngas
- Bio oil
- Lipids

Conversion

Chemical or thermal treatment of pretreated biomass to convert intermediates into final biofuel products

- Fermentation
- Syngas fermentation
- Fisher-Tropsch
- Hydrotreatment and refining
- Transesterification
- Steam reforming

Biofuels

Fuel that is derived from biomass feedstock

- Biomethanol
- Bioethanol
- Biobutanol
- Bio jet fuels
- Renewable diesel
- Biogasoline
- Biodiesel
- Hydrogen[1]
- Biogas
- Biomethane

Feedstock compatibility

- Animal waste
- Municipal solid waste
- Agricultural residues
- Algae
- Forestry residues
- Energy crops

1. Hydrogen value chain is assessed in an other FactBook "Hydrogen-based energy conversion" https://www.energy-transition-institute.com/insights/hydrogen-based-energy-conversion, thus we only mention it as a product of gasification but do not detail this here

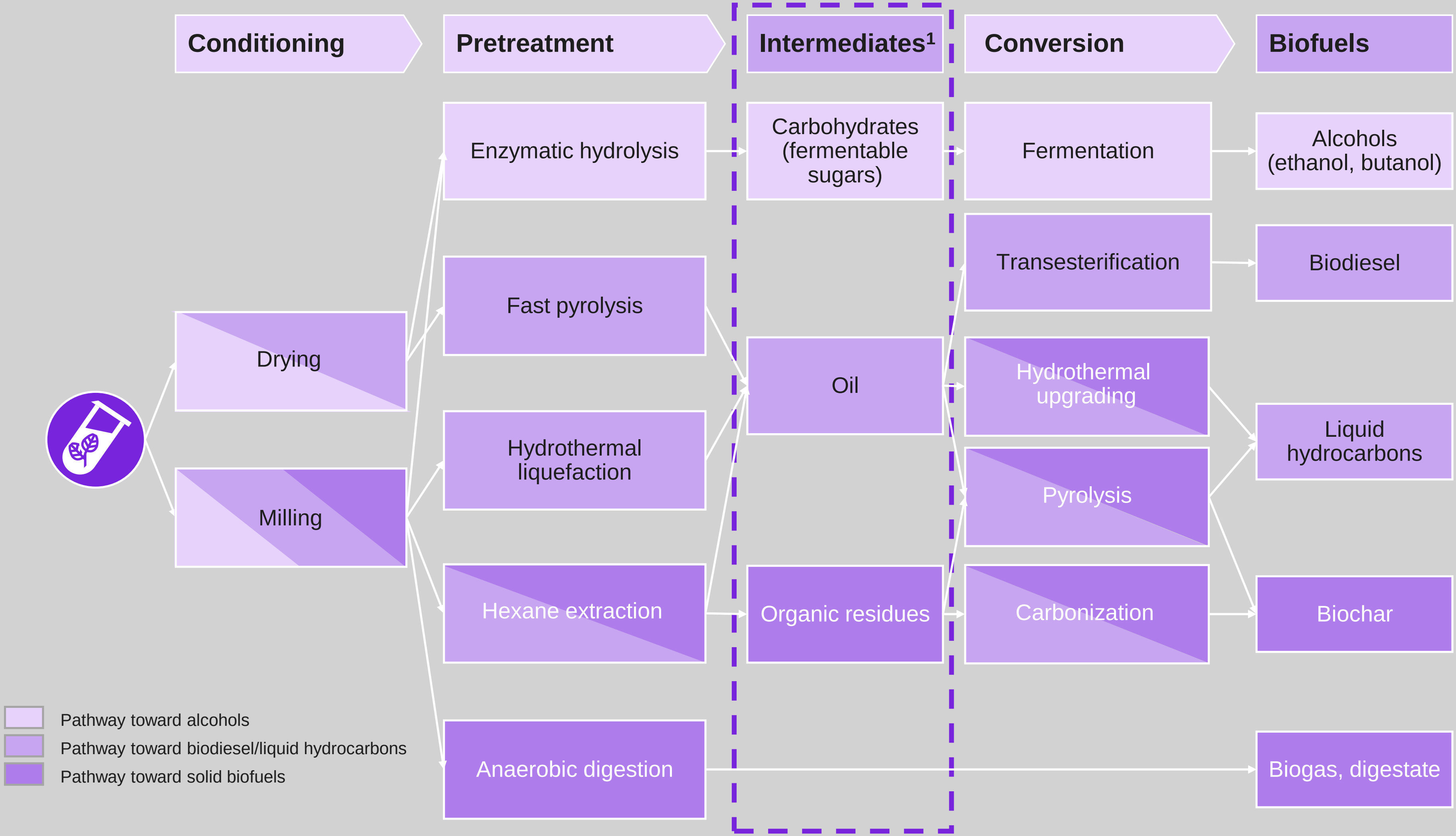
Sources: IEA Bioenergy roadmap; Kearney Energy Transition Institute

Despite the variety of conversion routes for a given feedstock, intermediates act as a bottleneck in the processing chain

Illustrative

For instance, from algae, numerous pretreatments are specifically producing oil that can be further refined in liquid hydrocarbons or biodiesel.

Processing methods: example of algae processing routes



Conditioning

- Drying
- Milling

Pretreatment

- Enzymatic hydrolysis
- Fast pyrolysis
- Hydrothermal liquefaction
- Hexane extraction
- Anaerobic digestion

Intermediates[1]

- Carbohydrates (fermentable sugars)
- Oil
- Organic residues

Conversion

- Fermentation
- Transesterification
- Hydrothermal upgrading
- Pyrolysis
- Carbonization

Biofuels

- Alcohols (ethanol, butanol)
- Biodiesel
- Liquid hydrocarbons
- Biochar
- Biogas, digestate

Pathway toward alcohols

Pathway toward biodiesel/liquid hydrocarbons

Pathway toward solid biofuels

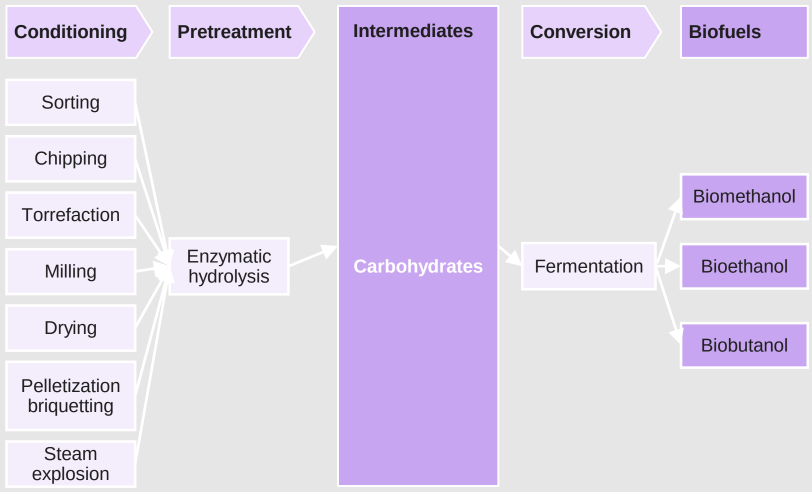
---

[1] Intermediates are preferred based on the largest fraction of interest in the feedstock; for example, if the feedstock is rich in fat or oil conditioning and pretreatment will be designed to extract this fraction of interest. Algae present two fractions of interest, the ratios of which can vary by species: carbohydrates (sugar) and lipids (oil). Based on the intermediate targeted, different routes are chosen.

Source: Kearney Energy Transition Institute

Intermediates are segmentation points: they can be produced from most feedstock but determine the obtained biofuel

Carbohydrates



Conditioning | Pretreatment | Intermediates | Conversion | Biofuels

Sorting
Chipping
Torrefaction
Milling
Drying
Pelletization briquetting
Steam explosion

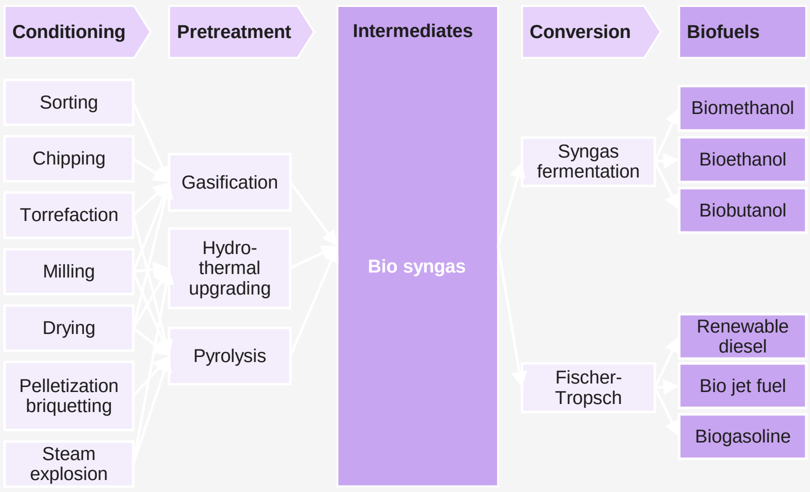
Enzymatic hydrolysis

Carbohydrates

Fermentation

Biomethanol
Bioethanol
Biobutanol

Bio syngas



Conditioning | Pretreatment | Intermediates | Conversion | Biofuels

Sorting
Chipping
Torrefaction
Milling
Drying
Pelletization briquetting
Steam explosion

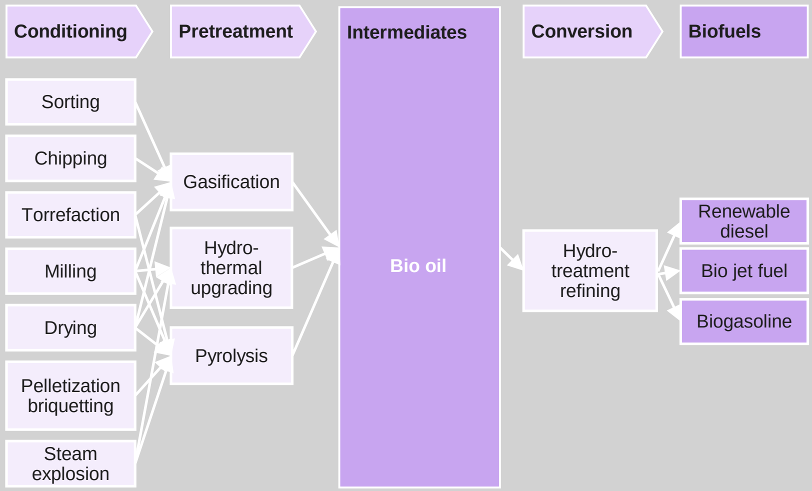
Gasification
Hydro-thermal upgrading
Pyrolysis

Bio syngas

Syngas fermentation
Fischer-Tropsch

Biomethanol
Bioethanol
Biobutanol
Renewable diesel
Bio jet fuel
Biogasoline

Bio oil



Conditioning | Pretreatment | Intermediates | Conversion | Biofuels

Sorting
Chipping
Torrefaction
Milling
Drying
Pelletization briquetting
Steam explosion

Gasification
Hydro-thermal upgrading
Pyrolysis

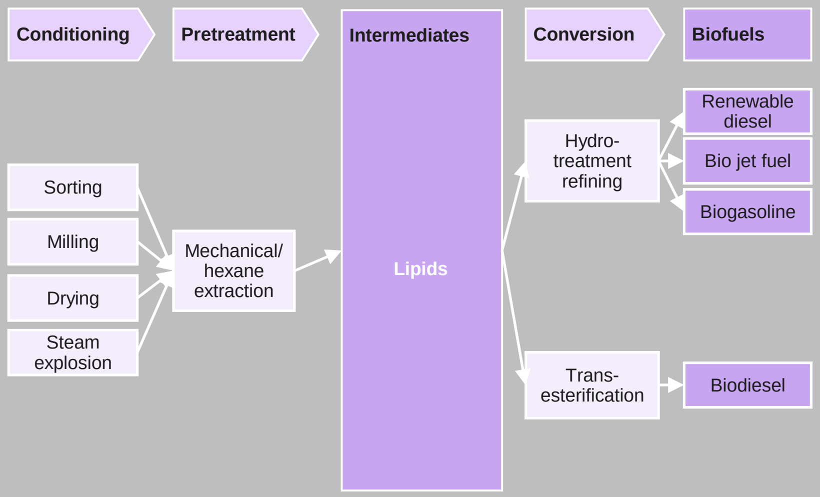
Bio oil

Hydro-treatment refining

Renewable diesel
Bio jet fuel
Biogasoline

Source: Kearney Energy Transition Institute

Lipids



Conditioning | Pretreatment | Intermediates | Conversion | Biofuels

Sorting
Milling
Drying
Steam explosion

Mechanical/ hexane extraction

Lipids

Hydro-treatment refining
Trans-esterification

Renewable diesel
Bio jet fuel
Biogasoline
Biodiesel

Processing methods – intermediates

Based on the targeted interest fraction, intermediates are selectively extracted from biomass and can be converted into biofuels

There are four different kinds of intermediate products: carbohydrates, biosyngas, oils, and lipids (fats)

Processing methods – intermediates

Overview of four types of intermediates

Carbohydrates

Definition

- Molecules composed of atoms of carbon, hydrogen, and oxygen with two hydrogen atoms for one oxygen atom (chemical formula Cm(H2O)n)

Pretreatment obtained from

- Hydrolysis

Compatible conversion processes

- Fermentation

Biosyngas

Definition

- Gas produced through gasification; mainly composed of carbon monoxide, hydrogen and carbon dioxide

Pretreatment obtained from

- Gasification

Compatible conversion processes

- Syngas fermentation
- Fischer-Tropsch

Pyrolysis oil

Definition

- Fuel obtained after pyrolysis; studied as a potential substitute for petroleum

Pretreatment obtained from

- Pyrolysis

Compatible conversion processes

- Hydrotreatment and refining

Vegetable oils and fats

Definition

- Vegetable oils and fats are lipids isolated after hydrothermal upgrading or mechanical extraction

Pretreatment obtained from

- Hydrothermal upgrading
- Mechanical/hexane extraction

Compatible conversion processes

- Hydrotreatment and refining
- Transesterification

Sources: Apanews (Picture), CBT Oil (Picture), Clariant (Picture), Indiamart (Picture); Kearney Energy Transition Institute

The assessment of feedstock to biofuel pathways is a two-step approach

Processing methods assessment methodology

Criteria	Definition and objectives	Output	Final result
Feedstock to intermediate performance assessment	– Feedstocks are assessed based on their intrinsic characteristics (compatibility, rentability, efficiency, availability, sustainability) giving a suitability regarding processes toward a given intermediate – A fact card with technical details and corresponding rate is produced for each relevant conditioning and pretreatment process	① **Ranking of feedstock and selection of the most suitable by processing methods given a targeted intermediate**	**Feedstock x processing method x biofuel optimal combination**
Intermediate to biofuel performance assessment	– Conversions are assessed based on their compatibility, efficiency, rentability, and sustainability for an intermediate regarding a given biofuel – Maturity level (in other words, room for efficiency increased) of each conversion process is used as a proxy to put the process performance rates in a dynamic perspective	② **Ranking of the conversion methods and selection of the most suitable by biofuels**	

Source: Kearney Energy Transition Institute

Processing methods - assessment methodology

Conditioning and pretreatment turn raw biomass into intermediate, suitable matter for conversion

①

Conditioning and pretreatment methods change feedstock physical properties to increase the efficiency of conversion processes toward biofuel.

Conditioning and pretreatment – results

Conditioning and pretreatment technologies and feedstock compatibility

			Feedstocks					
Processing methods	**Conditioning**	① Sorting		●	🟣	●		
		② Torrefaction		🟣		🟣	●	
		③ Chipping				🟣		
		④ Drying	●	●		●	●	🟣
		⑤ Pelletization and briquetting		●	🟣	🟣		●
		⑥ Milling		●	●	🟣	●	●
		⑦ Steam explosion		🟣		●	●	🟣
Processing methods	**Pretreatment**	① Enzymatic hydrolysis		🟣		●		🟣
		② Pyrolysis	●	🟣	●	●		🟣
		③ Anaerobic digestion	🟣	🟣	●			●
		④ Mechanical and hexane extraction					●	🟣
		⑤ Gasification	●	🟣	●	🟣		🟣
		⑥ Hydrothermal upgrading	●	🟣	●	●		●

ⓧ Detailed ● Applicable 🟣 Optimal conditioning x feedstock combination

Source: Kearney Energy Transition Institute

Most conditioning methods are applicable to a wide variety of feedstocks and can significantly improve value chain attractiveness

View of biomass conditioning technologies

		Sorting	Torrefaction	Chipping	Drying	Pelletization	Milling	Steam explosion
Global production dynamics	Feedstock applicability	MSW, residues (agricultural and forestry)	Forestry and agricultural residues, energy crops	Forestry residues	Forestry and agricultural residues, energy crops, algae, and animal waste	Forestry and agricultural residues, energy crops, and MSW	Forestry and agricultural residues, energy crops, algae, and animal waste	Energy crops, agricultural and forestry residues, algae
	Maturity index rating[1]	Deployment	Demonstration	Mature	Deployment	Deployment	Demonstration	Demonstration
	Main biofuel generated	None	Charcoal	Wood chips	None	Wood pellets	None	None
Production economics	Conversion efficiency[2]	35%	96%	≈ 90%	≈ 100%	≈ 100%	Data missing	≈ 80%
	Capex	Medium	High	Low	Low	Medium	Medium	Medium
	Opex drivers[3]	Labor Energy use Maintenance	Energy use	Maintenance costs (knives and blades)	Maintenance costs Energy use	Maintenance costs	Maintenance costs	Energy use Maintenance costs
	Overall attractiveness[4]	◑	◑	◕	●	◕	◑	◕

---

[1] Maturity of the process is given for its specific application to biomass.
[2] Conversion efficiency is calculated according to the fraction of interest of the product and might not be comparable between all conditioning processes.
[3] Opex highly depends on feedstock pick-up, transfer, and transport to final disposal site.
[4] Overall attractiveness does not take maturity of the process into account.

Source: Kearney Energy Transition Institute

Pretreatment technologies mostly have specific outputs; their efficiency and capex heavily impact the value chain attractiveness

①

View of biomass pretreatment technologies

		Enzymatic hydrolysis	Fast pyrolysis	Anaerobic digestion	Mechanical/ hexane extraction	Gasification	Hydrothermal upgrading
Global production dynamics	Feedstock applicability	Energy crops, agricultural residues, forestry residues	Agricultural residues, energy crops	MSW, animal waste	Energy crops (oily), algae	Forestry residues, agricultural residues, energy crops	Agricultural residues, energy crops
	Maturity index rating[1]	Ethanol, butanol, methanol	Renewable diesel, jet fuel, gasoline	Methane	Biodiesel	Methane Ethanol	Renewable diesel, jet fuel, gasoline
	Main biofuel generated	Mature	Pilot/demonstration	Mature	Mature	Pilot/demonstration	Pilot
Production economics	Conversion efficiency[2]	High	Low	Medium	Medium	Medium	High
	Capex	70%	60–80%	30–60%	95%	90%	60–90%
	Opex drivers[3]	Feedstock Energy use Enzymes	Feedstock Maintenance Energy use Labor	Feedstock	CO_2 Energy use Labor	Maintenance Fuel Water treatment Waste disposal	Raw material Operation Energy use
	Overall attractiveness[4]	◑	◕	◔	◕	◕	◑

[1] Maturity of the process is given for its specific application to biomass.
[2] Conversion efficiency is calculated according to the fraction of interest of the product and might not be comparable between all pretreatment processes.
[3] Opex highly depends on feedstock pick-up, transfer, and transport to final disposal site.
[4] Overall attractiveness does not take maturity of the process into account.
Source: Kearney Energy Transition Institute

Conversion processes are often selective toward a type of biofuel: biogas, liquid hydrocarbons, or alcohols

②

Conversion processes are often derived from the petroleum industry and adapted to biomass.

Conversion technologies – results

Advanced biofuels and conversion technologies compatibility

			Processing methods					
			Conversion					
			Fermentation ①	Syngas fermentation ②	Fischer-Tropsch ③	Trans-esterification ④	Hydro-treatment/ refining/ cracking ⑤	Anaerobic digestion[1] ③
Biofuels	Liquid	Biomethanol	●	🟣				●
		Bioethanol	🟣	●				
		Biobutanol	🟣					
		Biogasoline			●		🟣	
		Biodiesel				🟣		
		Renewable diesel			●		🟣	
		Bio jet fuels	●		●		🟣	
	Gas	Biomethane		●				🟣
		Biogas		●				🟣

ⓧ Detailed ● Applicable 🟣 Optimal biofuel x conversion technology combination

[1] Pretreatment process but it gives biofuel of interest.

Sources: European Biofuels Technology Platform; Kearney Energy Transition Institute

Conversion technologies are strongly linked with the pretreatment step but also impact the value chain economics with their efficiency and capex

②

View of biomass conversion technologies

		Fermentation	Hydrotreatment and refining	Fischer-Tropsch	Syngas fermentation	Trans-esterification	Incineration
Global production dynamics	Feedstock applicability	Based on sugar extracted from biomass	Ligno-cellulosic, wood residues…	MSW, energy crops, manure	Ligno-cellulosic, wood residues…	Oily energy crops, algae	All
	Maturity index rating[1]	Ethanol, butanol	Renewable diesel, jet fuel, gasoline	Renewable diesel, jet fuel, gasoline	Ethanol Methane	Biodiesel	None (only heat/power)
	Main biofuel generated	Mature	Mature	Mature	Pilot	Mature	Mature
Production economics	Conversion efficiency[2]	High	Medium	Low	High/medium	High/medium	Medium
	Capex	50%	50%	45%	57%	90%	17–30%
	Opex drivers[3]	Raw material Labor Utilities	Feedstock Utilities Chemicals	Purification catalysts	Microbial catalyst Purification	Raw materials Utilities Chemicals	Maintenance
	Overall attractiveness[4]	○	◑	◑	○	◑	◔

Conversion technologies - results

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[1] Maturity of the process is given for its specific application to biomass.
[2] Conversion efficiency is calculated according to the fraction of interest of the product and might not be comparable between all conversion processes.
[3] Opex highly depends on feedstock pick-up, transfer, and transport to final disposal site.
[4] Overall attractiveness does not take maturity of the process into account.
Source: Kearney Energy Transition Institute

For each biofuel the possible processing routes and associated feedstocks are listed and compared

②

A more detailed description and assessment of these biofuels is conducted alongside solid biofuels in the section II.1 of this report

Processing methods – conclusion

Possible biofuels produced through biomass conversion processes

	Definition	Conversion	Pretreatment	Feedstock compatibility
Biomethanol	Methanol (chemical formula CH_3OH) produced from biomass sources	🟪 Syngas fermentation	🟪 Gasification	○ ○ ● ● ○ ○
		◼ Methane reforming	◼ Anaerobic digestion	
			◻ Syngas fermentation	
		◻ Fermentation	◻ Enzymatic hydrolysis	
Bioethanol	Ethanol (chemical formula C_2H_5OH) produced from biomass sources, which is mainly used blended with gasoline in gasoline engines	🟪 Fermentation	🟪 Enzymatic hydrolysis	○ ○ ● ○ ○ ●
		◼ Syngas fermentation	◼ Gasification	
Biobutanol	Butanol (chemical formula C_4H_9OH) produced from biomass sources, mainly used to produce chemicals	🟪 Fermentation	🟪 Enzymatic hydrolysis	○ ○ ● ○ ○ ●
Biogasoline	Hydrocarbon with a similar chemical composition to fossil gasoline produced from biomass sources and studied as an alternative to gasoline	🟪 Hydrotreatment	🟪 Hydrothermal liquefaction	○ ● ○ ○ ● ●
			◼ Fast pyrolysis	
		◼ Fischer-Tropsch	◼ Hydrothermal liquefaction	
			◻ Fast pyrolysis	
Biodiesel	Liquid biofuels sourced from biomass suitable to be blended with fossil-fuel diesel	🟪 Transesterification	🟪 Mechanical/hexane extraction	● ○ ○ ● ● ○
Renewable diesel	Hydrocarbon with a similar chemical composition to fossil diesel which can be used without blending limits in diesel engines	🟪 Hydrotreatment	🟪 Hydrothermal liquefaction	● ● ○ ○ ● ○
			◼ Fast pyrolysis	
		◼ Fischer-Tropsch	◼ Hydrothermal liquefaction	
			◻ Fast pyrolysis	
Bio jet fuels	Liquid biofuels sourced from biomass suitable to be blended with fossil-fuel diesel	🟪 Hydrotreatment	🟪 Hydrothermal liquefaction	● ○ ● ○ ○ ●
			◼ Fast pyrolysis	
			◻ Mechanical/hexane extraction	
		◼ Fischer-Tropsch	◼ Hydrothermal liquefaction	
			◻ Fast pyrolysis	
			◻ Mechanical/hexane extraction	
		◻ Fermented sugars	◻ Enzymatic hydrolysis	
Biomethane	Methane (chemical formula CH_4) obtained from biomass sources	🟪 Anaerobic digestion	▨	● ● ● ● ○ ○
		◼ Syngas fermentation	◼ Gasification	
Biogas	Gas obtained either through the combustion or decomposition of waste through a thermal or a chemical process	▨	🟪 Anaerobic digestion	● ● ○ ● ○ ○

🟪 Preferred pathways/feedstock

◼ Second best pathways
Non-applicable or compatible feedstock

◻ Other possible pathways

Source: Kearney Energy Transition Institute

Section 2

Biofuels market opportunities and enablers

Key questions

What is the best biofuel x market segment combination?

i. What are the technical and environmental characteristics of biofuels?

ii. What are the competitive advantages vs. fossil fuels or other renewable energy sources?

iii. Which markets are the most promising?

