

Biomass to energy: developing carbon circularity

Photo by Benedikt Krieger
Kearney Alumnus

Looking at advanced applications and business models

Ecosystems and societies globally face dramatic and negative consequences as accelerated anthropogenic CO₂ emissions continue to place us well above the IPCC 2°C warming scenario target.

Biomass energy, as a distributed, abundant, and renewable resource combined with its ability to be transformed, stored, and transported under multiple forms (for example, in electricity, gaseous, liquid, or solid biofuel), is a powerful pilotable carbon neutral energy source, with benefits for both the energy system and end-use applications.

This document summarizes the FactBook that 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.

- Biomass could help reduce GHG emissions in multiple sectors, representing about half of global GHG emissions.
- The deployment of bio-based fuels could help decarbonize hard-to-abate sectors such as aviation and shipping.
- Biomass is historically the first contributor to the renewable mix, however its share is now decreasing compared to wind and solar as bioenergy development faces three main challenges: sustainability constraints, value chain complexity, and maturity of technologies.
- Current advanced bioenergy demand is concentrated in the energy (heat and power) and industry sectors, which each represent 34 percent of the advanced bioenergy demand, followed by the buildings sector with 18 percent and the transport sector with 14 percent.

The content of this summary is based on the Biomass to Energy FactBook.

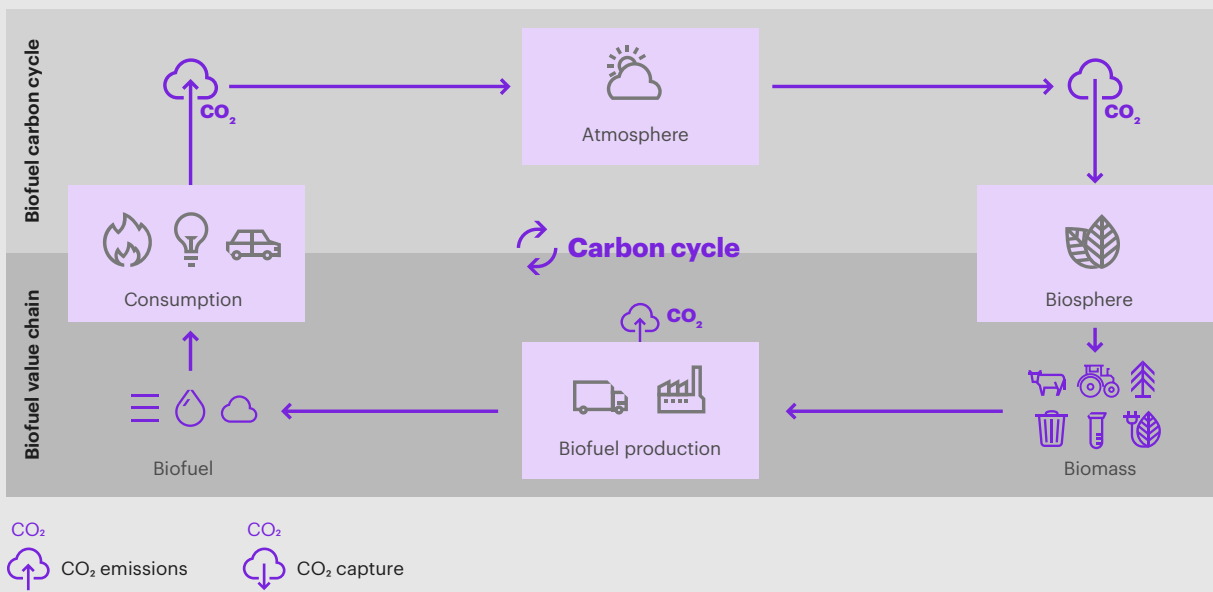
For the complete FactBook, please visit our [Energy Transition Institute website](#).

Biomass to bioenergy uses carbon circularity to turn organic matter into energy sources

Use of bioenergy is carbon neutral, and even carbon negative when combined with CCUS, if there are no emissions from non-renewable sources in its industrial value chain. The carbon neutrality of bioenergy relies on the natural carbon cycle of biomass.

Figure 1
The carbon neutrality of bioenergy relies on the natural carbon cycle balance

Biomass-to-energy carbon cycle



Source: Kearney Energy Transition Institute

As a renewable energy, bioenergy has a role to play in decarbonizing the energy mix and human activities

Biomass covers a large range of biomaterial with diverse chemical composition and properties. This makes biomass a highly versatile resource suitable for many applications that can be stored under multiple forms (for example, gaseous, liquid, or converted to other molecules). Biomass can be a viable option to decarbonize hard-to-abate end-use applications and sectors such as industrial processing and heavy transport.

Most of the anthropogenic greenhouse gas (GHG) emissions (excluding AFOLU) come from the production and transport of energy (including electricity and heat production), industry, buildings, and transport. Biomass provides multiple pathways to reducing GHG emissions in these sectors and could address about half of their GHG emissions if managed sustainably.

Figure 2
Bioenergy could theoretically help decarbonize sectors representing about 50% of global GHG emissions¹

Global GHG emissions per sector and bioenergies applicability 2010, GtCO₂eq/year, without AFOLU²