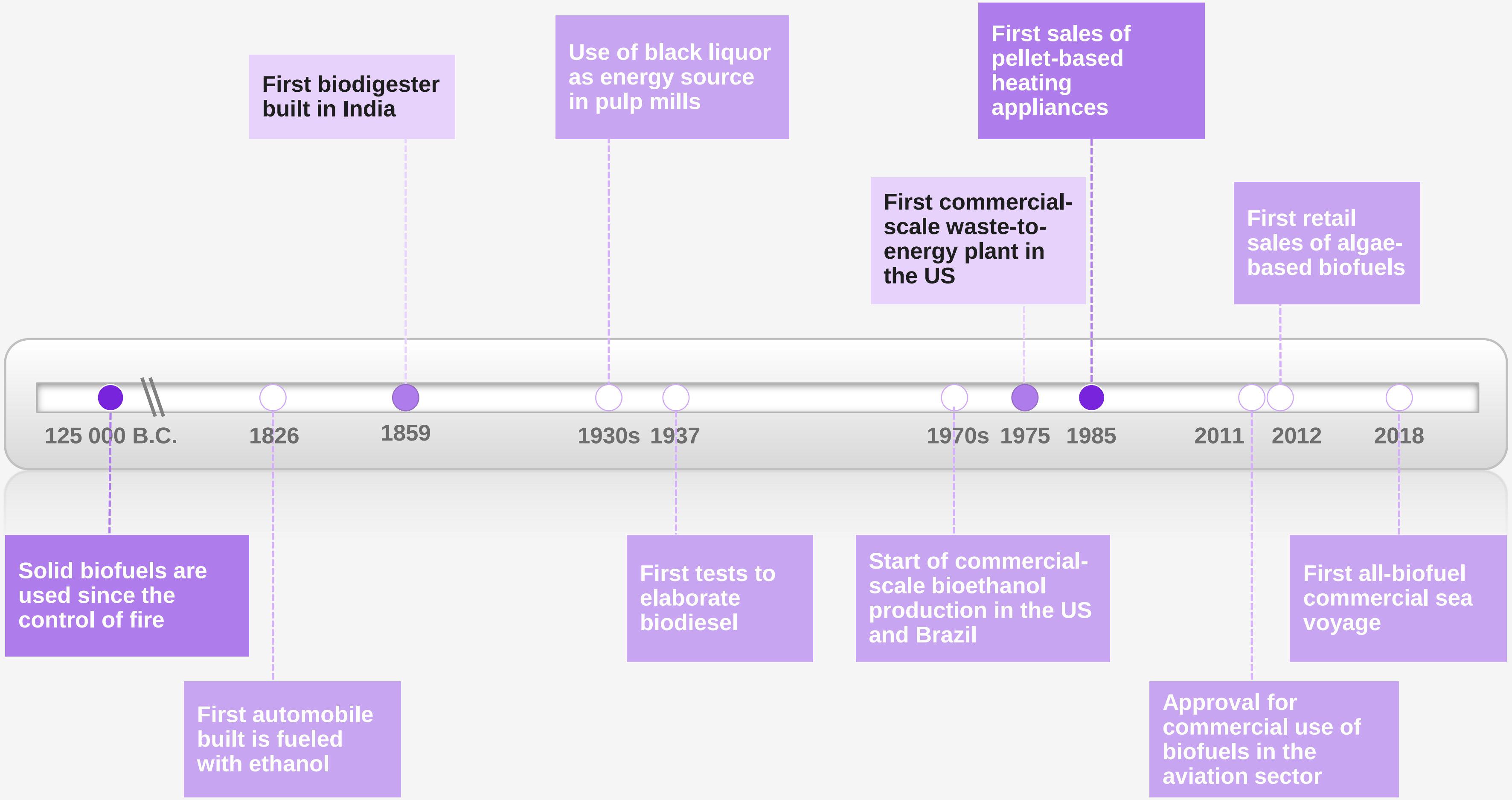
Sources: Kearney Energy Transition Institute

Historically, interest for biofuels started after the oil shocks in the 1970s

Non-exhaustive

Biofuels opportunities – introduction

History of selected biomass-to-energy value chain products



125 000 B.C.: Solid biofuels are used since the control of fire

1826: First automobile built is fueled with ethanol

1859: First biodigester built in India

1930s: Use of black liquor as energy source in pulp mills

1937: First tests to elaborate biodiesel

1970s: Start of commercial-scale bioethanol production in the US and Brazil

1975: First commercial-scale waste-to-energy plant in the US

1985: First sales of pellet-based heating appliances

2011: Approval for commercial use of biofuels in the aviation sector

2012: First retail sales of algae-based biofuels

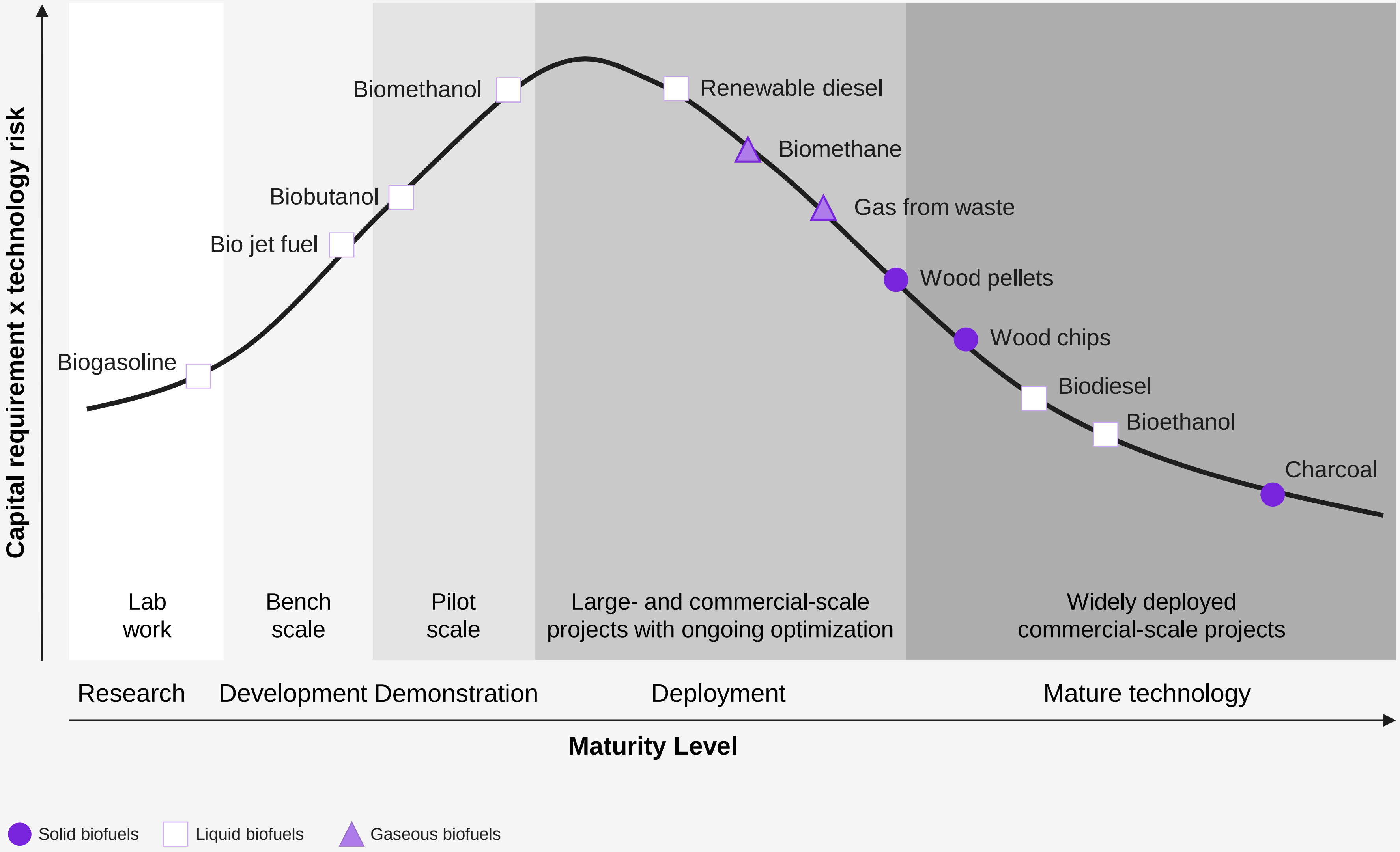
2018: First all-biofuel commercial sea voyage

● Solid biofuels ○ Liquid biofuels ● Gaseous biofuels

Source: Kearney Energy Transition Institute

Some promising biofuels are still in early stage or deployment phase

Technology maturity curve for bioenergy products



Sources: Advanced Biofuel Feedstocks – An Assessment of Sustainability (ARUP); Kearney Energy Transition Institute

Biofuels opportunities – introduction

Twelve biofuels—solid, liquid, and gaseous—are studied in the factbook

Wood chips

Small- to medium-sized pieces of wood formed by cutting or chipping larger pieces of wood

Biomethanol

Methanol (chemical formula CH_3OH) produced from biomass sources

Renewable diesel

Hydrocarbon with a similar chemical composition to fossil diesel which can be used without blending limits

Biodiesel

Liquid biofuels sourced from biomass suitable to be blended with fossil-fuel diesel

Solid pellets

Solid biofuels made from compressed organic matter or biomass

Bioethanol

Ethanol (chemical formula C_2H_5OH) produced from biomass sources, mainly used blended with gasoline

Bio gasoline

Hydrocarbon with a similar chemical composition to fossil gasoline

Biomethane

Methane (chemical formula CH_4) obtained from biomass sources

Charcoal

Dark or black porous carbon prepared from vegetable or animal substances

Source: Kearney Energy Transition Institute

Biobutanol and higher alcohols

Butanol (chemical formula C_4H_9OH) produced from biomass sources, mainly used to produce chemicals

Bio jet fuels

Liquid biofuels sourced from biomass suitable to be blended with fossil-jet fuel

Biogas

Gas obtained either through the combustion or decomposition of waste

☐ Solid biofuel (traditional)
☐ Liquid biofuel (advanced)
▨ Gaseous biofuel (advanced)

Biofuels opportunities – scope of analysis

To assess biofuels' attractiveness, the most performant biofuels are selected, and their competitive advantage is evaluated in the relevant market

Biofuels applications opportunity assessment methodology

Criteria 1

Biofuel performance assessment

- Biofuels applications are assessed based on their current intrinsic characteristics vs. fossil fuels and other renewable competitors
- Maturity level (in other words, room for efficiency increased) of each application will be used as a proxy to put the product performance rates in a dynamic perspective
- A fact card with technical details and corresponding rate is produced for each relevant biofuel

Output 1

1 **Ranking of biofuels and selection of the most promising**

Criteria 2

Competitive advantage assessment

- Biofuels applications are assessed based on their current positioning on the different markets vs. fossil fuels and other renewable competitors
- Maturity level (in other words, room for market share increase) of each application will be used as a proxy to put the competitive advantage rates in a dynamic perspective
- A fact card with economic details and corresponding rate is produced for each relevant market segment

Output 2

2 **Market potential assessment and selection of the top segment to target**

Final result

Biofuel x market segment optimal combination

Source: Kearney Energy Transition Institute

Biofuels opportunities – assessment methodology

Liquid and gaseous biofuels are the most promising bioproducts with a wide applicability

①

Numbers 7 and 9–11 are fully described in slides 79–82 and 1–6 and 8 are fully described in the Appendix.

Biofuel performance assessment – results

Biomass-to-bioenergy: final outputs and corresponding industry of application

			Bioenergy										
			Energy			Transport				Industry		Buildings	
			Power	Heat	CHP	Cars	Trucks	Aviation	Shipping	Pulp and paper	Other	Heating	Other
Biofuels	Solid	① Wood chips	●	●	●						●	●	●
		② Solid pellets	●	●	●						●	●	●
		③ Charcoal	●	●	●							●	●
	Liquid	④ Biomethanol	●	●	●	●	●		●			●	●
		⑤ Bioethanol				●	●		●			●	●
		⑥ Biobutanol and higher alcohols				●	●						
		⑦ Biogasoline				🟣	🟣						
		⑧ Biodiesel				●	●		●				
		⑨ Renewable diesel				🟣	🟣		🟣				
		⑩ Bio jet fuels						🟣					
	Gaseous	⑪ Biomethane	🟣	🟣	🟣	🟣	🟣		🟣			🟣	🟣
		⑫ Biogas	●	●	●							●	●

ⓧ Deep-dived ● Applicable 🟣 High product performance

Source: Kearney Energy Transition Institute

Technical attractiveness is strongly linked to energy performance, GHG emission weighted by maturity stage

①

Comparative view of selected biofuels

Not exhaustive

		Biogasoline	Biodiesel	Renewable diesel	Bio jet fuels	Biomethane	Biogas
Processing methods	Feedstock applicability	Agricultural residues, algae, energy crops	Animal waste, municipal solid waste, algae, energy crops	Animal waste, agricultural residues, algae	Animal waste, forestry residues, energy crops	Animal waste, agricultural residues, forestry residues, municipal solid waste	Animal waste, agricultural residues, municipal solid waste
	Optimal pathway	Hydrotreatment	Transesterification	Hydrotreatment	Hydrotreatment (HEFA)	Anaerobic digestion Syngas fermentation	Syngas fermentation
Technical diagnosis	Energetic performance	★★★	★★★	★★★	★★★	★★★	★★☆
	Applicability	★★★	★★☆	★★★	★★★	★★★	★★☆
	Infrastructure adaptability	★★★	★★☆	★★★	★★★	★★★	★★☆
	GHG emissions[1] gCO_{2eq}/MJ	3-50	25–60	38–58	5–37.5	5–15	18
	Maturity index rating	Research	Mature	Deployment	Development	Deployment	Deployment
	Technical attractiveness	◕	◕	◕	●	◕	◑

---

[1] Theoretical negative GHG emissions values were observed for some biofuels co-producing electricity and were not taken into account here

Source: Kearney Energy Transition Institute, Advanced Biofuels – GHG Emissions and energy balance, IEA 2013

Biogasoline is chemically similar to gasoline and thus could play a key role in energy transition with higher maturity

7 Biogasoline

Feedstock compatibility

Preferred processing method
Hydrotreatment

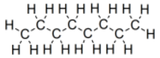
Preferred market segment
Light-duty vehicles

Technical maturity
Low Average High

Industry environment

Definition:

- Biogasoline is a fuel which is chemically similar to fossil-fuel gasoline but produced from a biomass feedstock. Contrary to bioethanol, which is an alcohol, it is composed of a mixture of hydrocarbons containing between 6 and 12 carbon atoms
- C_8H_{18}



Octane, represented here, is one of the main components of gasoline

Main feedstocks:

- Energy crops: sugar beet, sugarcane
- Agricultural residues: wheat, corn stalks
- Algae

Applications:

- Transport sector: cover the same range of applications as traditional gasoline, especially in light-duty vehicles. Biogasoline can be used alone or blended with fossil fuel gasoline.

Physico-chemical characteristics

	Biogasoline
LHV (MJ/l)	34.2
Kinematic viscosity at 40°C (mm²/s)	0.55–0.593
Density (kg/m3)	737
Oxygen (%)	0–4
Sulfur (%)	0.008–0.048
Flash point (°C)	-65–-43
Octane number	86–94

Values in the table above are the ones for gasoline, but are analogous to the ones for biogasoline due to similar chemical composition

Economic characteristics

	Biogasoline
Price	– $300–$2,600 for algae-based biogasoline per barrel (compared to $100 for fossil fuel gasoline)
Market size	– Very early stage technology, no dedicated market yet
Competing technologies	– Existing biofuels, fossil gasoline, electric batteries
Policy drivers/ barriers	– Too early-stage to benefit from dedicated policy support, apart from R&D grants
Future growth and development perspectives	– No forecasts available, will depend on the technology improvements realized in the years to come

Pros and cons

Pros	**Cons**
– Can be used in an internal combustion engine without any modification	– Very high production cost compared to fossil gasoline and to other biofuels – Early-stage technology not totally technically viable yet

Technical competitiveness

	Fossil fuel	Renew-able	Other bioenergy	Bio gasoline	Rate
	Gasoline	Electric batteries	Bioethanol		
Energy performance[1] (MJ/l)	★★★	★☆☆	★★☆	★★★	High
Applicability	★★★	★★☆	★★☆	★★★	High
Adaptability	★★★	★☆☆	★★☆	★★★	High
GHG emissions (gCO2/MJ)	87	0[2]	18–80	3-50	Avg.

[1] MJ of mechanical power (taking into account engine efficiency in the case of liquid fuels) divided by liter of fuel. For electric cars, the mechanical energy obtained after engine conversion is divided by the volume of the battery.

[2] Road emissions of electric vehicles does not take into account the emissions relative to the power generation.

Sources: Biogasoline: An out-of-the-box solution to the food-for-fuel and land-use competitions, Macroalgae-Derived Biofuel: A Review of Methods of Energy Extraction from Seaweed Biomass, Energetica Futura; Kearney Energy Transition Institute

Renewable diesel has higher potential vs. biodiesel since it is chemically similar to diesel, but it is not competitive yet

9 Renewable diesel

Feedstock compatibility

● ● ○ ○ ● ○

Preferred processing method
Hydrotreatment

Preferred market segment
Heavy-dty vehicles

Technical maturity

Low **Average** High

Industry environment

Definition:

– Renewable diesel is a biomass-derived transport fuel that is chemically similar to petroleum diesel (hydrocarbon) and is suitable for use in conventional diesel engines. Therefore, it is distinct from biodiesels which are methyl esters.

From $C_{10}H_{22}$ to $C_{15}H_{32}$

Main feedstocks:

– Animal waste and fats, agricultural residues and by-products (palm oil, palm fatty acid distillate, cooking oil residues), algae

Applications:

– Transport sector: notably heavy-duty vehicles, shipping, and aviation

– Main markets: United States, especially California which set ambitious targets to replace fossil fuels with renewables in the following decade (up to one billion gallons of renewable diesel expected per year by 2030)

Physico-chemical characteristics

	Renewable diesel	Diesel
LHV (MJ/l)	34.4	36.09–38.60
Kinematic viscosity (mm^2/s)	1.3–4.1	1.3–4.1
Density (kg/m3)	780	710
Sulfur (%)	0–15	0–15
Boiling point (°C)	180–340	180–340
Flash point (°C)	60–80	60–80
Cloud point (°C)	-35–5	-35–5
Pour point (°C)	-35 – -15	-35 – -15
Cetane number	40–55	40–55
LCA GHG emissions (g/MJ)	28–54	89

Economic characteristics

	Renewable diesel
Price	– $2.75–$3.75 per gallon in California at the pump in 2018
Market size	– 4.8 million tons per year in 2019 – 680 million gallons (equal to 2 million tons) for the largest producer (Neste)
Competing Technologies	– Biodiesel, fossil fuel diesel
Policy drivers/ barriers	– Specifications: ASTM D975 in the United States and EN 590 in Europe – Supportive policies: Renewable Fuel Standard in the US, Renewable Energy Directive in the EU, blending mandates in several countries
Future growth and development perspectives	– 19.7 million tons per year by 2030 (13% expected CAGR)

Pros and cons

Pros	Cons
– No blending limits in existing diesel engines and vehicles – Can be produced in the same facilities as conventional diesel – 40–68% lower GHG emissions than conventional diesel fuel	– Further research is required to fully characterize the effects of renewable diesel on engines – Slightly lower energy content compared to conventional diesel – Not competitive with conventional diesel fuel without incentives

Technical competitiveness

	Fossil fuel	Renew-able	Other bio-energy	Renewable diesel	Rate
	Diesel	Electric batteries	Biodiesel		
Energy performance[1] (MJ/l)	★★★	★☆☆	★★★	★★★	High
Applicability	★★★	★★☆	★★☆	★★★	High
Adaptability	★★★	★☆☆	★★☆	★★★	High
GHG emissions (gCO2/MJ)	89	0[2]	18–80	38–58	Avg.

---

[1] MJ of mechanical power (taking into account engine efficiency in the case of liquid fuels) divided by liter of fuel. For electric cars, the mechanical energy obtained after engine conversion is divided by the volume of the battery.

[2] Road emissions of electric vehicles does not take into account the emissions relative to the power generation.

Sources: USDOE Alternative Fuels Data Centre and Alternative fuel price report 2020, Emerging Markets Renewable Diesel 2030, GNA Consultants, NESTE Renewable Diesel handbook; Kearney Energy Transition Institute

Bio jet fuels are the most promising way to decarbonize aviation, but are not competitive yet and lack policy support

10 Bio jet fuels

Feedstock compatibility

● ○ ● ○ ○ ●

Preferred processing method
Hydrotreatment (HEFA)

Preferred market segment
Aviation

Technical maturity

Low **Average** High

Industry environment

Definition:
- Biomass-derived jet (bio jet) fuels are liquid biofuels suitable to be blended with or replace jet kerosene from fossil origin

From $C_{10}H_{22}$ to $C_{14}H_{30}$

Main feedstocks:
- Animal waste, forestry residues, and energy crops: most bio jet fuels are produced through the upgrade of vegetable oils and fats
- Various other feedstock (algae oil, lignocellulose biomass) can be used but their conversion pathways to bio jet fuels are not competitive yet

Applications:
- Main usage: blended with jet kerosene (up to 50% according to ASTM certifications)

Physico-chemical characteristics

	Bio jet fuel
LHV (MJ/l)	> 34.2
Sulfur (%)	< 0.3
Flash point (°C)	38
Density (kg/m3)	775–840
Freezing point (°C)	- 40
LCA GHG emissions (kgCO2/MWh)	50% to 95% savings compared with fossil jet fuels

Five biomass to bio jet fuel pathways are certified for blending with kerosene. But among these, only HEFA is technically mature and commercialized.

Economic characteristics

	Bio jet fuel
Price	– 0.7–1.6 $/L (HEFA) – 1–2.5 $/L (other methods) – (0.3–0.6 $/L for fossil-jet kerosene)
Market size	– 15 million L in 2018 (less than 0.1% of jet fuel consumption)
Competing technologies	– Fossil-based jet fuels – (Very) long term: electric or solar-powered aircrafts, cryogenic hydrogen aircrafts
Policy drivers/ barriers	– Voluntary targets from airlines and aircraft manufacturers – CORSIA carbon credit scheme from 2021 onward – Increase of bio jet green certificate schemes (RFS2 in the US, RTFO in the UK...)
Future growth and development perspectives	– 5 billion liters produced in 2025 (18% CAGR 2018–2025) – Up to 530 billion L required by 2050 to meet GHG targets

Pros and cons

Pros	Cons
– Jet engines do not require modifications for the use of bio jet fuels – Lack of other reliable means to decarbonize the aviation sector	– Not economically competitive with fossil bio jet fuels – Only 5 airports with regular biofuel supply (Bergen, Brisbane, Los Angeles, Oslo, and Stockholm) – Higher quality requirements and costs compared to road transport biofuels – Policy support made difficult by the international nature of air travel

Sources: National Renewable Energy Laboratory, Review of Biojet Fuel Conversion Technologies, IEA Are aviation biofuels ready for take off?, IEA Renewables 2018 Report; Kearney Energy Transition Institute

Technical competitiveness

	Fossil fuel	Renew-able	Other bioenergy	Bio jet fuel	Rate
	Kerosene	None	None		
Energy content (MJ/L)	★★★	NA	NA	★★★	High
Applicability	★★★	NA	NA	★★★	High
Adaptability	★★★	NA	NA	★★★	High
GHG emissions (gCO2/MJ)	70	NA	NA	5–37.5	High

Biomethane is a promising alternative to decarbonize heat and power supply potentially at a lower cost than natural gas

11 Biomethane

Feedstock compatibility

● ● ● ● ○ ○

Preferred processing method

Anaerobic digestion
Syngas fermentation

Preferred market segment

Grid injection
Heavy-duty vehicles, Shipping

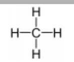
Technical maturity

Biomethane – deep-dive

Industry environment

Definition:
- Biomethane (or “renewable natural gas”) is near-pure methane produced either by removing CO_2 and other impurities from biogas or through the gasification and methanation of solid biomass

CH_4



$$\begin{array}{c} H \\ | \\ H-C-H \\ | \\ H \end{array}$$

Main feedstocks:
- Agricultural residues: residues from harvests of wheat, sugar beet, sugarcane, maize…
- Animal manure: Waste from livestock including cattle, pigs, poultry, and sheep
- Waste: municipal solid waste, wastewater sludge, industrial waste from the food-processing industry
- Forestry residues: residues from forest management and wood processing

Applications:
- Main usage: Residential: fuel used for heating and cooking or to generate power
- Other uses: Transport: compressed or liquefied, especially for heavy-duty vehicles and shipping
- Main markets: Europe, North America

Physico-chemical characteristics

	Biomethane
LHV (MJ/m3)	35.6–36
Fusion point (°C)	-182.47°C
Boiling point (°C)	-161.52°C
Density (gaseous, 15°C, 101,3 kPa) (g/cm3)	$0.6709.10^{-3}$
Auto-ignition point (°C)	537
LCA GHG emissions (gCO2/MJ)	5–15 (up to 37[1])

Economic characteristics

	Biomethane
Price	– $65/MWh (excluding grid injection) – $0.45–0.55/LGE for waste-based biomethane for vehicles
Market size	– World production biogas + biomethane: 35Mtoe
Competing technologies	– Liquid biofuels, renewable energy, fossil natural gas
Policy drivers/ barriers	– Germany, Italy, the Netherlands, and the United Kingdom introduced support for biomethane in transport – Support for household-scale digesters in China
Future growth and development perspectives	– Sustainable feedstocks set to grow by 40% by 2040 – 75–200 Mtoe expected by 2040 (2/3 in Asia Pacific) – 2–10 billion investment per year between 2020 and 2030

Pros and cons

Pros
- Potential to sustainably produce 30 Mtoe of biomethane at a lower price than natural gas
- Fully compatible with existing infrastructures
- Not subject to blend share obligations
- Can be used on demand to produce power and in remote areas needing decentralized sources of energy

Cons
- Today, most of the biomethane is more expensive than the prevailing natural gas prices in different regions, with the exception of some landfill gas

Technical competitiveness

	Fossil fuel	Renew-able	Other bioenergy	Bio-methane	Rate
	Natural gas	Solar photo-voltaic	Wood products		
Energy content (MJ/m3)	★★★	NA[2]	NA[3]	★★★	High
Applicability	★★★	★☆☆	★★☆	★★★	High
Adaptability	★★★	★★☆	★★★	★★★	High
GHG emissions (gCO2/MJ)	70–77	0	5–20	5–15	High

---

[1] 134 without land use and land use change (LULUC) and 24 with LULUC (avoided agricultural emissions linked to the decrease of fertilizers)

[2] No energy performance provided for solar photovoltaics, as the performance is provided in power per square meter of solar panel.

[3] Energy performance of wood products is not disclosed here as they are solid products which makes the comparison with gases not relevant.

Sources: IEA Outlook for biogas and biomethane, Carbone 4 Biomethane and Climate; Kearney Energy Transition Institute

Primary energy demand for biomass can be split in four sectors: transport, energy generation, industry, and buildings

Primary energy refers to the energy contained in a fuel “as input” and must be distinguished from energy resulting from the conversion of the raw fuel “as output” in order to avoid double counting (for example, electricity and heat produced in power plants).

Competitive advantage assessment – scope of analysis

Transport

Transport energy use gathers fuels and electricity used in the transport of goods or persons within the national territories and for international transport. It includes fuels and electricity delivered to light- and heavy-duty vehicles, as well as the ones used in the aviation and shipping sectors.

Energy (heat and power)

Energy sector use accounts for fuel use in electricity plants, heat plants, and combined heat and power (CHP) plants. It accounts for the primary fuel used to produce energy and does not look at the secondary energy produced by the plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Industry

Industry sector energy use includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded.

Buildings

The buildings sector includes energy used in residential, commercial and institutional buildings, and non-specified other buildings. In buildings, energy is used for space heating and cooling, water heating, lighting, and in appliances and cooking equipment.

Sources: World Energy Outlook (2019); Kearney Energy Transition Institute

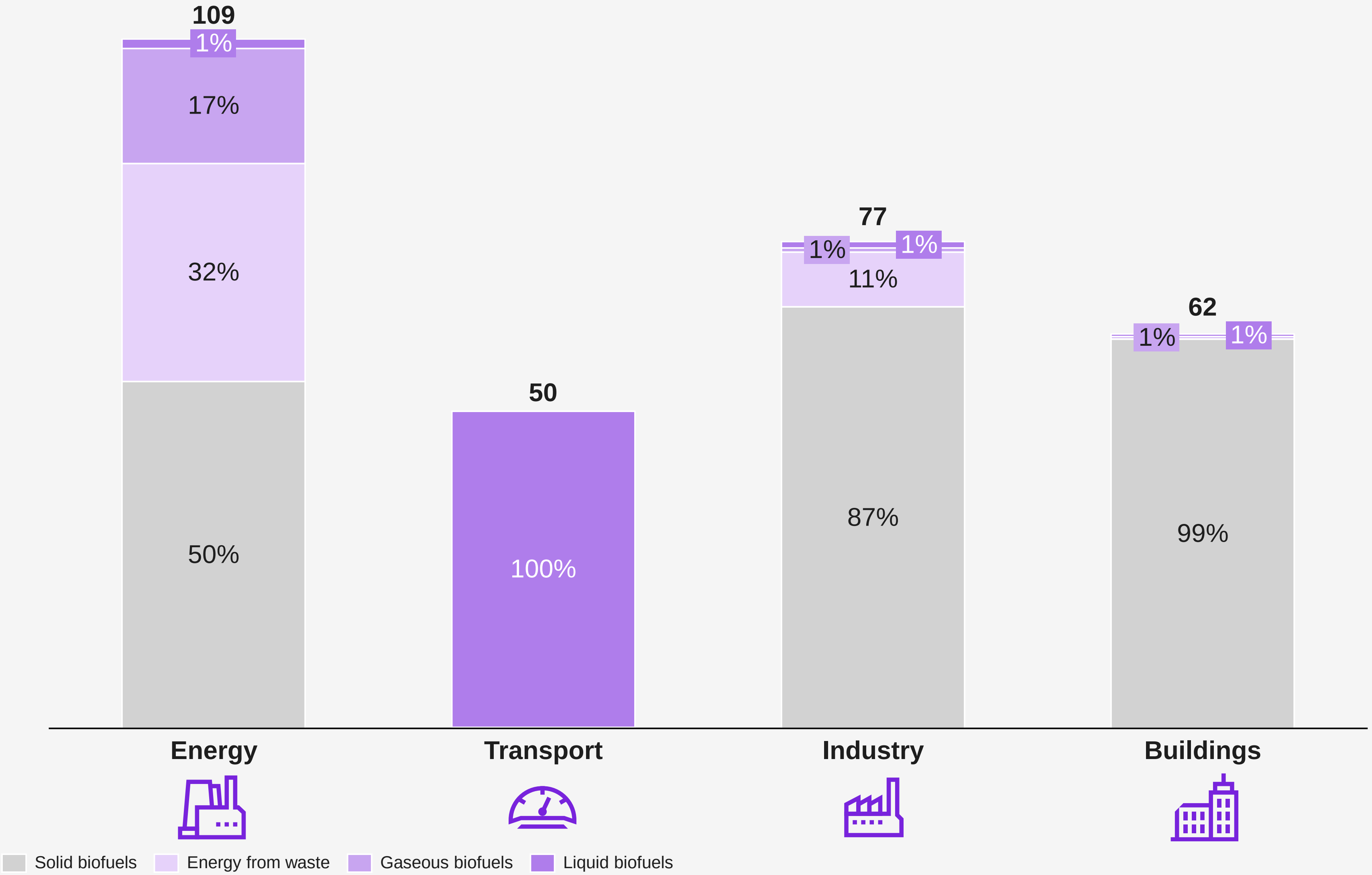
In OECD countries, more than half of the bioenergy generated comes from solid sources, except in the transport sector

This assessment is only performed for OECD countries because there is no data available at world level. As these countries are the ones where “advanced biofuels” are the most developed, the reliance on solid biofuels is even more significant at global level.

Competitive advantage assessment – introduction

Bioenergy consumption by sector and fuel type

Mtoe, 2017, OECD countries



Note: Percentages may not resolve due to rounding.
Sources: IEA Renewables Information 2019 Database, World Energy Outlook 2019 (IEA); Kearney Energy Transition Institute

Economic attractiveness is strongly linked to policy support and forecasted growth in the preferred market segment

Comparative view of selected biofuels

Not exhaustive

		Biogasoline	Biodiesel	Renewable diesel	Bio jet fuels	Biomethane	Biogas
Processing methods	Feedstock applicability	Agricultural residues, algae, energy crops	Animal waste, municipal solid waste, algae, energy crops	Animal waste, agricultural residues, algae	Animal waste, forestry residues, energy crops	Animal waste, agricultural residues, forestry residues	Animal waste, agricultural residues, municipal solid waste
	Optimal pathway	Hydrotreatment	Transesterification	Hydrotreatment	Hydrotreatment (HEFA)	Anaerobic digestion Syngas fermentation	Anaerobic digestion Syngas fermentation
Technical diagnosis	Technical attractiveness	◕	◕	◕	●	◕	◑
	Maturity index rating	Research	Mature	Deployment	Development	Deployment	Deployment
Production economics	Price	★★★	★★☆	★★⯪	★★⯪	★★☆	★⯪☆
	Policy support	★⯪☆	★★☆	★★☆	★★⯪	★★⯪	★★☆
	Preferred market segment	**Cars**	**Cars/trucks**	**Trucks/shipping**	**Aviation**	**Heat and power**	**Heat and power**
	Forecasted growth in preferred market	★⯪☆	★★☆	★⯪☆	★☆☆	★★★	★★★
	Economic attractiveness	◑	◑	◕	◕	◕	◕

Competitive advantage assessment – results

Source: Kearney: Energy Transition Institute

Promising sectors potential depends on regulation and dependencies

Biomass-to-bioenergy: promising sectors regulation, dependencies and potential

	Bioenergy			
	Energy	Transport		
	Power	Trucks	Aviation	Shipping
Regulation	– 2017: **150 countries had renewable power targets** and 125 implemented dedicated policies and regulations (e.g. quotas and obligations, feed-in tariffs, auction mechanisms, financial and fiscal instruments) – **Reductions of government support for fossil fuels** are witnessed in OECD and BRICS countries – Among renewables, solar PV and wind benefit from the most developed policy frameworks – **Biomethane lacks specific policy support** in developing countries	– Transition toward more efficient trucks, driven by fuel economy standards, specific weight and speed limits, grants, tax breaks, and other fiscal **measures aimed at reducing fossil fuels and promoting biofuels and EV** – Blending limits less of a concern for biofuels because **growth** is mainly forecasted **in developing countries** with low biofuel penetration for now – **Lack of policies specifically dedicated** to the trucks segment supporting renewables uptake	– A detailed analysis of aviation policies is presented in slide 97	– Two main regulations in place: the **Energy Efficiency Design Index** (efficiency standard for new ships) and the **Ship Energy Efficiency Management Plan** – Establishment of Emission Control Areas in 2020 **with limited SOX and PM emissions** near ports and **reduction of fuel sulfur content** (from 3.5% to 0.5%) provides an advantage to biofuels – The International Maritime Organization agreed **to reduce GHG emissions by at least 50% by 2050** compared with a 2008 baseline – Limited support for other renewables because of moderate technical potential in the sector
Dependencies and potential	– Power derived from coal-fueled power plants can be converted to biomass-fueled plants (for example, Drax UK), which indicates **a successful alternative** as countries move toward retiring coal – Biomass is a **suitable resource for combined heat and power** plants, as their combustion to produce power also releases heat – Deployment of biomass solutions for power generation are increasingly viewed as supportive to more efficient renewable technologies (for example, wind and solar) because they **can be used on demand**	– Biofuels and oil vehicles have **more room to compete on long-distance routes**, as trucks have a high energy consumption, and as performance of EV and hydrogen trucks and refueling infrastructures availability requires improvement – Electric and hydrogen trucks get an advantage in cities and for short routes because of **lower emissions than biofuels and noise reduction**	– **Policy support** for renewable made **difficult** by the international nature of air travel – Energy density of batteries and pure hydrogen too low compared to liquid fuels in the context of aviation where **weight reduction plays a key role** – Hydrogen needs for cryogenic storage requires changes in aircraft design and new refueling and storage infrastructure making its **adaptability** more difficult – **Air transport efficiency improvements** of 2% per year forecasted until 2050 should reduce energy consumption and slow the increase in energy demand	– Compared to road transport and aviation, the **shipping sector uses much less refined or processed fuel types** – Development of **hydrogen-** and ammonia-based fuels is hindered by the **lack of refueling infrastructure** – **Electrification is challenging for long-distance routes** because the range of batteries is too restrictive – The **lower sulfur emissions from biofuels** is likely to boost their market penetration in regard to the recent policy evolutions

Source: Kearney Energy Transition Institute

Impact on attractiveness of value chain: Negative | Positive

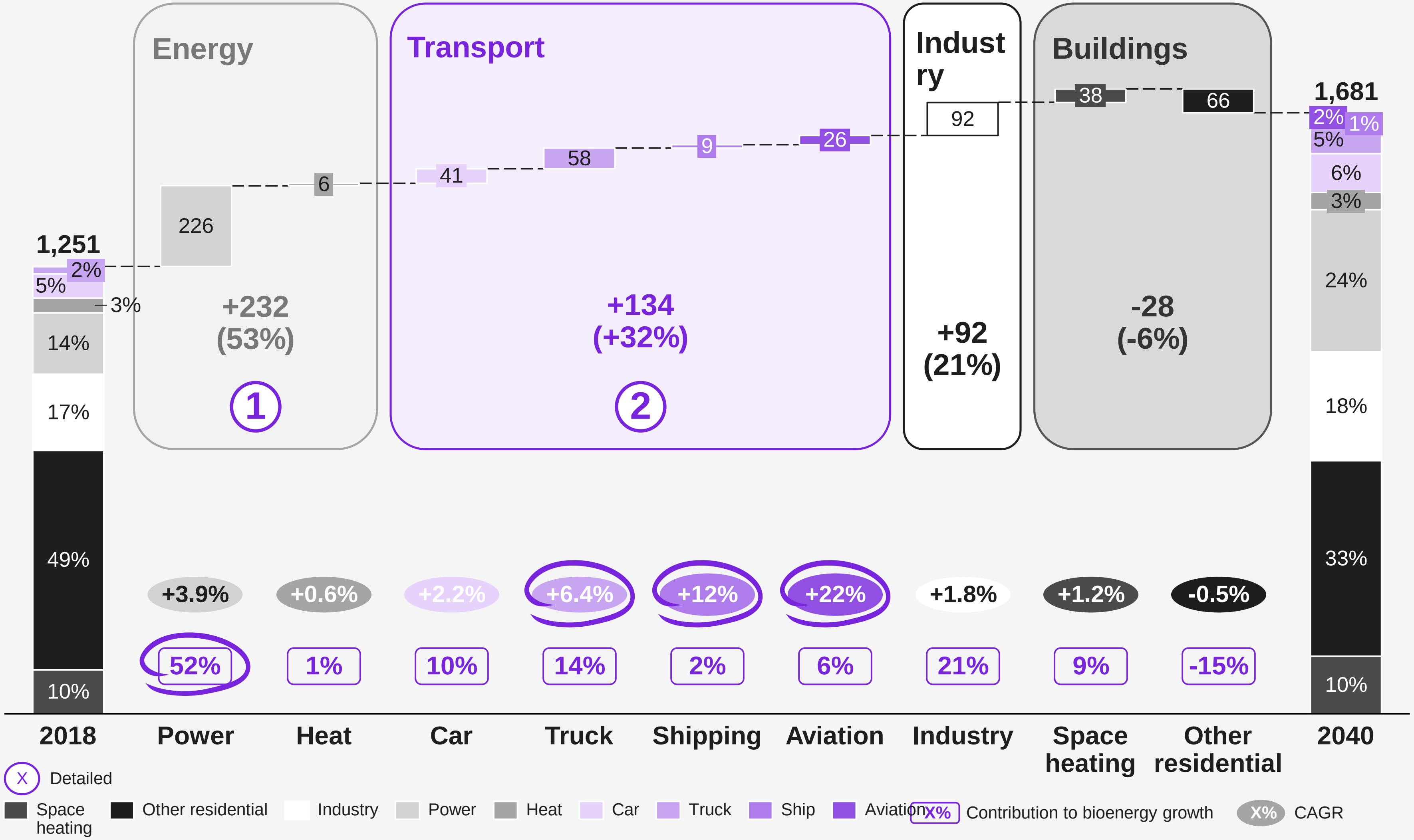
Overall, energy and transport are the top two contributors to bioenergy growth forecast until 2040

Bioenergy growth will be supported by the power sector (~50% total demand increase) but the highest growth rates are in transport (+22% per year in aviation and +12% in shipping)

Competitive advantage assessment – results

World bioenergy consumption by sector

Mtoe, 2018–2040, world[1] – stated policies scenario



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[1] Excluding "Other" which gathers the energy used for transformation activities (for example, energy industry own use) as well as the final energy used in sectors other than industry, transport, and buildings (~8% of total bioenergy consumption in 2018)

Note: Percentages may not resolve due to rounding.

Sources: World Energy Outlook 2019 (IEA); Kearney Energy Transition Institute

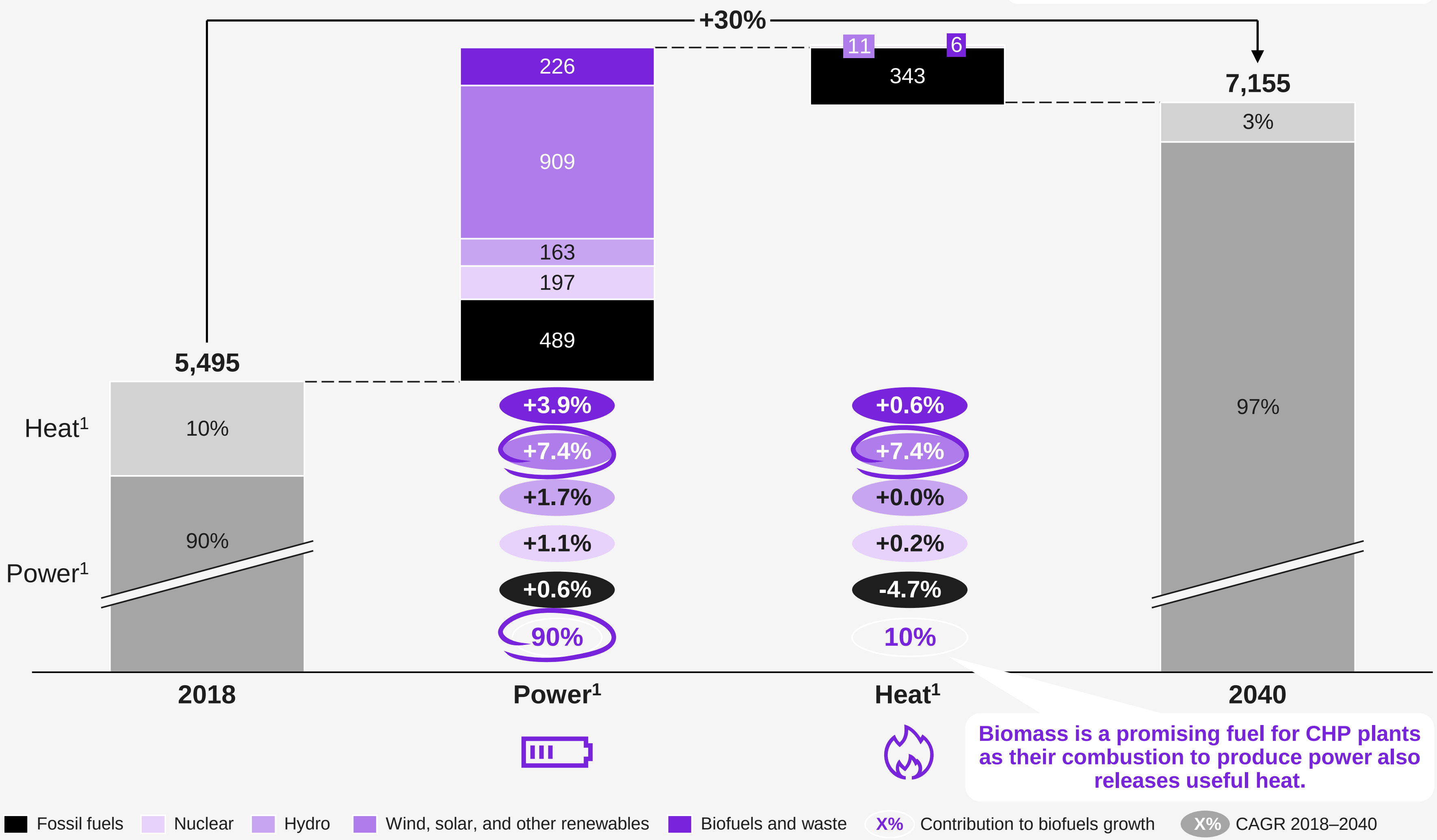
Bioenergies will contribute to the decarbonization and electrification of the energy sector

1 Energy

Energy sector: energy consumption forecast by subsectors

Mtoe, 2018–2040, world – stated policies scenario

+232 Mtoe cumulative growth for biomass in energy industries



Biomass is a promising fuel for CHP plants as their combustion to produce power also releases useful heat.

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[1] The output of combined heat and power plants (CHP) has been split between heat and power respectively, with respect to average heat to power ratio of CHP plants for 2017 obtained from IEA World Energy Balances.

Sources: World Energy Outlook 2019 (IEA), Market Report Series: Renewables 2018 (IEA), Are aviation biofuels ready for take off? (IEA), Tracking Transport, International shipping (IEA); Kearney Energy Transition Institute

Competitive advantage assessment – energy

About 50% of total bioenergy growth by 2040 will come from the **power segment** since storage provides competitive advantage vs. other must-run renewables

1 Energy

	2018	2040
Fuel market size (Mtoe)	4,935	6,920
Biofuels share (%)	3%	6%

Economic maturity

Low **Medium** High

Energy – deep-dive

Industry environment

Macro trends

- Between 2019 and 2040, electricity demand is expected to grow twice as fast as total primary energy demand
- Power demand growth is mainly expected in developing countries, as efficiency improvements are witnessed in developed countries
- Electricity supply is expected to shift toward low-carbon sources
- In addition to cogeneration plants using solid biomass feedstocks, a growing part of the power produced through biomass is expected to come from energy from waste and biogas plants

Impact on attractiveness of value chain Negative Positive

Bioenergy economic competitiveness

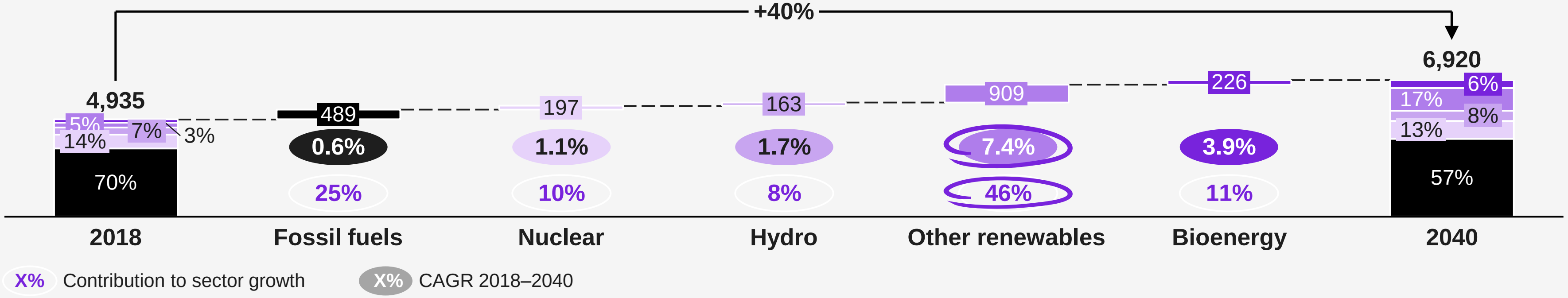
	Fossil fuel		Other renewable	Bioenergy		
	Coal	Natural gas	Wind onshore	Gas from waste	Bio-methane	Rate[1]
CAGR (2019–2030)	0.23%	1.74%	8.36%	3%	20%	**High**
Current LCOE ($/MWh)	50–120	50–95	56 (45–100)	10–60	65 (15–100)	**Avg.**
Forecasted LCOE 2040 ($/MWh)	55–145	60–115	50–85	7–50	12–80	**Avg**
Policy support	↘	↘	↗	→	→	**High**
Other enablers	↗	↗	→	→	↗	**High**

[1] Rating of the best biomass alternative, here biomethane

Power energy consumption forecast by fuel type

Mtoe, 2018-2040, world - stated scenario

+225 Mtoe, or about 97% of biomass growth in the energy sector



Sources: World Energy Outlook 2019 (IEA), Renewable Energy Policies in a Time of Transition (IRENA), Energy Technology Perspectives (IEA), Outlook for biogas and biomethane (IEA); Kearney Energy Transition Institute

In transport, trucks will contribute to 43% of biofuels growth but new applications in the aviation and shipping sectors offer longer-term potentials

2 Transport

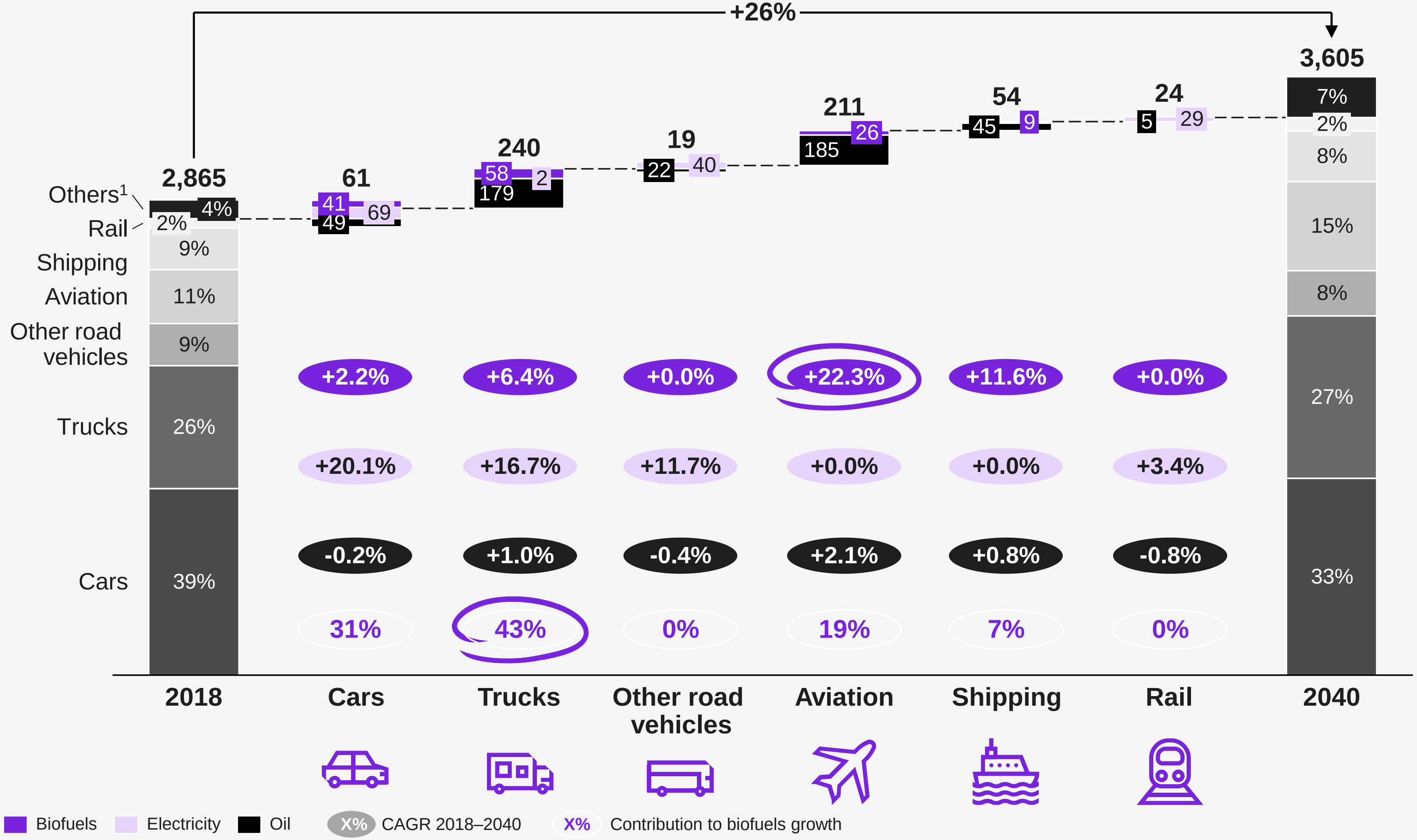
Biofuels growth perspective is very low for « Other road vehicles » and « Rail » sectors, they show low percentage of contribution to biofuels growth compared to other sectors.

Competitive advantage assessment – transport

Transport: energy consumption forecast by subsectors

Mtoe, 2018–2040, world – stated policies scenario

+134 Mtoe cumulative growth for biomass in transport industries



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[1] "Others" accounts for the fuels used in the transport sector which are different from oil, electricity, and biofuels (for example, hydrogen, natural gas…)

Sources: World Energy Outlook 2019 (IEA), Market Report Series: Renewables 2018 (IEA), Are aviation biofuels ready for take off? (IEA), Tracking Transport, International shipping (IEA); Kearney Energy Transition Institute

Biofuels have high potential in the **trucks industry** since other renewable sources are limited by technical constraints

2 Transport

	2018	2040
Total fuel market size (Mtoe)	740	980
Biofuels share (%)	3%	8%

Economic maturity

Low — Medium — High

Transport – deep-dive

Industry environment

Macro trends

- Almost all the increase in road freight fuel demand is forecasted to come from emerging and developing countries
- Small EV penetration because of technical constraints (higher energy demand per km compared to LDV)
- Biodiesel is expected to be the fuel driving the growth of the consumption of biofuels in the sector by 2050
- Oil demand increase for trucks by 2040 is expected to be the second-largest of any sector after petrochemicals
- Good potential for hydrogen uptake as truck fleets can help overcome the low utilization rate of refueling stations

Impact on attractiveness of value chain: Negative | Positive

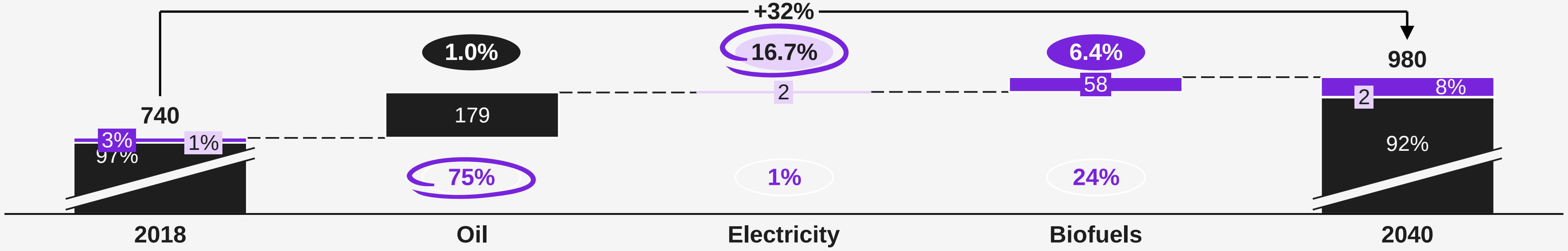
Bioenergy economic competitiveness

	Fossil fuel		Other renewable	Bioenergy		
	Diesel	H2	Electric	Bio-diesel	Renew-able diesel	Rate[1]
CAGR[2] (2019–2030)	0.8%	47%	22.3%	5% (2019–2024)	13%	Avg.
Current price	644 $/tonne	9,200 $/tonne	80–240 $/MWh	1,211 $/tonne	930–1,270 $/tonne	Avg.
Forecasted price (2030)	755 $/tonne	5,000 $/tonne	100–250 $/MWh	1,297 $/tonne	Data missing	Avg.
Policy support	↘	⇨	⇨	⇨	⇨	Avg.
Other enablers	↗	↘	↘	⇨	↗	High

Trucks energy consumption forecast by fuel type

Mtoe, 2018–2040, world – stated scenario

+58 Mtoe, or about 43% of biomass growth in all transport modes



X% Contribution to sector growth   X% CAGR 2018–2040

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[1] Rating of the best biomass alternative, here renewable diesel
[2] CAGR estimated for the entire road market (cars, trucks, and other vehicles)
Sources: World Energy Outlook 2019 (IEA), Global EV Outlook (IEA), The Future of Hydrogen (IEA), The Future of Trucks (IEA); Kearney Energy Transition Institute

Biofuels are the only reliable renewable alternative for **aviation,** whose energy demand is expected to grow by 65% by 2040

2 Transport

	2018	2040
Total fuel market size (Mtoe)	325	535
Biofuels share (%)	0.1%	5%

Economic maturity

[✓ Low] Medium High

Transport – deep-dive

Industry environment

Macro trends

- – Demand will increase by 3.8% annually and reach 17 trillion passenger kilometers by 2040, more than triple that in 2010
- – Aviation emissions are forecasted to increase by 70% by 2050 compared to 2020 levels and to account for 4.5% of all CO_2 emissions by this date
- – Alternative solutions to decarbonize aviation remain at an early stage of development

Impact on attractiveness of value chain Negative Positive

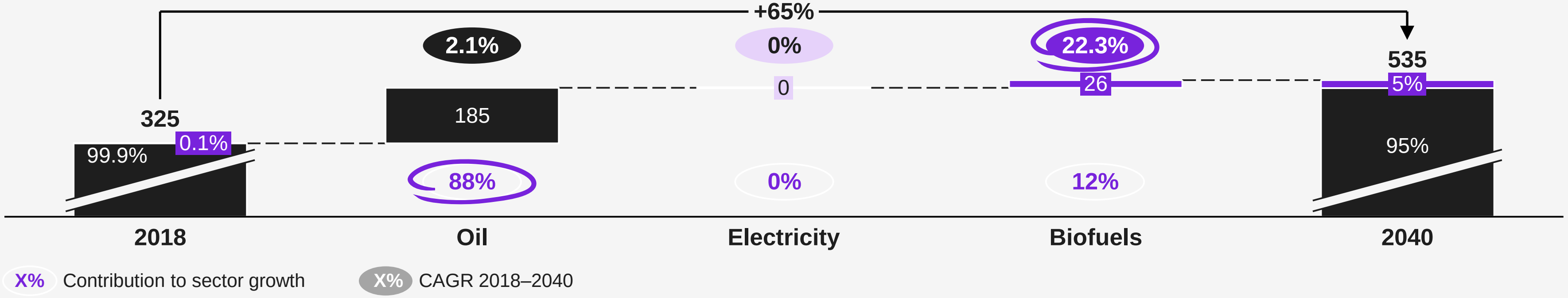
Bioenergy economic competitiveness

	Fossil fuel	Other renewable	Bioenergy		
	Jet kerosene	Power to liquid	Electric	Bio jet fuel	Rate[1]
CAGR (2018–2040)	+2.1%	Data missing	NA	+22.5%	**High**
Current price	0.5 $/L	1.8–2.7 $/L	NA	0.7–1.6 $/L	**Avg.**
Forecasted price (2030)	0.6 $/L	Data missing	NA	Data missing[2]	**Avg.**
Policy support	↘	→	→	→	**High**
Other enablers	↗	↘	↘	→	**Avg.**

Aviation energy consumption forecast by fuel type

Mtoe, 2018–2040, world – stated scenario

+26 Mtoe, or about 20% of biomass growth in all transport modes



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[1] Rating of the best biomass alternative, here bio jet fuel

[2] Cost reduction through technical learning is limited as the technology is broadly mature. However, costs could be reduced thanks to economies of scale, as for now bio jet fuel is produced on a batch basis.

Sources: World Energy Outlook 2019 (IEA), Global EV Outlook (IEA), The Future of Hydrogen (IEA), The Future of Trucks (IEA); Kearney Energy Transition Institute

International, national, and corporate regulations are struggling to achieve the decarbonization of the aviation sector

2 Transport

International policy-making appears as the most appropriate level to significantly change the status quo.

Governments and legal targets and obligations

The regulatory levers of these bodies are limited because of the international dimension of air travel. Some of the main national and regional schemes are presented below.

EU Emissions Trading Scheme:

- Cap and trade system which obliges companies, notably in the aviation sector, to keep their emissions below 95% of 2004–2006 historical aviation emissions
- Higher emissions than this threshold must be compensated by purchasing and trading CO_2 emissions allowances

National taxes:

- Norway and Japan directly implemented a tax on jet fuels
- A larger amount of countries have taxes on tickets based on flight distance:
  - UK Air Passenger Duty: settled in 1994, the rate depends on the distance between a travel's country capital and London and the type of aircraft
  - German Air Travel Tax: settled in 2011 for flights departing from Germany, its level depends on the distance between Frankfurt and the largest commercial airport in the destination country
  - Other countries with similar policies: Sweden, France, Norway, Austria, and South Africa

International aviation organization targets

International regulations are set by the International Civil Aviation Organization, a UN agency gathering its 193 member states responsible for setting aviation standards and recommended practices and policies in the civil aviation sector

Fuel Consumption Standards:

- Standards ratified by the ICAO limiting the emissions of new aircraft and obliging to modify them if the targets are not met
- The Standard applies to new aircraft models from 2020, and to aircraft models already in production from 2023 on

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA):

- Agreed in 2013, the main objective is to ensure carbon neutral growth for international aviation from 2020
- Obligation for airlines to offset their increase in emissions after 2020 by purchasing credits from emissions mitigation projects outside the aviation sector

Private companies' voluntary targets

The cost of fuel accounts for 20% of aviation ticket prices and leads airlines to pursue energy efficiency improvements. In addition, airlines can also set voluntary CO_2 reduction targets

Use of sustainable fuel blends:

- 100,000 flights using bio jet blends achieved in 2017 and 1 million forecasted for 2020
- More than 10 long-term biofuel offtake agreements between airlines and producers currently in place, covering over 1.5 billion L of supply

Infrastructure adaptation:

- Five airports currently have regular bio jet fuel distribution (Bergen, Brisbane, Los Angeles, Oslo, and Stockholm)

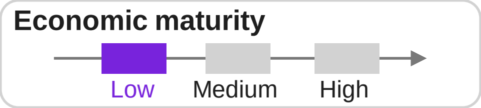
Sources: Renewables 2018 (IEA), IEA Tracking Transport, Energy Efficiency 2018 (IEA), IEA Are aviation biofuels ready for takeoff?, Jörgen Larsson, Anna Elofsson, Thomas Sterner & Jonas Åkerman (2019) International and national climate policies for aviation: a review, Climate Policy; Kearney Energy Transition Institute

Biofuels are the only reliable alternative to decarbonize the **shipping industry**

2 Transport

	2018	2040
Total fuel market size (Mtoe)	250	305
Biofuels share (%)	0.1%	3%

Economic maturity



Transport – deep-dive

Industry environment

Macro trends

- The shipping sector accounts for 80% of all goods transported via international shipping routes, using more than 85,000 vessels
- In 2017 shipping accounted for 2-3% of CO_2 emissions but 4-9% of SOX emissions and 10-15% of NOX emissions worldwide
- Maritime freight activity is set to grow by around 45% and oil demand in the sector is set to rise by 20% by 2030

Impact on attractiveness of value chain Negative Positive

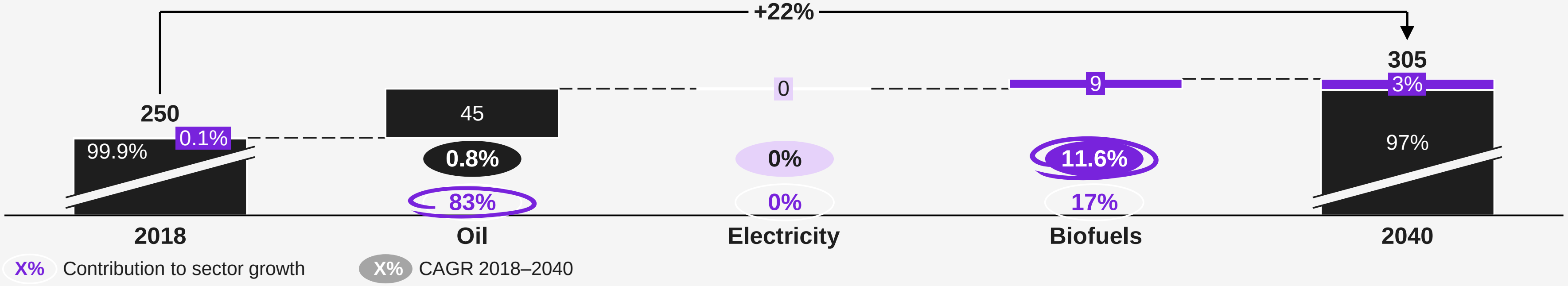
Bioenergy economic competitiveness

	Fossil fuel	Other renewable		Bioenergy		
	Heavy fuel oil Marine diesel oil	NH3 or H2	Electric	Bio-diesel	Renew-able diesel	Rate[1]
CAGR (2018–2040)	+0.8%	NA	NA	Data missing	Data missing	Avg.
Current price	0.29–0.45 $/L	NA	NA	0.44–0.92 $/L	0.8–1.15 $/L	Avg.
Forecasted price (2030, $/L)	0.3–0.5[2] $/L	NA	NA	0.4–0.8[2] $/L	Data missing	Avg.
Policy support	↘	⇨	⇨	↗	↗	High
Other enablers	↗	↘	↘	⇨	↗	Avg.

Shipping energy consumption forecast by fuel type

Mtoe, 2018–2040, world – stated scenario

+9 Mtoe, or about 7% of biomass growth in all transport modes



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[1] Rating of the best biomass alternative, here biodiesel

[2] Cost reduction through technical learning is limited as the technology is broadly mature. However, costs could be reduced thanks to economies of scale, as for now bio jet fuel is produced on a batch basis.

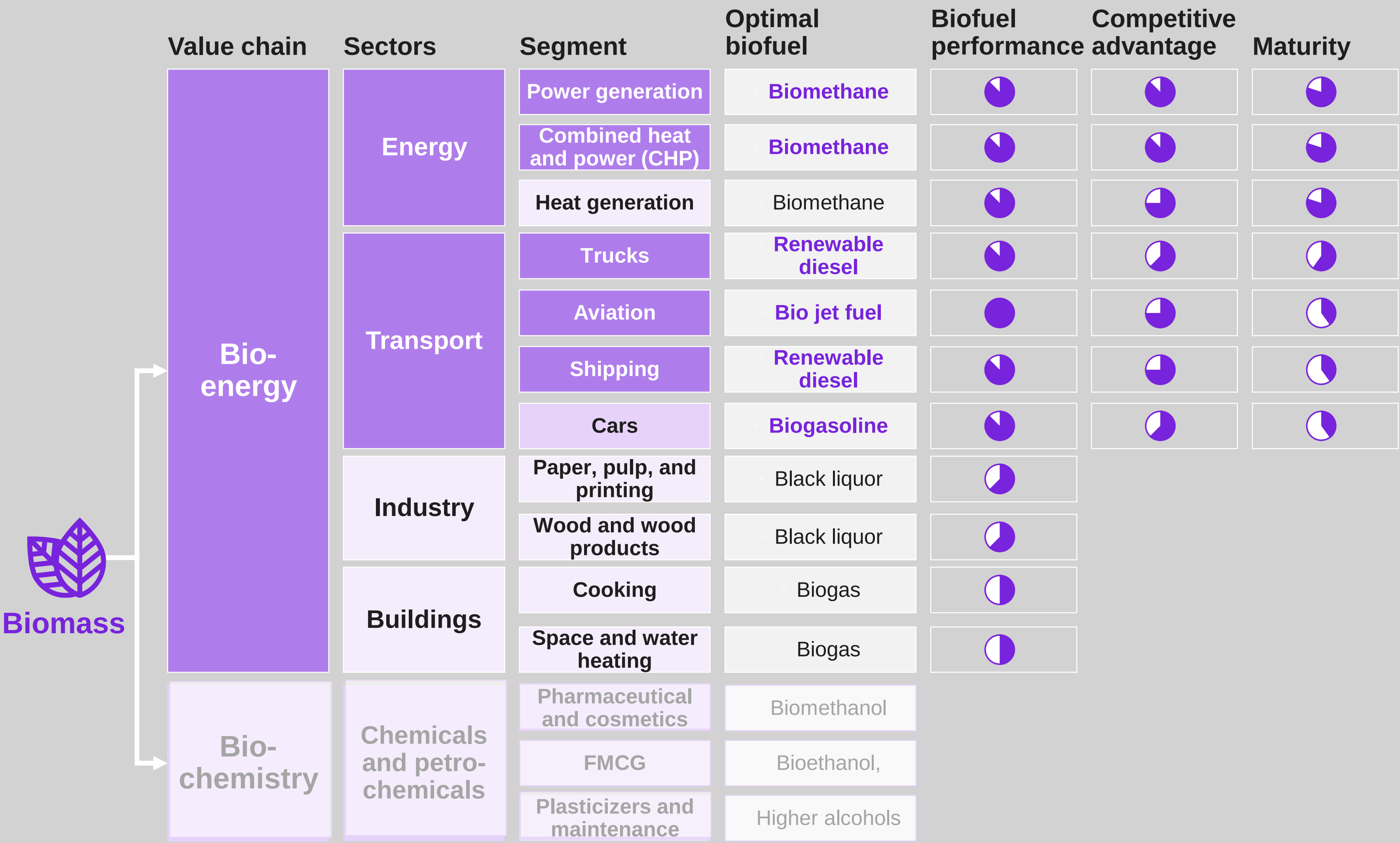
Sources: World Energy Outlook 2019 (IEA), Global EV Outlook (IEA), The Future of Hydrogen (IEA), The Future of Trucks (IEA), Oak Ridge National Laboratory, Understanding the Opportunities of Biofuels for Marine Shipping, IEA Bioenergy Biofuels for the Marine Sector; Kearney Energy Transition Institute

Renewable diesel for road transports and biogas in power generation are the best medium-term opportunities for biofuels

In the longer term, bio jet fuel in aviation and biodiesel in shipping are expected to play a significant role.

Biofuel market attractiveness and maturity – conclusion

Biofuel x market combination[1]



Biomass

Value chain	Sectors	Segment	Optimal biofuel	Biofuel performance	Competitive advantage	Maturity
Bio-energy	Energy	Power generation	Biomethane	◕	◕	◕
		Combined heat and power (CHP)	Biomethane	◕	◕	◕
		Heat generation	Biomethane	◕	◕	◕
	Transport	Trucks	Renewable diesel	◕	◑	◑
		Aviation	Bio jet fuel	●	◕	◑
		Shipping	Renewable diesel	◕	◕	◑
		Cars	Biogasoline	◕	◑	◑
	Industry	Paper, pulp, and printing	Black liquor	◕		
		Wood and wood products	Black liquor	◑		
	Buildings	Cooking	Biogas	◑		
		Space and water heating	Biogas	◑		
Bio-chemistry	Chemicals and petro-chemicals	Pharmaceutical and cosmetics	Biomethanol			
		FMCG	Bioethanol,			
		Plasticizers and maintenance	Higher alcohols			

🟪 High attractiveness 🟪 Average attractiveness ⬜ Low attractiveness

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[1] The attractiveness of a given biofuel depends on the perspectives of the market segment where it is assessed. This is the reason why the same biofuel can have different attractiveness ratings.

Source: Kearney Energy Transition Institute

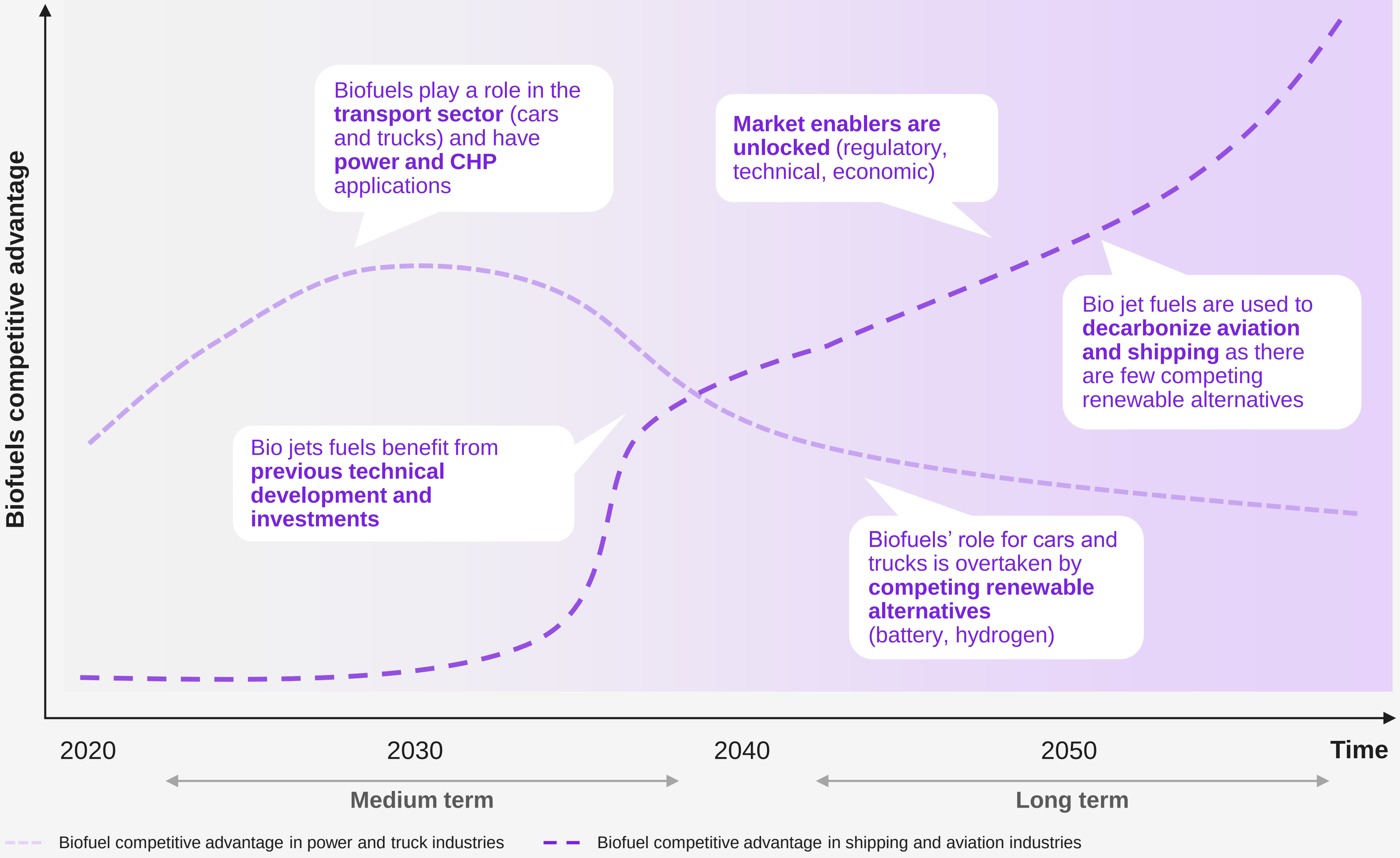
Market dynamics reveal two possible markets shaping the future of advanced biofuels

Illustrative

There are two types of market segments for advanced biofuels: the “pivot market” where they are more mature with applications in the power and CHP sector and as fuel for trucks, and the “end-game market” where advanced biofuels will still be early stage by 2040

Biofuel market attractiveness and maturity – conclusion

Advanced biofuels market dynamics show distinct medium- and long-term markets



Biofuels play a role in the **transport sector** (cars and trucks) and have **power and CHP** applications

Market enablers are unlocked (regulatory, technical, economic)

Bio jet fuels are used to **decarbonize aviation and shipping** as there are few competing renewable alternatives

Bio jets fuels benefit from **previous technical development and investments**

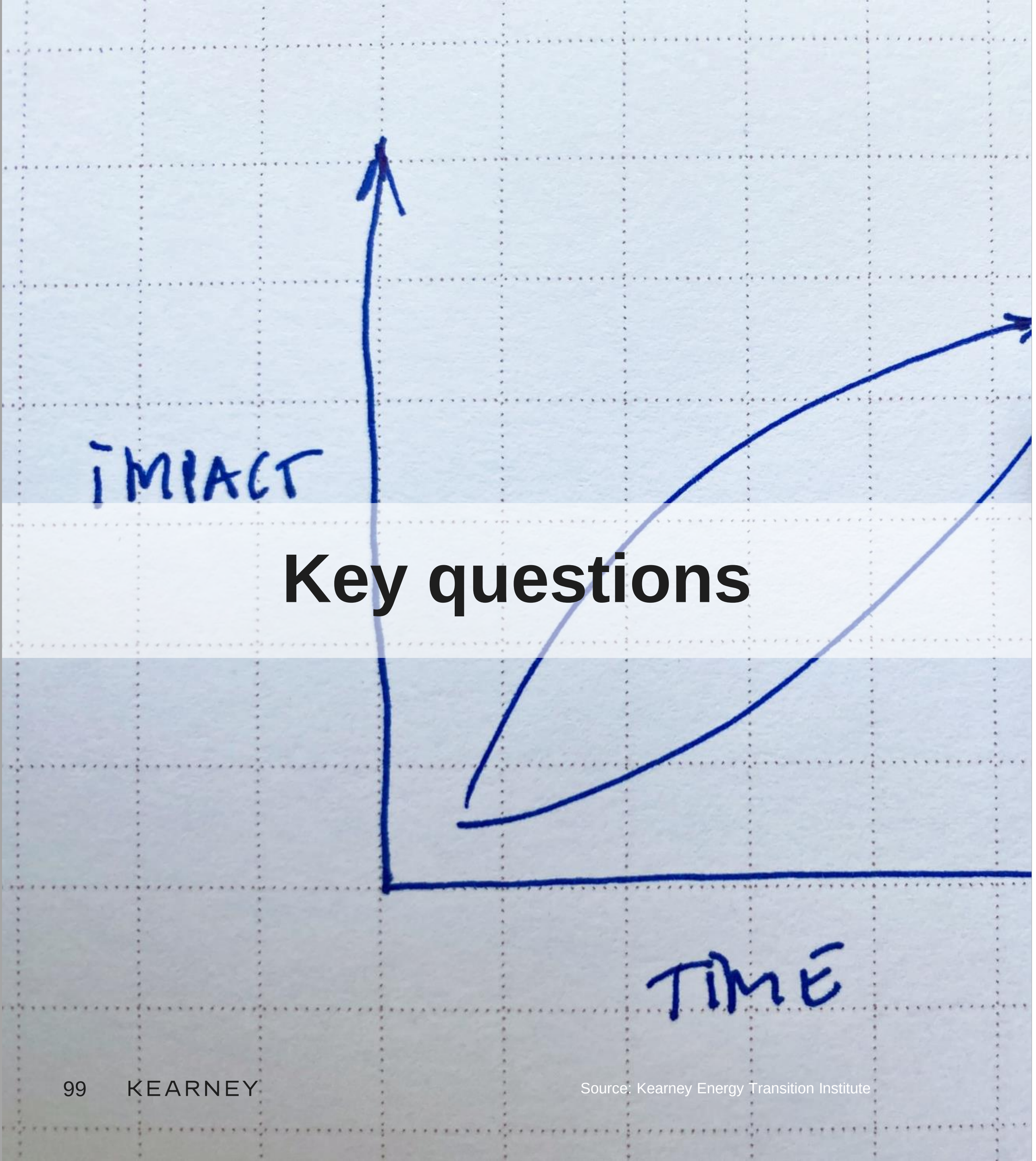
Biofuels’ role for cars and trucks is overtaken by **competing renewable alternatives** (battery, hydrogen)

Biofuel competitive advantage in power and truck industries

Biofuel competitive advantage in shipping and aviation industries

Source: Kearney Energy Transition Institute

Kearney XX/ID



Key questions

What are the market conditions that facilitate biomass-to-bioenergy uptake?

i. What are biomass-to-bioenergy market drivers?

ii. What are the corresponding levers to activate in order to increase attractiveness?

Source: Kearney Energy Transition Institute

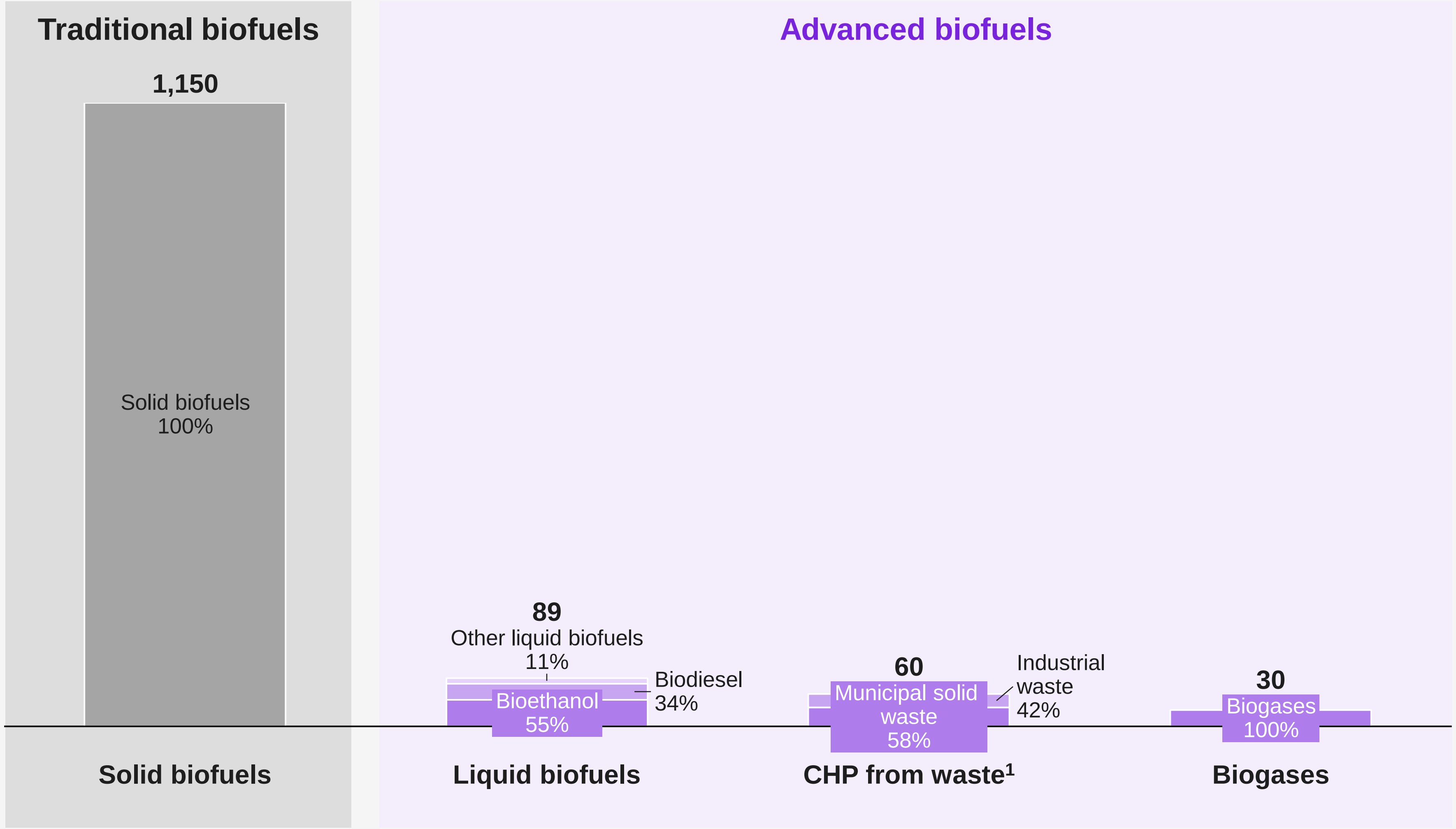
World biofuel demand is overwhelmingly dominated by traditional biofuels

Nevertheless it has to be weighted with the yield of the device: a Mtoe of traditional biofuel is often burnt in a low efficiency device which makes it less valuable than a Mtoe of advanced biofuel consumed with a high yield.

Market enabler – introduction

World biofuels demand by fuel type

Mtoe, 2017, World, IEA Energy Balances



[1] Combined heat and power

Sources: IEA Renewables Database (2019); Kearney Energy Transition Institute

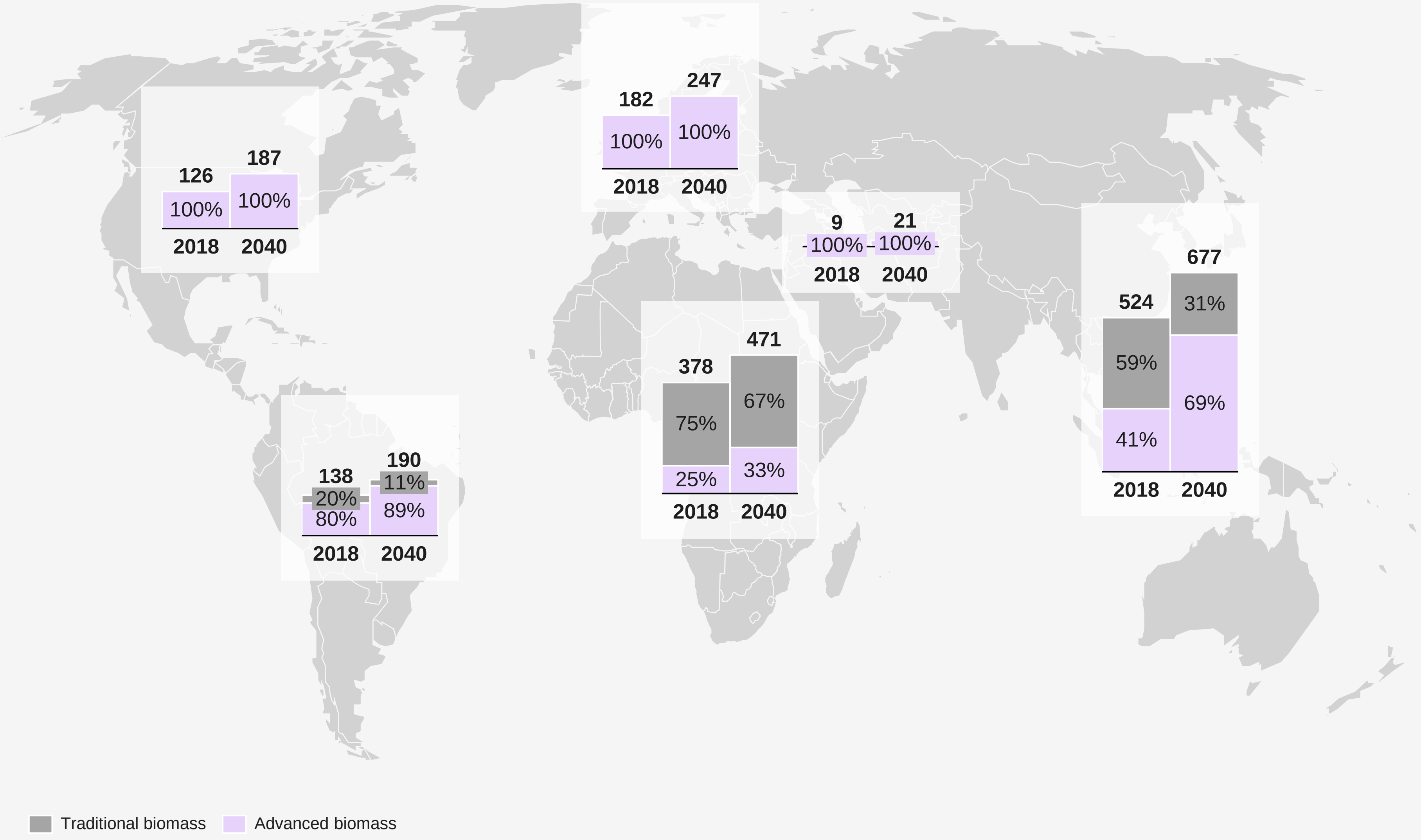
The demand is driven by Southeast Asia and Africa but developed countries are favorable markets for advanced bioenergy

> **Modern bioenergy is the overlooked giant** of the renewable energy field … but the right policies and sustainability regulations will be **essential to meet its full potential.**
>
> *Dr. Fatih Birol, IEA Executive Director*

Market enabler – introduction

Bioenergy primary energy demand by continent

World, 2017, Mtoe, WEO – stated policies scenario



Sources: World Energy Outlook 2019 (IEA); Kearney Energy Transition Institute

Five main drivers set the market conditions to ease advanced bioenergy penetration

① Feedstock supply

Land use
Competition with food crops, culture rotation, energy density per area, land available for cultivation

Biomass production yield

Sustainable collection standards
Forest management, soil management, and so on

Competing uses
Other local products/ activities, recycling

② Infrastructure maturity

Waste collection ecosystems
Collection system types and agents, dedicated infrastructures

Biomass transport capacities
Rail, waterways, trucks, trailers

Biomass treatment and processing facilities

Biomass-to-energy conversion facilities

Energy transport and distribution infrastructure

③ Regulation and acceptance

Overall regulations and policies related to biomass management
NDCs, Basel Convention for waste management

Feedstock-specific policies
Health and safety regulations, handling and treatment of animal by-products, landfill directive

Public awareness
Environmental movement
Sensitivity to environmental issues, overall footprint

Behavior and pattern
Waste management, practice, patterns of consumption and generation of waste

Purchasing power

④ Technologies and economics

Technology economics
Capex, opex, process efficiency

Technology performance
Conversion factor, energy efficiency, by-product valorization

Feedstock quality and cost
Organic vs. inorganic fraction, specific processes for biomass upgrading

Economic conditions
Labor costs, taxes, local economic growth

⑤ Substitution

Existence of alternative renewable technologies

☐ Sub-driver ▨ Sub-driver detailed

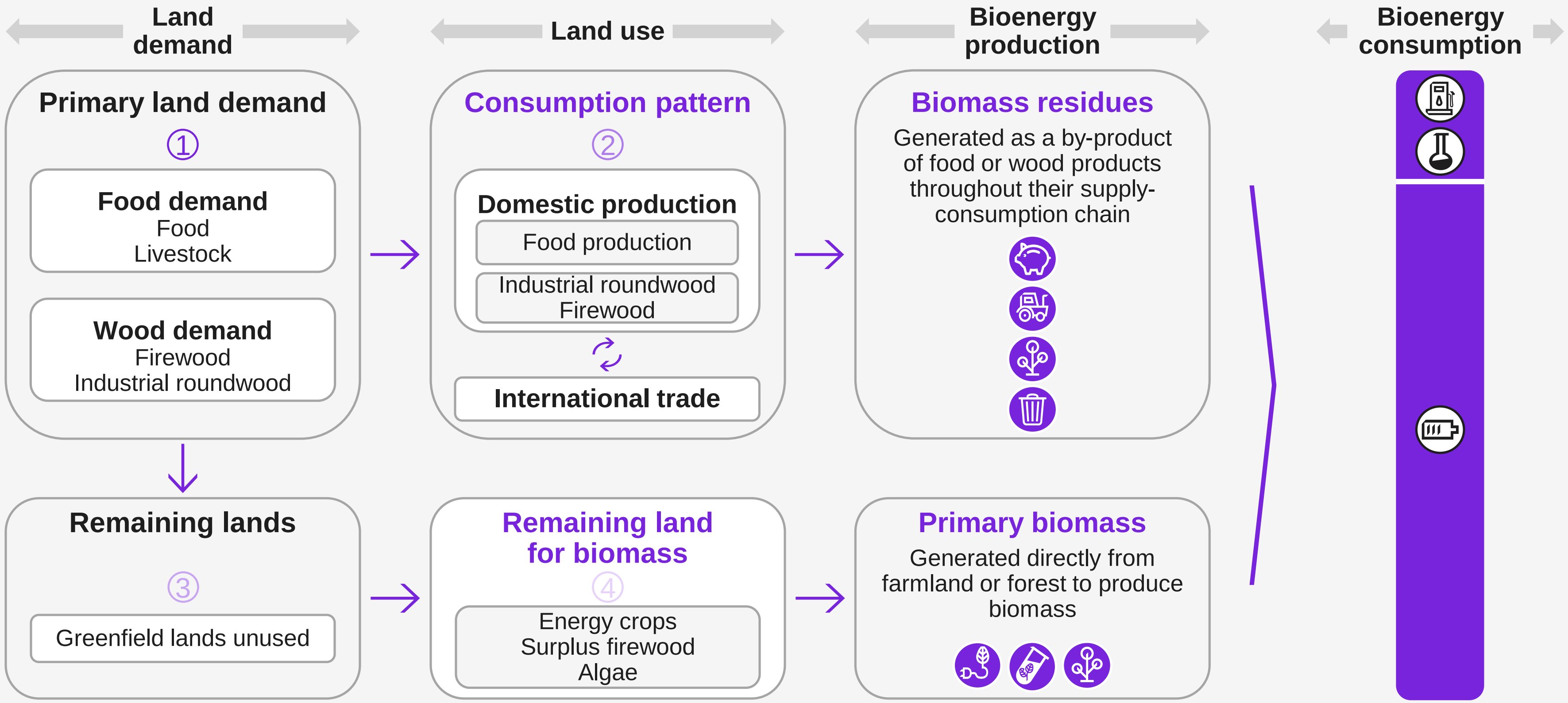
Source: Kearney Energy Transition Institute

Market enabler – methodology

Feedstock supply is the limiting factor of bioenergy production; it depends on consumption patterns and remaining land use

① Feedstock supply

Biomass feedstock market dynamics



Land demand

Primary land demand ①

Food demand
Food
Livestock

Wood demand
Firewood
Industrial roundwood

Remaining lands ③

Greenfield lands unused

Land use

Consumption pattern ②

Domestic production
Food production
Industrial roundwood
Firewood

International trade

Remaining land for biomass ④

Energy crops
Surplus firewood
Algae

Bioenergy production

Biomass residues
Generated as a by-product of food or wood products throughout their supply-consumption chain

Primary biomass
Generated directly from farmland or forest to produce biomass

Bioenergy consumption

Biomass residues drivers

① – Primary land demand determines the **theoretical potential for biomass residues**, driven by the **world population** evolution and the **consumption/production patterns (waste rate)**

② – Food and wood supply determines the **technical potential for biomass residues**, driven by the **waste collection rate** of harvesting, processing, and delivering

Primary biomass drivers

③ – Remaining lands determine the **theoretical potential** for primary biomass, driven by **the natural capacity to grow biomass** (climatic, geological, geographic conditions, and so on)

④ – Biomass production determine the **technical potential** for primary biomass, driven by value chain efficiency

Source: Kearney Energy Transition Institute

Feedstock supply – deep-dive

Each biomass category has specific sub-drivers

① Feedstock supply

Animal waste	**Supply depends on:** **– Amount of manure generated** **– Volume (%) of manure treated** **– Percentage of treated manure applied to soil**	Improve manure treatment, fertilizer substitutes
Agricultural residues	Supply depends on: – Amount of land available for **cultivation** – Residue-to-crop ratios – Collection efficiencies – **Competing uses** – **Burning** ratios	High residue ratio, lower competing uses and burning
Forestry residues	Supply depends on: – Total amount of **forest land** (hectares) – Total **accessible forest land** (hectares) – Primary/secondary **residue portion** (%) of biomass stock – Collection efficiencies – Average rotation cycle	Short rotation species, increase forest land
Municipal solid waste	Supply depends on: – Demographics (population, urban %) – Amount of **MSW per capita** – Waste **composition** (organic, recyclables) – **Collection** rates by type – **Recycling** rates by type	Improve collection, change the waste composition
Algae	Supply depends on: – Amount of **space available** for algae cultivation – Attainable **yield** – Collection efficiencies	Select performant species, improve collection
Energy crops	Supply depends on: – Amount of **land available** for energy crop cultivation – Attainable **yield** – Collection efficiencies	Select performant species, use degraded land

Enabler

Source: Kearney Energy Transition Institute

Feedstock supply – deep-dive

Alternative uses of feedstock act as competition for supply and drive available volume down

① Feedstock supply

Commercially relevant feedstock applications

Feedstock	Competing application	Description	Comparison to bioenergy pathways	Enablers
🗑	**Biogas recovery**	– Use of sanitary/managed landfill to capture biogas from natural decomposition of waste	– Lower investment and infrastructure requirement, reliable end market, adoption of more advanced WtE pathways likely to lower advantage	Produce advanced biofuel, decrease investment costs for methanization
🗑	**Recycling**	– Conversion of waste into re-usable materials and objects	– Most preferred by carbon emission and circularity principles, growing political focus and willingness	Increase energy efficiency
🗑	**Open/ unmanaged landfills**	– Waste disposed in open or unmanaged dumps, uncollected, or otherwise unaccounted for	– Significant environmental and health hazard, reducing volume in developed markets	Strengthen political willingness and environmental protection
🌳	**Secondary products**	– Manufacturing of wood products using residues like saw-dust, off-cuts, and so on	– Low environmental impact, in line with circularity principles, employs existing infrastructure and labor	Improve circularity, develop local economy
🚜	**Food/bedding for cattle**	– Use of agriculture residue as animal food or bedding	– Significantly lower environmental impact, adherence with circularity principles, limited economical alternatives for food/bedding	Develop economical alternatives or high-value end-products
🚜	**Compost for agriculture**	– Use of agriculture residue for horticultural purposes, as compost for mushroom cultivation, and so on	– Not relevant for energy players, relatively small scale compared to other competing uses	Develop economical alternative
🚜	**Left on field**	– Residue left on field as fertilizer or to avoid soil erosion or loss of carbon content	– Important for sustainability, particularly soil health	Develop alternative solutions or high-value end-products
🐖	**Household fuel**	– Use of raw animal manure as household fuel (for example, dry dung cakes)	– Hazardous to health, highly distributed production (usually household level), usage declining over time	Increase energy efficiency

Source: Kearney Energy Transition Institute

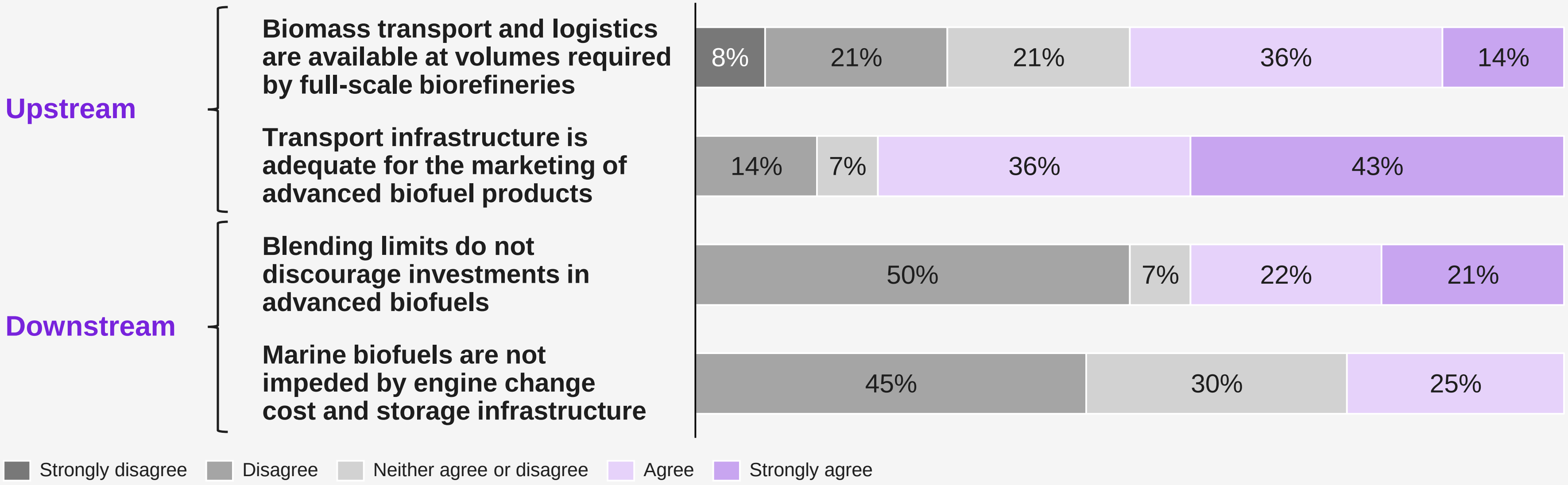
Advanced biofuels benefit from their compatibility with mature infrastructure in developed countries

② Infrastructure maturity

In 2019, the IRENA issued a survey to 14 biofuel industry executives to determine the main barriers to biofuels uptake.

Infrastructure maturity – deep-dive

Biomass potential—infrastructure adaptability



Upstream

- Only 29% of surveyed people consider feedstock transport and storage unavailable at volumes required by commercial-scale biorefineries
- Only 21% of surveyed stakeholders present transport infrastructure as a constraint to biofuels uptake

- Improvement of storage facility to handle biofuels' lower stability and poorer storage conditions
- Reorientation of conversion facilities from fossil fuels (for example, coal boilers) to biomass

Downstream

- Lack of integration of biofuels solutions in existing engines perceived as a major barrier to biofuels uptake
  - Biofuels blending shares range from 0 to 7% for biodiesel and from 5 to 10% for ethanol
  - In Europe, 90% of petrol cars compatible with 10% bioethanol blend

- Development of flex-fuel vehicles able to run on biofuels
- Stretch of blending limits to E15, E20, or E25 for ethanol, or up to B20 for biodiesel (for example, Indonesia)
- Increase in availability of refueling stations
- Higher policy stability enabling long-term visibility for stakeholders

Enabler

Sources: Advanced Biofuels, What holds them back? (IRENA 2019); Kearney Energy Transition Institute

Regulation and legislation are strong drivers since they impact both biomass supply and bioenergy demand

③ Regulation and acceptance

Regulation – deep-dive

Drivers, common outcomes, and impacts of bioenergy legislations

	Driver	Enabler	Impact
A. Waste management regulations	Policies regarding waste management: collection, sorting, recycling, disposal, waste reduction, revalorization	– Focus on increasing recycling rates and reuse of materials – Reduce MSW generation per capita with regulations to further improve efficiency of collection and disposal infrastructure	– Higher collection rates, execution of policies, investment in infrastructure 🟪 – Decreased composition of waste as recycling rates increase ◼
B. Decarbonization targets	Targets for GHG emissions reduction per industry sector Set up carbon credits	– Reduce GHG emissions via lower-carbon sources of energy (for example, emission trading schemes, carbon tax)	– Strengthens demand for bioenergy products (for example, biofuels) 🟪
C. Blending mandates	Regulation concerning blending (quality, quantity) in transport sector to help biofuel penetration and push the need for blended biofuels	– Increase share of renewables in power supply (for example, electricity) and in transport industry via biofuels – Apply specific taxes on energy use (for example, gasoline or diesel taxes)	– Increase competition with other renewables (wind, solar, geothermal) ◼
D. Land use and planning regulations	Land use and planning regulation such as forest management plants, arable land repartition between cultures	– Train for sustainable utilization plans – Strengthen policies to achieve zero deforestation and increase carbon sequestration – Enforce agricultural planning to enhance sustainable repartition of arable land	– Improve sustainability credentials of biomass feedstocks 🟪 – Increase complexity and limit supply availability ◼
E. Fiscal incentives/ government subsidies	Policy support via fiscal incentives/ government subsidies managed and distributed by established agencies or government bodies toward bioenergy or biofuels	– Create fiscal incentives (for example, tax credits, subsidies, differential pricing) to support transition to clean energy alternatives – Enhanced initiatives and programs to support R&D and innovation in renewable energy sector	– Support bioenergy product competitiveness 🟪 – Creates risk of reliance on incentives ◼
F. Other sustainability policies	Other sustainability policies or strategies to drive green energies or renewables	– Develop sustainability strategies and increasing national capacity for low-carbon energy (for example, feed-in tariffs, green electricity schemes) – Focus on sustainability goals in agricultural, transport, and energy sectors	– Increase sustainability credentials of biomass feedstocks 🟪 – Reduce supply availability and intensify scrutiny on biomass value chains ◼

Enabler

Impact of legislation 🟪 Positive ◼ Negative

Source: Kearney, Kearney Transition Institute

Regulatory framework maturity is country-specific and depends on government environmental targets

3 Regulation and acceptance

Illustrative

Policy examples split by legislation category and assessment

	Waste management regulations	Decarbonization targets and blending mandates	Land use and planning regulations	Fiscal incentives/ government subsidies	Other sustainability policies
Lagging	India	US	Argentina	Japan	Mexico
	– In 2016, the Solid Waste Management Rules (SWM) replaced the Municipal Solid Wastes Rules of 2000, which had never been implemented	– Withdrawal of the Paris Agreement in 2017 (effective in 2019); no specific renewable energy target at federal level	– Minimum Standards for the Protection of Native Forests set up in 2007, but the law lacks enforcement	– No substantial tax incentive for biodiesel, which is subject to the same diesel tax as on-road diesel	– Regulatory issues and lack of an established supply chain prevented the country from fully establishing its “clean-fuel” strategy
Emerging	Russia	Canada	India	Mexico	US
	– Set up of a Russian Ecological Operator by the State in January 2019 to ensure sound regulation of household waste is in practice, build adequate infrastructure for waste management, and raise awareness among consumers and producers	– Intent accounted in December 2016 to develop Clean Fuel Standard to achieve 30 million tons of annual reductions in GHG emissions by 2030	– Aim to create an additional carbon sink of 2.5 to 3 billion tons of CO_2 equivalent through additional forest and tree cover by 2030 (NDC to the UNFCCC)	– Clean Energy Certificates (CELs) scheme where energy producers must acquire a given amount of certificates by producing clean energy	– Currently, 23 states and the District of Columbia (out of 51) have implemented statewide GHG targets
Advanced	UK	France	Indonesia	US	Germany
	– Waste Framework Directive requiring the United Kingdom to recycle at least 50% of household waste by 2020 and 65% by 2035	– The Law on Energy and Climate sets climate emergency and the objective of carbon neutrality by 2050 in the law	– Temporary moratorium (made permanent in 2019) on granting permits to clear primary forests and peatlands for plantations or logging	– Set of federal tax incentives or credits for renewable energy projects (Production Tax Credit, Investment Tax Credit, Residential Energy Credit, Modified Accelerated Cost-Recovery System)	– National Sustainability Strategy, which was adopted in 2002, sets out quantified goals for 21 key areas related to sustainable development

Source: Kearney Transition Institute

Regulation – deep-dive

Bioenergy attractiveness is also driven by social, market, and political acceptance; lower than for other renewables

3 Regulation and acceptance

Assessment framework of sustainable energy social acceptance through sociopolitical, community. and market acceptances was developed by Wüstenhagen et al. in 2007.

Acceptance – deep-dive

Biomass potential—social acceptance

Sociopolitical acceptance

Acceptance and support of general public opinion, NGOs, and government

- Lower recognition of bioenergy as “renewable energy” than wind or solar
- Severe social controversies because of expected land use or food competition
- Low experience of farmers in bioenergy crops cultivation raising viability concerns
- Heterogeneity of NGOs’ positions regarding bioenergy uptake
- Developing government support through policy implementation

- Increase public general information level about bioenergy solutions
- Mitigate risks for farmers through increased support actions

Community acceptance

Acceptance of local residents or stakeholders in regard to biomass projects

- Air pollution from bioenergy plants is a major concern for local communities
- Communities’ perception of bioenergy plants influenced by local energy availability

- Provide quality information to the public all along the planning process
- Settle compensating measures such as reduced energy costs

Market acceptance

Adoption and support of market parties (consumers, firms, investors)

- Inattention to bioenergy from consumers, who have misconceptions about its interest
- Consumer concerns about supply security, availability of efficient and updated technology and price
- Perceived instability and uncertainty of national policies by investors

- Increase consumer information on the reliability and benefits of biomass solution
- Increase policy stability to provide longer-term vision and security to investors

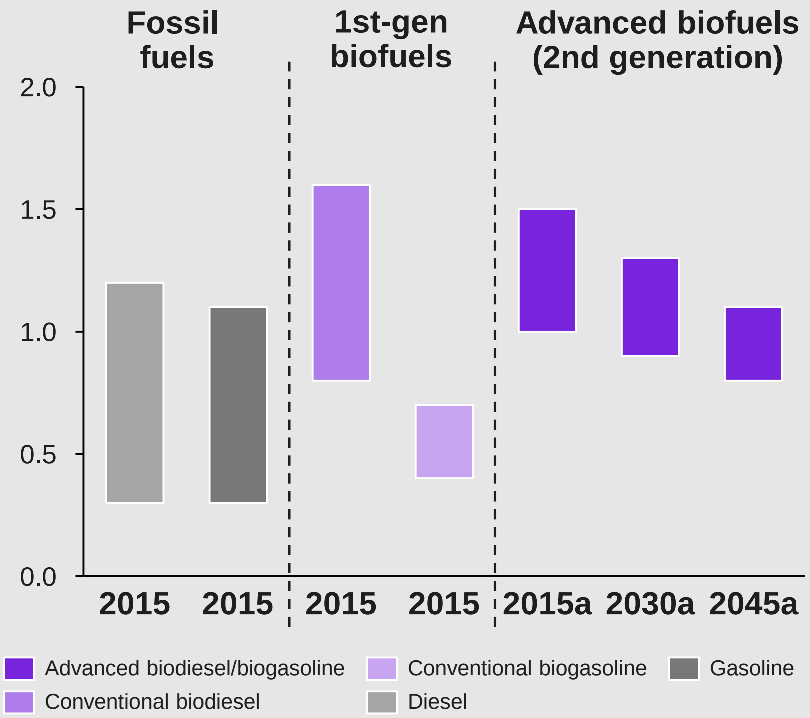
Enabler

Sources: Role of Community Acceptance in Sustainable Bioenergy Projects in India (VK Eswarlal, 2014), Social Acceptance of Bioenergy in Europe (Segreto et al., 2019), Social Acceptance of Bioenergy in Europe (Alasti, 2011), Social Acceptance of Renewable Energy Innovation: an Introduction to the Concept (Wüstenhagen et al., 2007); Kearney Energy Transition Institute

Biomass-to-biofuel/gas is likely to remain more expensive than fossil fuels—opportunity driven by country regulation

4 Technologies and economics

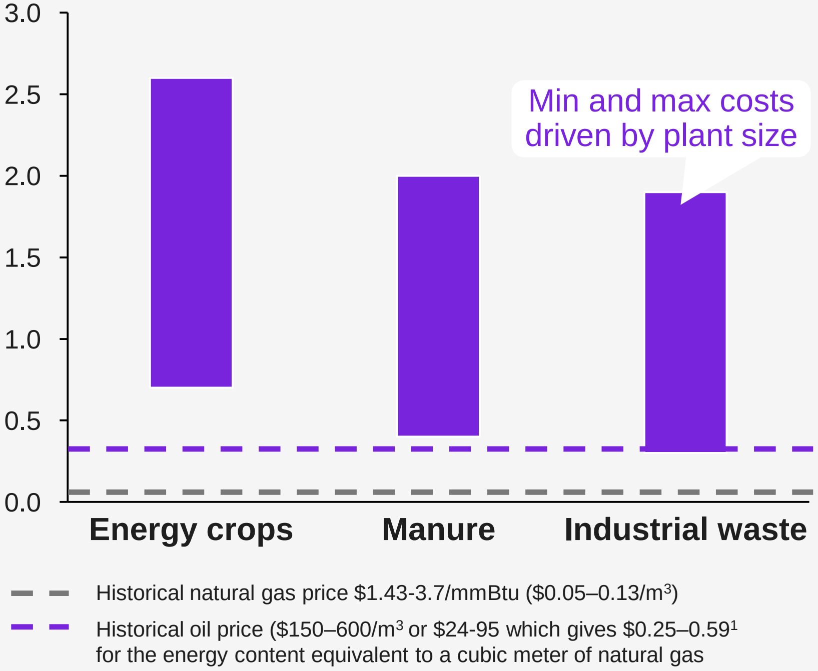
Projected biofuel production cost
$/l



- Improve feedstock economics with optimized production, collection, and transport
- Improve process economics with better yields, better energy efficiency (use of combined cycle or catalysts), and economic valorization of the by-products

Enabler

Biomethane production cost
$/m³



- Increase size of power plant to reach economies of scale
- Decrease feedstock price by optimizing feedstock collection and identifying zone with high potential

Technologies and economics – deep-dive

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[1] To compare crude oil and gas price per cubic meter, prices were normalized with their respective energy density, 0.0364 MJ/L for natural gas and 37 MJ/L for crude oil

Sources: IRENA Innovation Outlook Advanced Liquid Biofuels, IRENA EU report on biogas potential beyond 2020; Kearney Energy Transition Institute

Biomass should focus on segments without other sustainable alternatives, and where storable energies are valued to get the most of its competitive advantage

Bioenergy substitution matrix

	Sector	Sector energy consumption (Mtoe, 2018)	Potential technologies to reduce CO_2 emissions (2040 time horizon)			Substitution score	Biofuels opportunity	Biofuel potential by sector							
			H2	Electrification (renewables + storage)	Carbon capture storage[1]			Bioethanol	Biogasoline	Biodiesel	Renewable diesel	Black liquor	Bio jet fuels	Biomethane	Gas from waste
Transport	Car	1,124	◑	●	○	+++	▼	✓	◯✓	✓	✓	✗	✗	✓	✗
	Truck	740	◑	◑	○	++	▲	✓	✓	✓	◯✓	✗	✗	✓	✗
	Aviation	326	○	○	○	+	▲	✗	✗	✗	✗	✗	◯✓	✗	✗
	Shipping	251	◔	◔	○	+	▲	✓	✗	✓	◯✓	✗	✗	✓	✗
Energy	Power	4,294	◑	●	◑	+++	▶	✗	✗	✗	✗	✓	✗	◯✓	✓
	Heat	113	◑	●	◑	+++	▼	✗	✗	✗	✗	✓	✗	◯✓	✓
	CHP	1,086	◑	●	◑	+++	▶	✗	✗	✗	✗	✓	✗	◯✓	✓

Maturity of technologies:
- ● Commercialized
- ◑ Pilot projects
- ◔ Research stages
- ○ Not an option

Maturity of substitution options:
- +++ At least one commercial option
- ++ At least one pilot project
- + Ongoing R&D investment

Potential product-sector combination opportunity: ◯

Substitution – deep-dive

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[1] Use of CO_2 from CCS is not considered in the range of possible solutions
[2] Based on 2017 figures
[3] Minimal use of methanol in truck transport
Sources: IEA WEO 2019; Kearney Energy Transition Institute

Identifying drivers' impacts on the value chain highlights the enablers to activate in order to improve market environment

① Feedstock supply

- Quantity and quality of bioenergy available
- Value repartition between conversion routes
- Overall carbon footprint of bioenergy production

- Increase space dedicated to feedstock cultivation
- Increase feedstock production and collection efficiencies
- Limit feedstock cultivation impact on the environment

▲ ▲ ▲

② Infrastructure maturity

- Pace of bioenergy solutions integration
- Investors' security
- Reduce processing and transport costs

- Public–private partnership to secure private investment
- Public investment to support for production scale up (roads, trains, and so on)
- Regulations to support energy transition (tax incentives)

▲ ▽ ▲

③ Regulation and acceptance

- Affordability and market size of bioenergy solutions, infrastructure adaptability
- Accessibility of sustainable feedstock

- Adopt integration targets for biofuels
- Increase incentives and policy support on demand and offer side (feed-in-tariffs, tax incentives)

▲ ▽ ▲

- Size of biofuels market and of feedstock available
- Investors' interest
- Level of policy support

- Ensure communication to the public
- Increase demand-oriented incentives for bioenergy solutions
- Limit bioenergy consumption in segments where competing uses are identified

▲ ▽ ▲

④ Technologies and economics

- Rentability and scalability of biomass-to-energy investments
- Competitiveness vs alternative

- Development of conditioning and pretreatment technologies improving feedstock quality
- Increase policy support and R&D funding

▽ ▲ ▽

⑤ Substitution

- Price of biofuels available on market segment
- Penetration rate and speed of bioenergy

- Development of conditioning and pretreatment technologies improving feedstock quality, increase policy support and funding

▲ ▲ ▲

Driver | Enabler | ▲ ▲ ▲ Effect on price/volume/mix | ▽ ▽ ▽ No effect on price/volume/mix

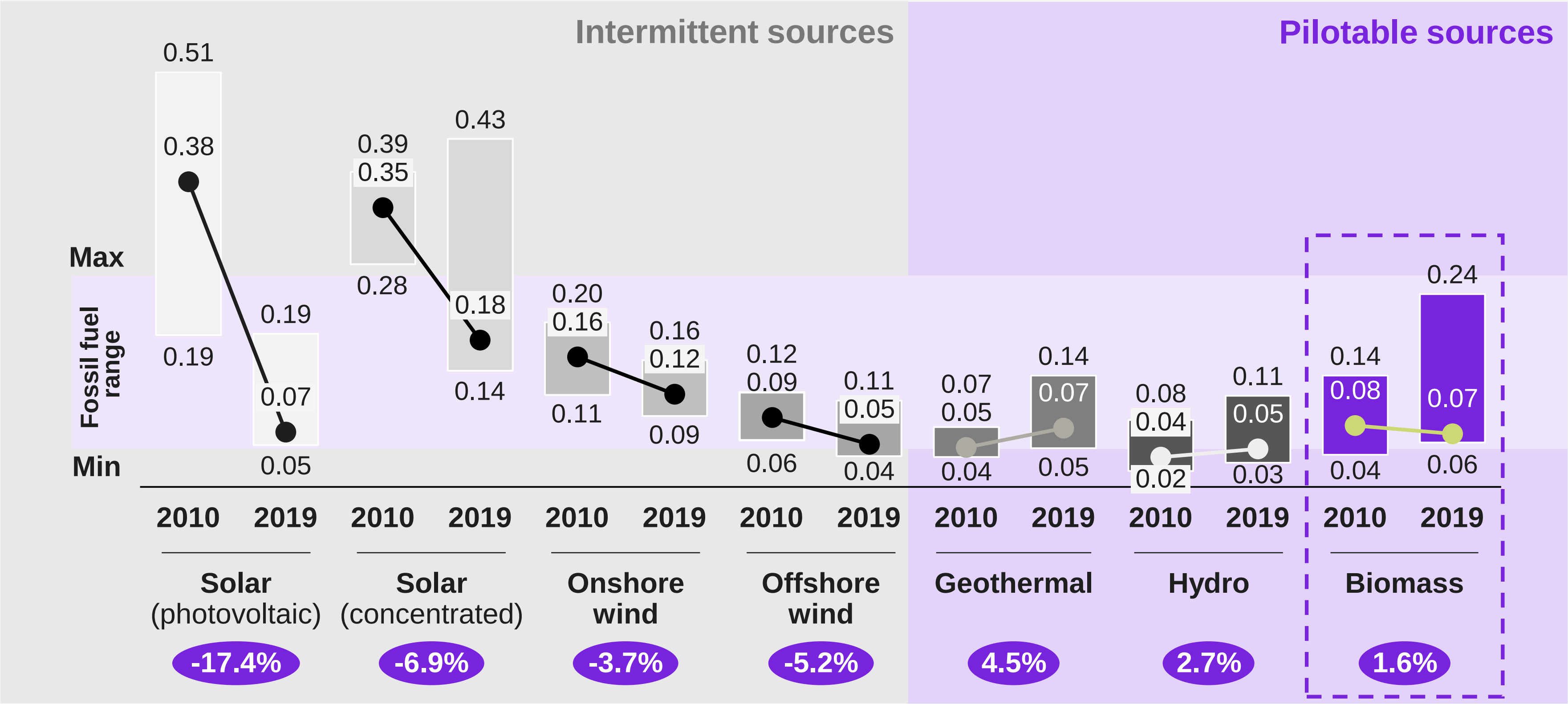
Source: Kearney Energy Transition Institute

Market enabler – results

Biomass-to-power can be competitive with fossil fuels, but wind and solar prices are expected to fall further

LCoE[1] by renewable energy source

Global, USD / kWh[2], 2010–2019



- Improve feedstock economics
- Improve infrastructure compatibility or deployment
- Improve process economics (yield, efficiency, feedstock cost, energy consumption)
- Develop acceptance, leverage financial incentives and government subsidies

Enabler ● Weighted average X% CAGR (%) 2016–2018

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[1] LCoE = levelized cost of energy; outliers not considered in max/min but included in weighted averages

[2] kWh = kilowatt hours

Sources: IRENA, Wood Mackenzie (MAKE); Kearney Energy Transition Institute

Market enablers – results

Drivers have various evolution perspectives in the next decades and will strongly influence B2E penetration

The drivers of biomass will shift as enablers successively arise

	2010	2020	2030	2040	2050+
1 Supply of feedstocks will increase	– Biofuel from cane sugar develops as the dominant technology	– Bio jet fuel develops further	– Wider biotechnology developments (for example, biomass feedstock)	– Cost-effective biological crop waste fuels developed	– A much larger global population will generate substantially more MSW and other waste – An increasing infrastructure maturity and efficiency will enable better collection of the feedstock – Biofuels can be cost competitive to petroleum based on carbon pricing and industry adoption (for example, aviation) – Regulation and public sentiment will call for biofuel value chains – Given the expected opportunities, many competitors will be playing in this sector
2 Infrastructures will gain in maturity	– Collection and recycling are increasingly performed across the world	– Circularity and revalorization principles create interest for residues and waste	– Wider infrastructure development that increases the sustainable potential	– Reduced environmental impact of collection and transport	
3 Sociopolitical pressures are rising	– Environmental concerns become increasingly widespread	– Sustainability to be a major focus across all OECD politics	– Maturing emerging markets will demand more sustainability	– Maturity of Gen Z will make sustainability non-negotiable	
4 Biofuel technology is developing	– Feedstock supply increases despite push for circularity	– Better household practices raise MSW availability	– Feedstock management practices (for example, collection) increase supply	– Global population up 750 million from 2020	
5 Rivals will increasingly look for opportunities	– Initial interest in biomass, but it remains non-core to energy players	– All oil majors are looking at opportunities in biomass	– New entrants with proprietary technology will be emerging	– Market should have evolved to produce dominant players	

Source: Kearney Energy Transition Institute

Section 3

Conclusion: Successful business models

Key questions

What are the successful business models of bioenergy production?

i. What are the promising commercial applications of B2E?

ii. What is their market situation, the related regulations, their environmental and economic impact?

iii. What is their evolution potential?

Source: Kearney Energy Transition Institute

Five business cases studied in Europe, the US, and China show the diversity of biomass potential applications

1

Waste to energy

In the UK

Energy production as a waste management solution is developed in the UK from MSW non-recyclable fraction

2

Bio jet fuel

In the US

Bio jet fuel is a promising way to decarbonize aviation and the production is developing in the US from forestry residues and oily crops

3

Biomethane

In China

Biomethane is produced from biomass feedstock digestion or gasification/ methanation in China as a substitute to natural gas

4

Renewable diesel

In the US

Renewable diesel is a promising alternative to petroleum diesel and is developed in the US from vegetable oil and waste oil and fats

5

Co-firing

In cement industry

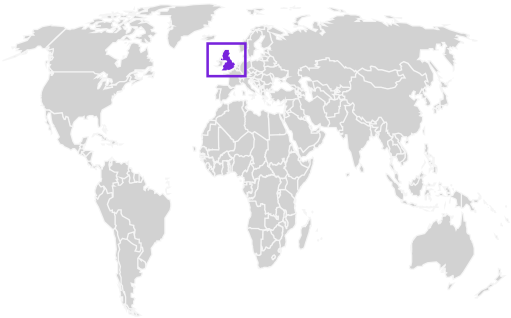
Co-firing biomass with traditional solid fuels is an efficient way to decarbonize the cement industry without major infrastructure investments

Source: Kearney Energy Transition Institute

Energy from waste is developed in the UK as it combines energy generation and waste management solution

1

Waste to energy
In the UK



Business case 1

Description

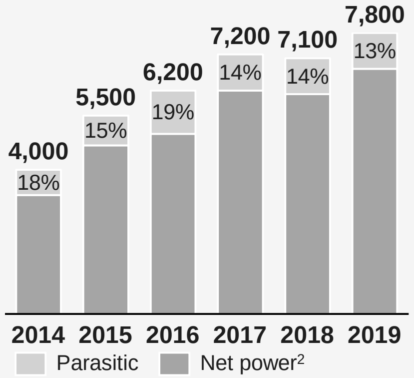
- In 2019, **53 energy-from-waste plants** were active in the UK
- Energy-from-waste stream produces **6.7 TWh (2% of UK total power generation)** together with **1.4 TWh of heat**
- **Inputs:** Municipal solid waste, commercial and industrial waste (residual)
- **Outputs:**
  - **Electricity** (efficiency with indirect generation[1] 15-27%)
  - **Heat** (efficiency up to 90%) but difficulty to find the long-term customers to support the investment
  - **CHP** (efficiency 40%)
  - **Transport fuel**

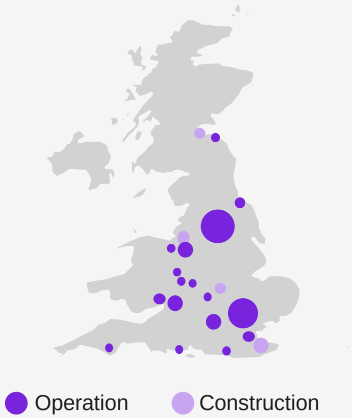
Process characteristics

- **Process steps**: Reception, thermal treatment, conversion to energy, emissions clean-up
- **Technology used:** Incineration, advanced thermal treatment such as gasification and pyrolysis
- **Hot gases** from the thermal step used to boil water to create steam
- **Steam** used in a steam turbine to produce electricity and/or for heating
- **Advanced thermal treatment** enables further upgrading into more complex liquid biofuels

Global market overview

UK, 2019, power generation GWh





1. Indirect generation: from residual heat/hot gases
2. Parasitic power is withdrawn by the grid and has to be deduced from the power generated to obtain net power.

Sources: Energy from Waste – A Guide for Debate, Feb 2014, Department for Environment, Food and Rural Affairs, UK Energy from Waste Statistics 2019; Kearney Energy Transition Institute

Drivers/barriers

Drivers

- Efficiency of the plant
- Organic fraction of the waste
- Non-intermittent partially renewable electricity generation
- Contribute to energy security
- Contribute to renewable share target

Barriers

- Discourages greater recycling
- Air pollutant health impacts
- Lack of heat customers due to location or relative cost of alternatives

Incineration and thermal treatment release carbon dioxide but are less harmful than landfill for the environment

1

Waste to energy
In the UK

Business case 1

Process description

- **Reception:** Receive and store waste, get it ready for combustion
- **Pretreatment**: Material recovery, mechanical biological treatment (sorting and anaerobic digestion), mechanical heat treatment
- **Conversion:** Incineration, gasification, pyrolysis, anaerobic digestion
- **Emissions clean-up:** Ensuring waste gases are safe and meet the limits placed by EU legislation

Key metrics

Lifetime of plant	20–30 years
Residual waste processed in 2019 (Mt)	12.63
Energy from waste share on the residual waste market	41.8% (2018) 45.5% (2019)
Incinerator scale	25–600 kt of waste processed per year
Advanced thermal treatment scale	30–60 kt of waste processed per year

Feedstock characteristics

- **Composition:** Residual waste (mixed waste that cannot be usefully reused or recycled) from municipal solid waste and any commercial and industrial waste (C&I)
- **Waste source:** In 2019, 81.5% from MSW and 18.5% from C&I
- **Organic content:** Between half and two-thirds of a typical black bag of waste contains biogenic carbon (renewable carbon)
- **Energetic value:** Average net calorific value for residual MSW is 8.9MJ/kg and for C&I is 11MJ/kg

Environmental performance

- **Negative net impact:** Energy from waste impact (0.343 tCO2eq) - avoided landfill impact (0.375 tCO2eq) = -0.032 tCO2eq per ton of input waste
- **Proportion and type of biogenic content** is key to environmental performance, only the energy generated by the organic fraction of the waste is considered renewable
- Requires **emissions** cleaning and monitoring (dioxine/furane emissions)
- **Incineration produces carbon dioxide only** whereas landfills produce carbon dioxide and methane in equal proportion

Sources: Energy from Waste – A Guide for Debate, Feb 2014, Department for Environment, Food and Rural Affairs, UK Energy from Waste Statistics 2019; Kearney Energy Transition Institute

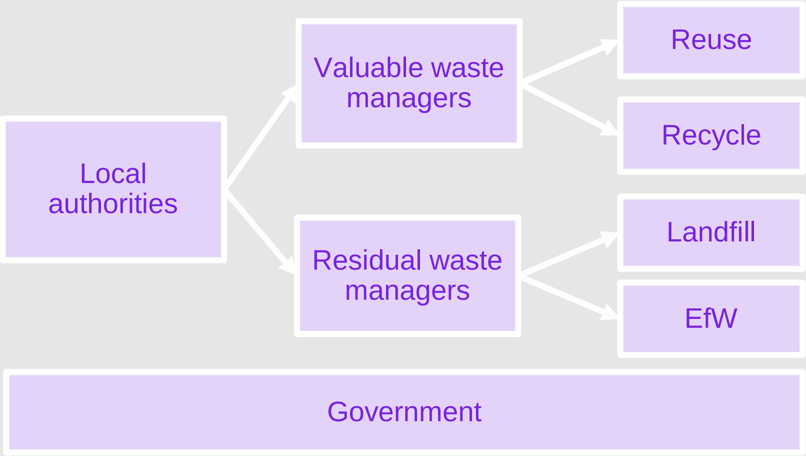
Energy from waste is more and more competitive, supported by landfill tax and increasing emission controls

1

Waste to energy
In the UK

Business case 1

Value chain stakeholders



Local authorities

Valuable waste managers

Residual waste managers

Reuse

Recycle

Landfill

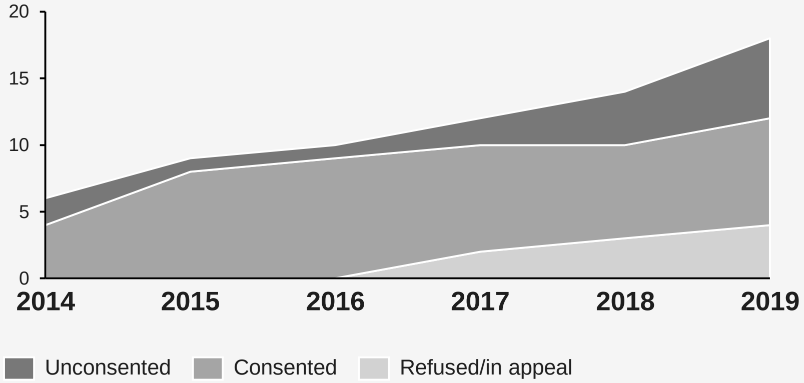
EfW

Government

Market information

Energy from waste in development
Million tonnes

- **Market players and respective share:** Viridor 22.1%, Veolia 18.6%, Suez 17.6%



Production cost analysis

	MBT	EfW	Landfill
Gate fee range (£/t of feedstock)	66–82	32–126	8–49
Comment	Various waste management streams	Gate fee increase for newer facilities	80–121 range with landfill tax

Key regulation and policy

- Historically the main treatment route for UK was landfill (suitable sites created by past mineral extraction)

1989 **Tighter incineration controls**

2000 **Waste incineration directive**

2010 **Industrial emissions directive**

Sources: Energy from Waste – A Guide for Debate, Feb 2014, Department for Environment, Food and Rural Affairs, UK Energy from Waste Statistics 2019, Wrap Gate fee report 2013; Kearney Energy Transition Institute

The US is one of the main emerging markets for bio jet fuels but their uptake is still limited by technical and market constraints

2

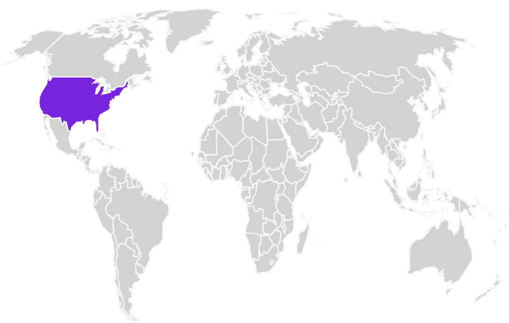
Bio jet fuel
In the US

Description

- **Five operational plants producing bio jet fuel in the US**, but only one has jet fuel as the main outcome product
- Production ranging from 3 Mmgal/year to 160 Mmgal/year for a total of **353 Mmgal/year of fuel produced**
- Four other plants in project with an **additional forecasted production of 29 Mmgal/year**
- **Key enablers:**
  - Legal and regulatory framework
  - Infrastructure deployment
  - Agriculture potential for feedstock production

Process characteristics

- By February 2020, **6 conversion processes** to produce SAF (Synthetic Aviation Fuel) had been certified:
  - Synthesized Paraffinic Kerosene (SPK) from the **Fischer-Tropsch process** (FT-SPK)
  - SPK from **hydroprocessed esters and fatty acids** process (HEFA-SPK)
  - SPK from the **alcohol-to-jet** process (ATJ-SPK)
  - SPK from **catalytic hydrothermolysis** (CHJ-SPK)
  - FT-SPK with increased aromatic content (FT-SPK/A)
  - Synthetic isoparaffins (SIP) **from hydroprocessed fermented sugars** (HFS-SIP)
- In the US, **7 projects rely on HEFA–SPK and 2 on FT–SPK**

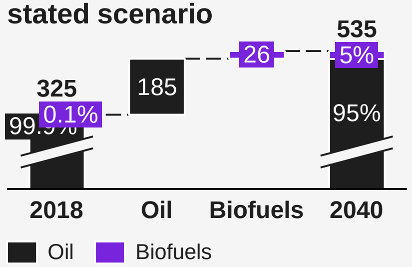


Business case 2

Global market overview

- Biofuels expected to play a **key role in the aviation sector**
- Very **limited growth expected for alternative renewable** fuels (electricity, hydrogen) because of a low technological maturity and high technical constraints

Aviation energy consumption forecast by fuel type
Mtoe, 2018–2040, world – stated scenario



Drivers/barriers

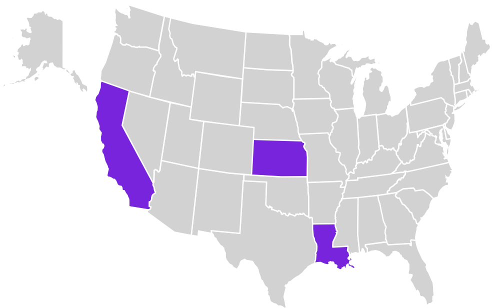
Drivers	Barriers
– Need for reducing emissions – Oil price fluctuation and fuel insecurity – Carbon price – Lack of alternative technology – New growth market for biofuels – Green public relations	– High quality standards to ensure safety – High costs and funding – Fuel consistency and infrastructure – Low feedstock supply readiness – Timid policy incentives

Sources: Sustainable Aviation Fuels Guide (ICAO, 2018), The cost of supporting alternative jet fuels (ICCT, 2019), Alternative jet fuels: Case study of commercial-scale deployment (ICCT, 2017), Biofuels for Aviation: Technology Brief (IRENA, 2017), Review of Biojet Fuel Conversion Technologies (NREL, 2016), The Flight Paths for Biojet Fuel (EIA, 2015), Are aviation biofuels ready for take off? (IEA, 2019); Kearney Energy Transition Institute

HEFA appears as the most viable solution from a technical perspective to produce bio jet fuels

2

Bio jet fuel
In the US



Process description

- **Hydroprocessed esters and fatty acids SPK:**
  - Removal of oxygen fraction of the feedstock by **hydrotreatment**
  - Split of feedstock in different hydrocarbons (mainly diesel and kerosene) through **hydrocracking**
- **Fischer-Tropsch SPK:**
  - **Gasification** of the solid biomass at elevated temperatures to obtain “syngas”
  - **Purification** of the gas and synthesis of kerosene and other hydrocarbons in a **catalytic reaction** known as Fischer-Tropsch process

Key metrics

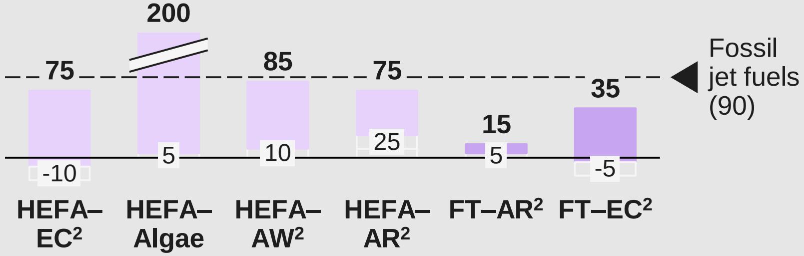
Conversion yield (tfuel/tfeedstock)	90% (HEFA) 12% (FT)
Jet fuel share among products (%)	15–55 (HEFA) 25–50 (FT)
LHV (MJ/kg)	42.8 min.
Density (kg/m³)	775–840
Flash point (°C)	38 min.
Freezing point (°C)	- 47 max.
Sulfur content (%)	0.3 max.
Maximum blending ratio with fossil jet fuel (%)	50% (FT, HEFA, ATJ, and CHJ) 10% (HFS)

Feedstock characteristics

- **Variety of sources possible** to produce jet fuel (including forestry and agriculture residues or crops, waste, algae) depending on the conversion process used
- HEFA conversion processes are based on **feedstocks with a high oil content**, such as inedible waste oils and fats, mostly animal fats such as tallow and lard, or algae
- FT conversion process relies on the **heating of small feedstock particles**, mainly agricultural and forestry residues or energy crops (corn stover, switchgrass)

Environmental performance

LCA GHG emissions by conversion process and feedstock[1]
gCO2/MJ, 2018



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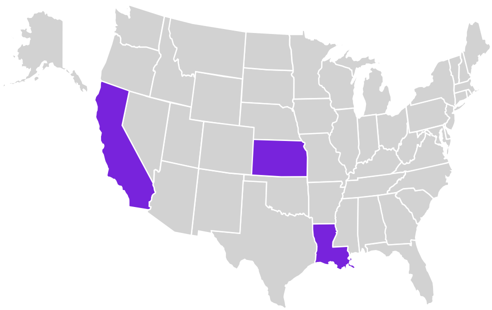
[1] Emissions over the whole life cycle, without land use change considerations. Negative values can be obtained because of the displacement of CO_2 emissions (for example, jet fuel production from sugarcane produces bagasse which can be used as a fuel and avoids energy-related CO_2 emissions).
[2] EC is energy crops, AW is animal waste, AR is agricultural residues
Sources: Sustainable Aviation Fuels Guide (ICAO, 2018), The cost of supporting alternative jet fuels (ICCT, 2019), Alternative jet fuels: Case study of commercial-scale deployment (ICCT, 2017), Biofuels for Aviation: Technology Brief (IRENA, 2017), Review of Biojet Fuel Conversion Technologies (NREL, 2016), Are aviation biofuels ready for take off? (IEA, 2019); Kearney Energy Transition Institute

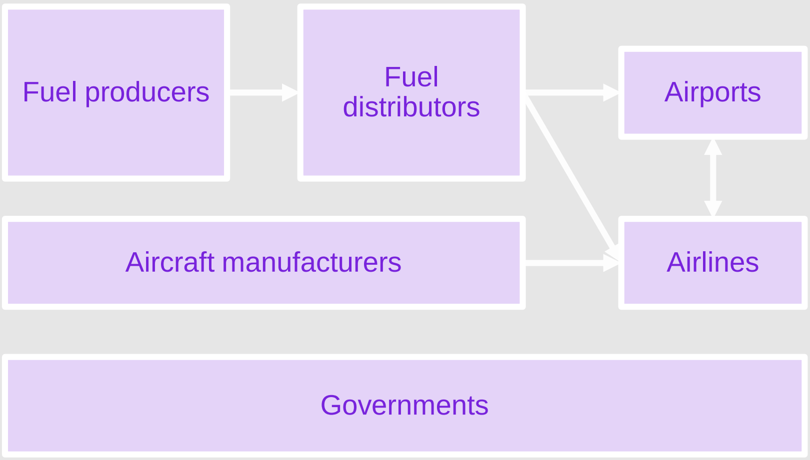
Bio jet fuel production is not cost-competitive yet and therefore requires strong policy support

2 **Bio jet fuel**
In the US



Business case 2

Value chain stakeholders



Fuel producers

Fuel distributors

Airports

Aircraft manufacturers

Airlines

Governments

Market information

- **Market share**: The US accounts for 20% of the world bio jet fuel production (other main players are Northern Europe and Singapore)
- **Key market players**:
  - Producers: AltAir, Amyris, Fulcrum, GEVO, Red Rock…
  - Airlines: United Airlines (50% of bio jet fuel volume purchased in 2018), FedEx, AirBP, Cathay Pacific…
- **Infrastructure**: Limited opportunities as only 5 airports have regular biofuel distribution (Bergen, Brisbane, Los Angeles, Oslo, and Stockholm)
- **Development perspectives**: Low capex reduction opportunities for HEFA conversion, higher ones for FT

Production cost analysis

	HEFA	FT
Investment range (M\$)	200–700	350–1,230
Capex (\$/L_{output}/year)[1]	0.3–1.1	2.8–4.2
Opex drivers (% production costs)	Feedstock (80%)	Feedstock and plant operations (15–35%)
Production costs (\$/L)	0.7–1.6	1.0–2.5

Key regulation and policy (US)

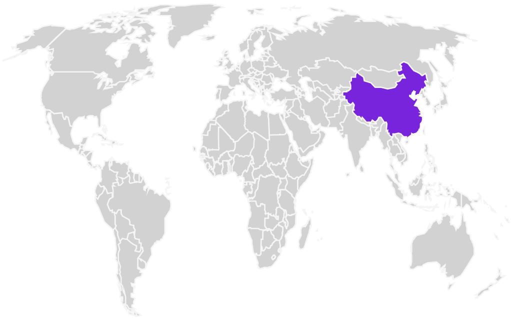
2006	**CAAFI: Pioneer initiative gathering state, airlines, airports, and manufacturers engaged in various activities to enable and facilitate near-term development of bio jet fuels**
2013	**Extension of the Renewable Fuel Standards (fuels green certificates scheme) to "advanced biofuels" (including bio jet fuels)**
2016	**Launch of the Great Green Fleet Initiative by the US Navy aiming to reach a 50% "green fuel" target**
2020	**CORSIA's objective to reach carbon neutral growth for the aviation sector from 2020 on**

[1] Bio jet fuel is only one of the outputs of the conversion plants (along with renewable diesel and light ends). Therefore, not all the capex is included in the bio jet production cost.

Sources: Sustainable Aviation Fuels Guide (ICAO, 2018), The cost of supporting alternative jet fuels (ICCT, 2019), Alternative jet fuels: Case study of commercial-scale deployment (ICCT, 2017), Biofuels for Aviation: Technology Brief (IRENA, 2017), Review of Biojet Fuel Conversion Technologies (NREL, 2016), The Flight Paths for Biojet Fuel (EIA, 2015), Are aviation biofuels ready for take off? (IEA, 2019); Kearney Energy Transition Institute

Biomethane is forecasted to play a rising role in the decarbonization of the power and transport sectors

3 **Biomethane**
In China



Business case 3

Description

- Biomethane is a **near-pure source of methane** (chemical composition CH_4) produced from biomass feedstocks
- Biomethane can be **produced either through biogas upgrading or by gasification of solid biomass** followed by methanation
- The annual production capacity reaches **60 million cubic meters** in China
- **Biomethane represents less than 1% of the natural gas consumption in China** but the number of biomethane plants has tripled since 2015

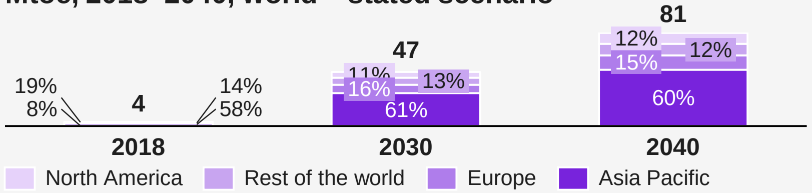
Process characteristics

- There exists two main biomethane production methods: biogas upgrading and gasification followed by methanation
- **Biogas upgrading:**
  - **90% of biomethane produced worldwide**
  - Only 2% of biogas is upgraded in Asia
- **Gasification of solid biomass:**
  - **10% of biomethane produced worldwide**
  - Technique **mainly used in Europe** (80% of worldwide biomethane produced through gasification)
  - Possible from wood and forestry residues only

Global market overview

- Current biomethane demand represents about 0.1% of current natural gas demand
- World biomethane sustainable potential is estimated at 730 Mtoe

Biomethane demand forecast by continent
Mtoe, 2018–2040, world – stated scenario



Drivers/barriers

Drivers

- Indistinguishable from natural gas
- No changes required in transmission infrastructure or end-user equipment
- CO_2 emissions reduction and embodiment of a more circular economy through waste use
- Way to provide a low-carbon energy source in rural communities

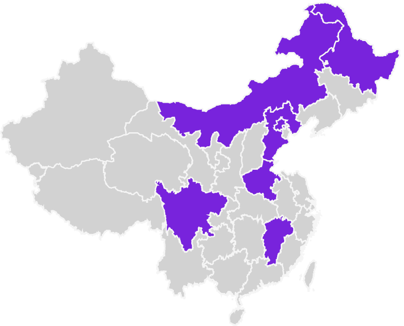
Barriers

- Lack of specific policies dedicated to biomethane
- High capital costs for biomethane facilities
- Lack of awareness, information, and expertise, especially in rural areas
- Low prices of natural gas from fossil origin

Sources: Outlook for biogas and biomethane (IEA, 2020), IEA Policies Database (IEA Website), Calculation of GHG emission caused by biomethane (Biosurf Project, 2016), A sustainable biogas model in China: the case study of Beijing Deqingyuan biogas project (Chen et al.), Opportunity and challenge of Biogas market in China (Qian Mingyu et al.), Biomethane efforts gaining traction (ChinaDaily, 2019); Kearney Energy Transition Institute

Biogas upgrading from animal waste appears to be the most widely deployed and most performant biomethane production route

3 **Biomethane**
In China



Business case 3

Process description

- **Biogas upgrading**
  - **Separation** of the different biogas components (carbon dioxide, nitrogen…) to isolate methane
    - Water scrubbing: biogas is sprayed with water to capture impurities in water droplets
    - Membrane separation: biogas flows through a membrane separating CO_2 and impurities from CH_4
- **Gasification and methanation**
  - **Pyrolysis** of woody biomass (700–800°C, low oxygen environment) producing syngas (H_2, CO, CO_2, CH_4)
  - **Syngas cleaning** followed by **methanation:** a catalyst is used to provoke a reaction between hydrogen and carbon oxides to form methane
  - Removal of excess water and carbon dioxide

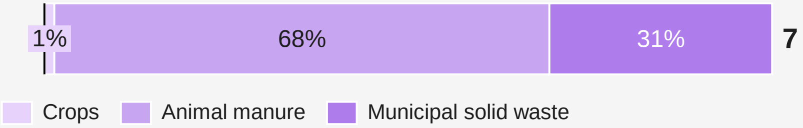
Key metrics

LHV (MJ/m3)	35.6–36
Fusion point (°C)	-182.47°C
Boiling point (°C)	-161.52°C
Density (gaseous, 15°C, 101.3 kPa) (g/cm3)	0,6709.10^{-3}
Auto-ignition point (°C)	537

Feedstock characteristics

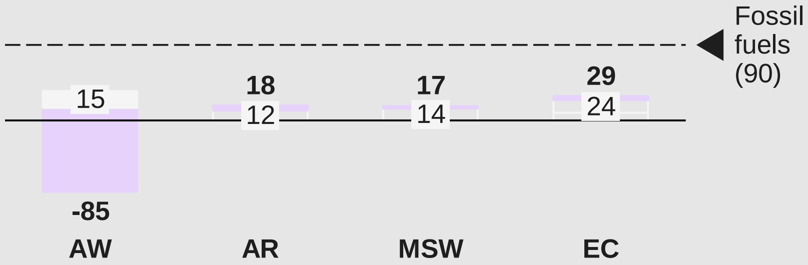
- **Wood biomass** is the most used feedstock for biomethane production through **gasification and methanation**
- Biogas production can rely on **very different feedstocks**: crop residues, animal waste, organic fraction of MSW, wastewater sludge…

Biogas production by feedstock type
Mtoe, 2018, China – stated scenario



Environmental performance

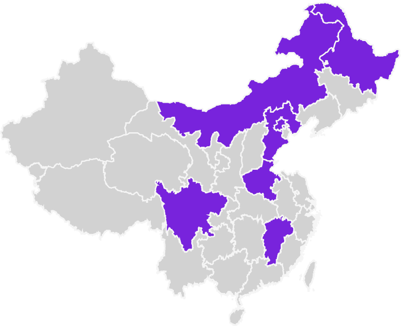
LCA GHG emissions by feedstock
gCO2/MJ biomethane, 2016



Sources: Outlook for biogas and biomethane (IEA, 2020), IEA Policies Database (IEA Website), Calculation of GHG emission caused by biomethane (Biosurf Project, 2016), A sustainable biogas model in China: the case study of Beijing Deqingyuan biogas project (Chen et al.), Opportunity and challenge of Biogas market in China (Qian Mingyu et al.), Biomethane efforts gaining traction (ChinaDaily, 2019); Kearney Energy Transition Institute

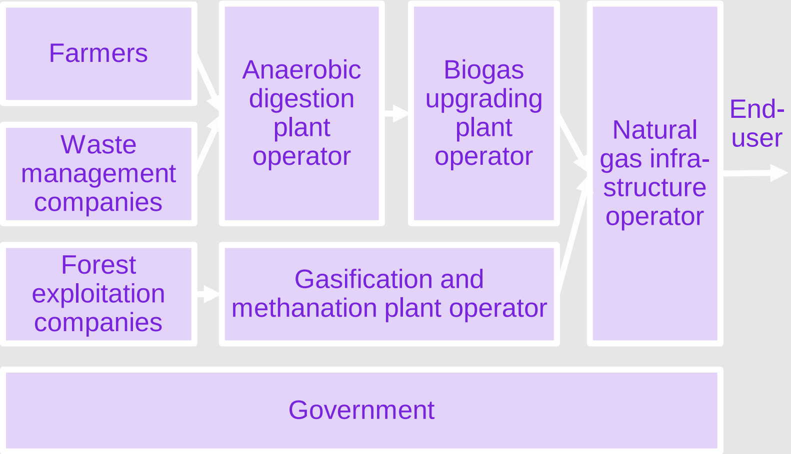
The promising development perspectives of biomethane are sustained by a supportive policy framework in China

3 **Biomethane**
In China



Business case 3

Value chain stakeholders



Market information

- **Market share**:
  - Biomethane production expected to surpass 30 Mtoe in China by 2040
  - 12% of the world sustainable biomethane potential located in China
  - 25% of world biogas demand for direct use in 2018 (share expected to decrease to 20% by 2040 but volume expected to almost double)
- **Key market players**:
  - Biomethane plant operators: EnviTech biogas, Xebec, Gasmet Technologies…
  - Gas grid owner and operator: CNPC (operating 75% of the Chinese natural gas network)
- **Development perspectives**: High biomethane uptake potential but limited cost reduction perspectives

Production cost analysis

	Key economics
Capex (¥M)	65 (60% from anaerobic digestion system and biogas upgrade system)
Opex drivers (% production costs)	10% per year (mainly maintenance and accessories costs)
Expected payback period	9–14 years

Key regulation and policy

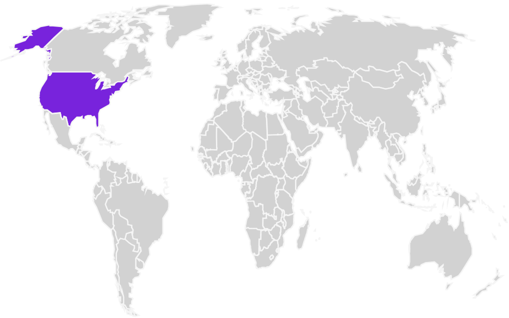
2003	**VAT reduction on biogas projects**
2006–2010	**National Biogas Project Construction Plan: financial and technical supports to projects at household level and to medium- and large-scale projects in mass production farms**
2007	**Rural biomass development plan aiming to develop biogas access in rural areas**
2019	**Guidance document issued by the National Development and Reform Commission supporting biogas upgrade in biomethane and its use in the transport sector**

Sources: Outlook for biogas and biomethane (IEA, 2020), IEA Policies Database (IEA Website), Calculation of GHG emission caused by biomethane (Biosurf Project, 2016), A sustainable biogas model in China: the case study of Beijing Deqingyuan biogas project (Chen et al.), Opportunity and challenge of Biogas market in China (Qian Mingyu et al.), Biomethane efforts gaining traction (ChinaDaily, 2019); Kearney Energy Transition Institute

Renewable diesel is mostly produced in the US and Western Europe and is competing with biodiesel[1]

4 Renewable diesel

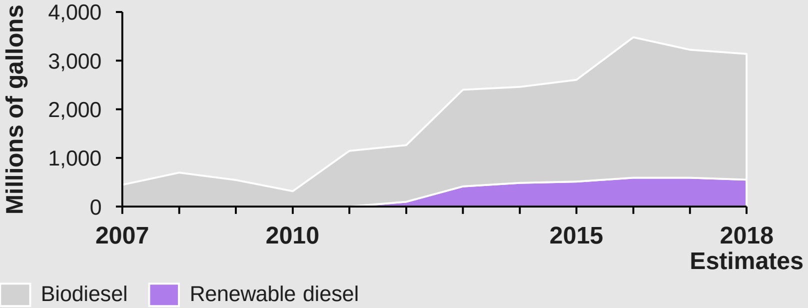
In the US



Business case 4

Description

- In 2019, in the US, there were **five renewable diesel plants** with combined capacity of **25.9k barrels per day**
- US biodiesel and renewable diesel market (Source EPA EMTS)



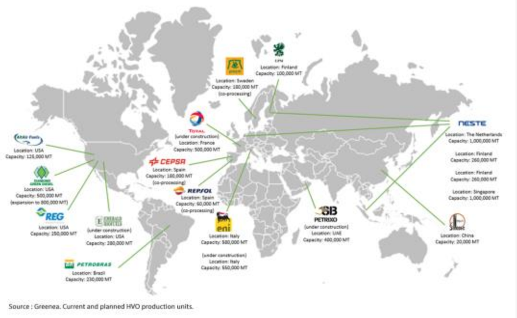
Process characteristics

Renewable diesel can be produced through multiple processes:

- **Hydrotreating of fats/oils/esters**
- **Fermentation of sugars**
- Coprocessing with petroleum, biomass pyrolysis/hydrotreatment, catalytic upgrading of sugar, Fischer-Tropsch diesel (biomass to liquid)—but none of these processes are done at commercial scale, demonstration stage only
- Currently the easiest way to produce renewable diesel is **hydrotreating** (removing oxygen, sulfur, and other compounds by hydrogenation) **fats and oil**, so it **uses the same feedstock as biodiesel production**; nevertheless, **transforming cellulosic biomass** to crude oil and upgrading it is a promising differentiated pathway

Global market overview

Global production of renewable diesel: 28.5M barrels per year



Source : Greenea. Current and planned HVO production units.

Drivers/barriers

Drivers	Barriers
– Carbon reduction policies – Financial incentives – Vehicle performance advantages – Easy way to "green" a fleet	– Competition with biodiesel and other renewable alternatives (electric vehicles) – Feedstock nature and availability

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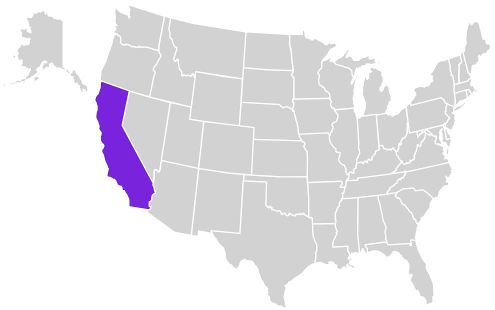
[1] Renewable diesel has the same chemical structure than conventional diesel when biodiesel does not

Sources: NREL Renewable Diesel Fuel 2016, Conoco Philips Renewable Diesel Study, ADI Analytics – Regulations to Drive US RD capacity growth through 2025, Valero Basics of Renewable Diesel, March 2020, EIA, Neste; Kearney Energy Transition Institute

Today, renewable diesel is mostly produced from waste oils and fats but use of cellulosic biomass for its production is upcoming

4 **Renewable diesel**
In the US



Business case 4

Process description

- **Co-products:** naphtha, renewable jet fuel, fuel gas (likely burned on site)

Renewable diesel production

Feedstock

Animal fat | Vegetable oil | Greases

Process

Hydrotreating | Pyrolysis | Gasification

Most widely used

Renewable diesel

Key metrics

Importation	Renewable diesel imports from Singapore only grew 49% since 2015 to a record of 17k bbl/day in 2019
Cetane number[1]	Renewable diesel 75–85 Petroleum diesel >40
Specificities	No odor, no impurities decrease maintenance cost for engines

Feedstock characteristics

- **Composition:** Today, almost all renewable diesel is produced from vegetable oil, animal fat, waste cooking oil, and algal oil.
- **Feedstock sources** in 2018:

	Soybean oil	Distillers corn oil	Canola oil	Yellow grease	Animal fats
Feedstock composition	46%	15%	11%	15%	13%

- **Feedstock will shift toward a higher share of cellulosic biomass**: agricultural residues, dedicated energy crops (oily), and eventually algae when process maturity will increase

Environmental performance

- **Relative CO_2 life cycle emissions of renewable diesel are 60 to 80% less than for petroleum diesel**
- **Renewable diesel** has a **low carbon intensity** compared to diesel, gasoline, and even California grid electricity

Conventional renewable fuel (D6)
Required life cycle GHG reduction: 20% or more

Advanced biofuel (D5)
Required life cycle GHG reduction: 50% or more

Cellulosic biofuel (D3)
GHG reduction: 60% or more
Example feedstock: corn stover

Biomass-based diesel (D4)
GHG reduction: 50% or more
Example feedstock: waste oil

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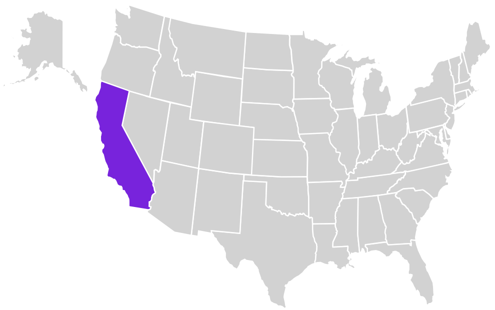
[1] Cetane number: high cetane number is linked with the ability of a hydrocarbon fuel to have better throttle response, start up quickly in cold conditions, and consume less for low loads.

Sources: NREL Renewable Diesel Fuel 2016, Conoco Philips Renewable Diesel Study, ADI Analytics – Regulations to Drive US RD capacity growth through 2025, Valero Basics of Renewable Diesel, March 2020, EIA, Neste; Kearney Energy Transition Institute

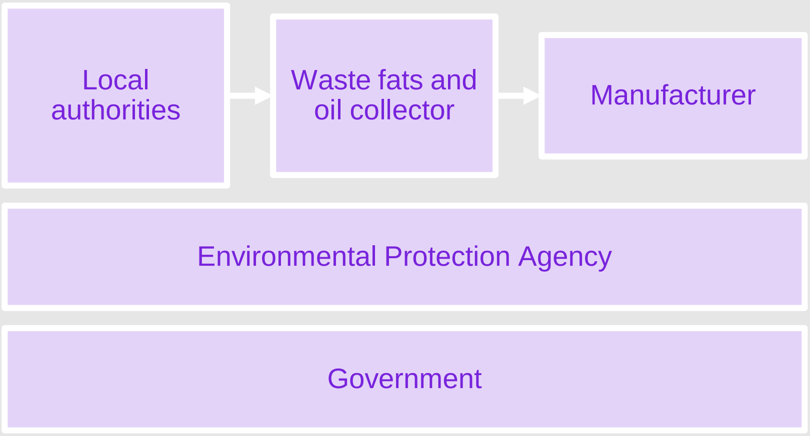
Renewable share of biofuel market in the US is growing because of its technical advantages and regulation incentives

4 **Renewable diesel**
In the US



Business case 4

Value chain stakeholders



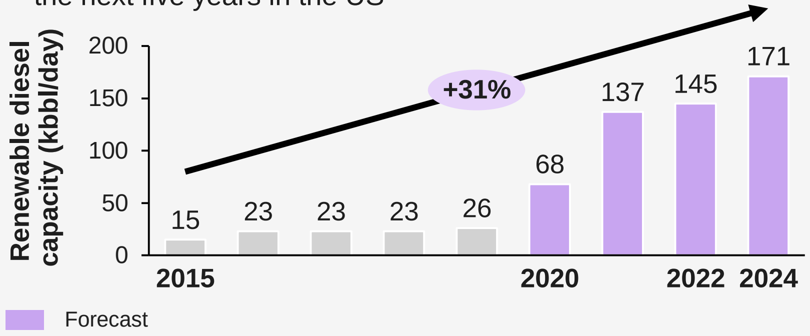
Local authorities → Waste fats and oil collector → Manufacturer

Environmental Protection Agency

Government

Market information

- **Market players:** Neste, REG, ENI, Diamond Green
- **In 2019**, **renewable diesel capacity** was around **26k barrels per day** and is expected to **grow to 171k barrels per day** in the next five years in the US



Production cost analysis

- Renewable diesel shows **higher capital costs than biodiesel**, thus it needs larger economy of scale

	From agricultural residues and cellulosic biomass	**Soy, rapeseed, palm**
Production cost of renewable diesel	0.98–1.27$/L	0.8–1.3$/L
Maturity	Experimental stage	Commercial
Process	Pyrolysis and hydrotreatment	Extraction and hydrotreatment

Key regulations and policy

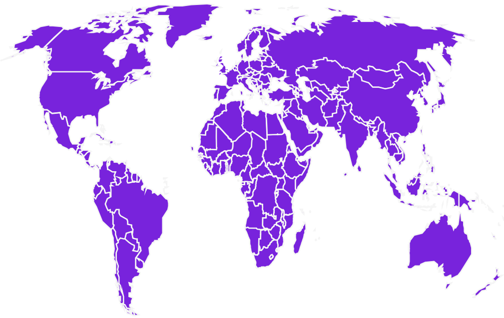
- Historically the main treatment route for UK was landfill (suitable sites created by past mineral extraction)

2000	**CCC Bioenergy Program**
2007	**Low Carbon Fuel Standards enacted by California Air Resources Board (CARB)**
2020	**Low Carbon Fuel Standards extended to 2030 by CARB**

Sources: NREL Renewable Diesel Fuel 2016, Conoco Philips Renewable Diesel Study, ADI Analytics – Regulations to Drive US RD capacity growth through 2025, Valero Basics of Renewable Diesel, March 2020, EIA, Neste, Fuel processing Technology August 2019, IRENA; Kearney Energy Transition Institute

The cement industry was responsible for 4% of world global GHG emissions in 2018 and must find pathways toward decarbonization

5 **Biomass in cement kilns**
World overview



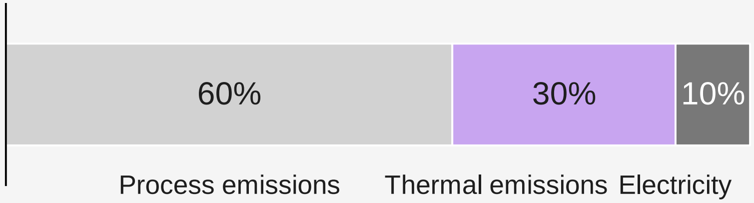
Business case 5

Description

- **Cement production** is an **energy- and emission-intensive** process due to the high temperatures required to transform limestone into cement.
- **Two types of GHG emissions** have to be tackled: **direct emissions** (CO_2 is released during calcination-limestone combustion) and **indirect emissions** (fuel is burned to heat the kilns). The direct emissions can be cut off with **CCS** and **using biomass as an alternative fuel** is a possible way to address the indirect emissions issue.
- Biomass can be used in cement plants through two major modes, namely **direct combustion** and transformation into **producer gas** (syn gas).

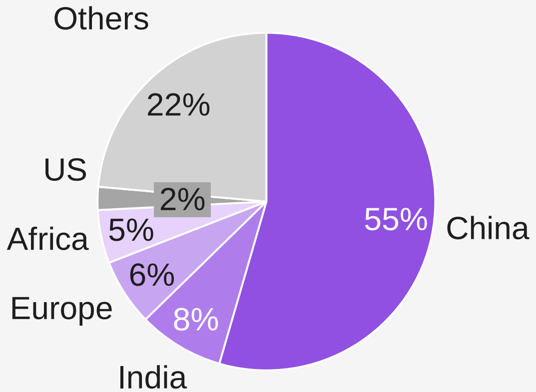
Process characteristics

- **The cement industry** was responsible for **4%** (1.5Gt) **of world global GHG emissions** (37.9 Gt) in 2018.
- **Process steps**: Limestone is heated to produce clinker and release CO_2, clinker is further refined into cement.
- The overall process emissions are distributed as follows, fossil fuel replacement by biomass could tackle the **30% due to thermal emissions.**



Global market overview

World cement production, 2018: 3.99Bt



Drivers/barriers

Drivers

- Biomass can be blended up to 20%[1]
- Reduce the fossil fuel use
- Reduce cement industry GHG emissions
- Boost local economy
- Improve energy autonomy
- Reduce landfill emissions
- Ashes from waste is integrated to the clinker

Barriers

- Variable availability of the biomass resource subject to seasonal variations
- Conditioning and transporting biomass associated costs and emissions
- Fragmented, small-scale supply
- Storage requirements

---

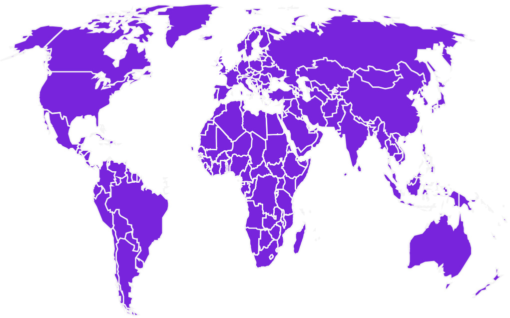
[1] Without investment to transform existing infrastructure, with a retrofit of the kilns, biomass use can reach 100%.

Sources: Global CO_2 emissions from cement production 1928–2018, Robbie M. Andrew, Kearney Energy Transition Institute, CEMBUREAU, UNDP Biomass Energy for cement production opportunities in Ethiopia, EPA Emission factors for GHG Inventories, McKinsey Laying the foundation for zero-carbon cement, Cement Technology Roadmap 2009, IEA; Kearney analysis

Co-processing releases carbon dioxide but is less harmful than landfill for the environment, or fossil fuel use

5

Biomass in cement kilns
World overview



Business case 5

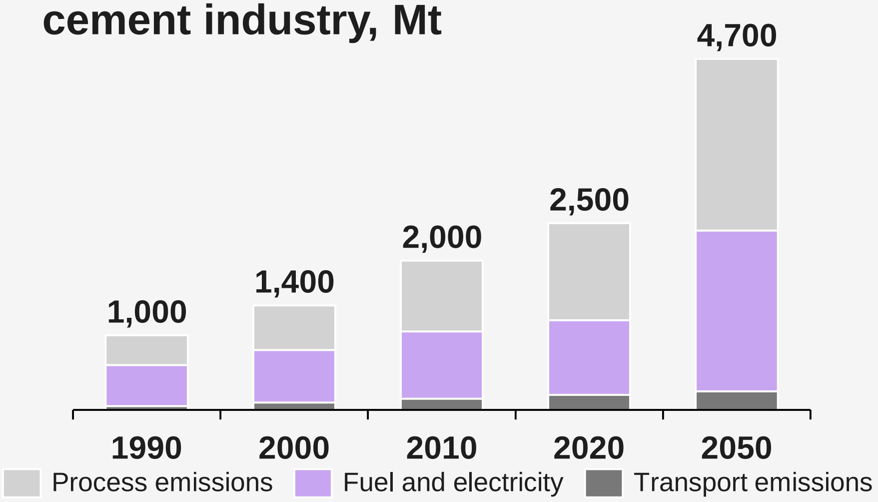
Technical options

- **Partial substitution:** mixing crushed and pulverized biomass with coal or petcoke for use in the kiln can substitute up to 20% of the fossil fuel without requiring major investment or changes in the process.
- **Direct feeding** of biomass in solid lump form (such as pellets and briquettes) into the rotary kiln and/or pre-heater/pre-calciner combustion chamber.
- **Transforming biomass** into producer gas (or "syngas") and co-firing it in the kilns using a gas burner.

NB: Other alternative fuels are also considered which are not in the scope of this factbook: petroleum-based wastes, chemical and hazardous wastes.

Key metrics

World, CO$_2$ emissions of the global cement industry, Mt



Feedstock characteristics

Fuel	LHV (MJ/kg)	CO$_2$ emissions (kg/GJ)
Coal	29.3	100–110
Petcoke	33.9	108
Furnace oil	34	74
Natural gas	47	56
Agricultural residues	16–19	124[1]
MSW	8–11	96

Environmental performance

- **Emissions reduction:** alternative fuel use can contribute 0.75Gt of CO$_2$ reduction worldwide up to 2050 (IEA)
- **Proportion and type of biogenic content** is key to environmental performance, only the energy generated by the organic fraction of the waste is considered renewable
- **Co-processing produces carbon dioxide only** whereas landfills produce carbon dioxide and methane in equal proportion

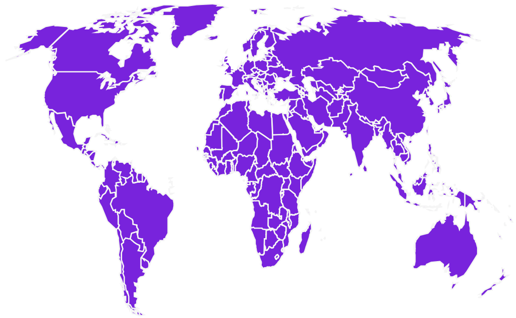
[1] These are the relative emissions of biomass, but they account for zero in the global carbon cycle.

Sources: UNDP Biomass Energy for cement production opportunities in Ethiopia, EPA Emission factors for GHG Inventories, McKinsey Laying the foundation for zero-carbon cement, Cement Technology Roadmap 2009, IEA; Kearney analysis

Biomass use in cement kilns is a growing solution, but facing disparities between countries

5

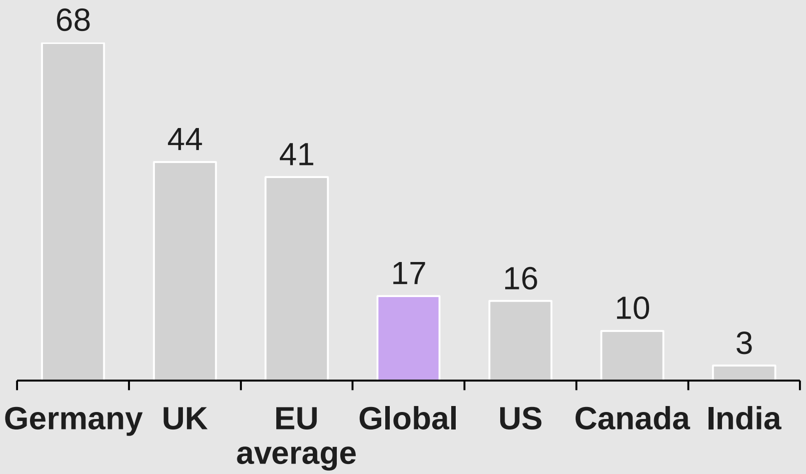
Biomass in cement kilns
World overview



Business case 5

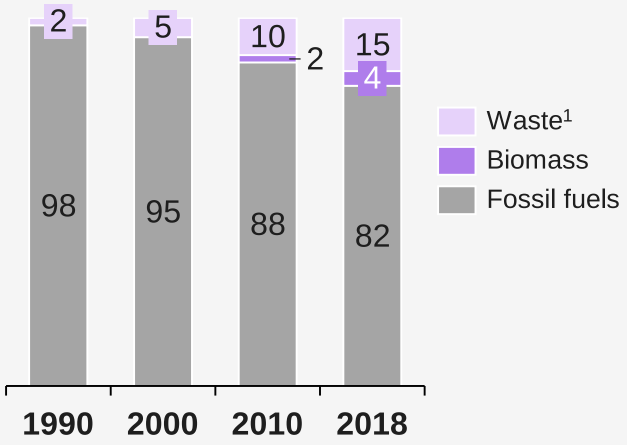
Country scale market information

% of alternative fuels use in cement production, 2017



Global market information

World, % of biomass and waste penetration as alternative fuels, 2018



Production cost analysis

– **Investment**: 5–15 M€ for a clinker production capacity of 2Mt/a
– **Retrofit:** 8–16 €/t clinker for a clinker production capacity of 2Mt/a
– **Alternative fuel cost** is forecasted to reach 30% of conventional fuel cost in 2030 and 70% in 2050

Other perspectives for cement industry

Key barriers for co-processing: permitting, regulations and standards, supportive policies, public acceptance, cost, infrastructure, lack of qualified workforce

Cement industry has several **additional possibilities** to explore in order to reduce its GHG emissions:

- Alternative fuels use
- Thermal and electric efficiency
- Clinker substitution
- Carbon capture and storage

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[1] Waste cover a mix of organic waste and waste from fossil origin (such as tires or refuse derived fuel) thus is to be differentiated from biomass.

Sources: GNR – GCCA in Numbers, Status and prospects of co-processing of waste in EU cement plants (Ecofys 2017), UNDP Biomass Energy for cement production opportunities in Ethiopia, EPA Emission factors for GHG Inventories, McKinsey Laying the foundation for zero-carbon cement, Cement Technology Roadmap 2009, IEA; Kearney analysis

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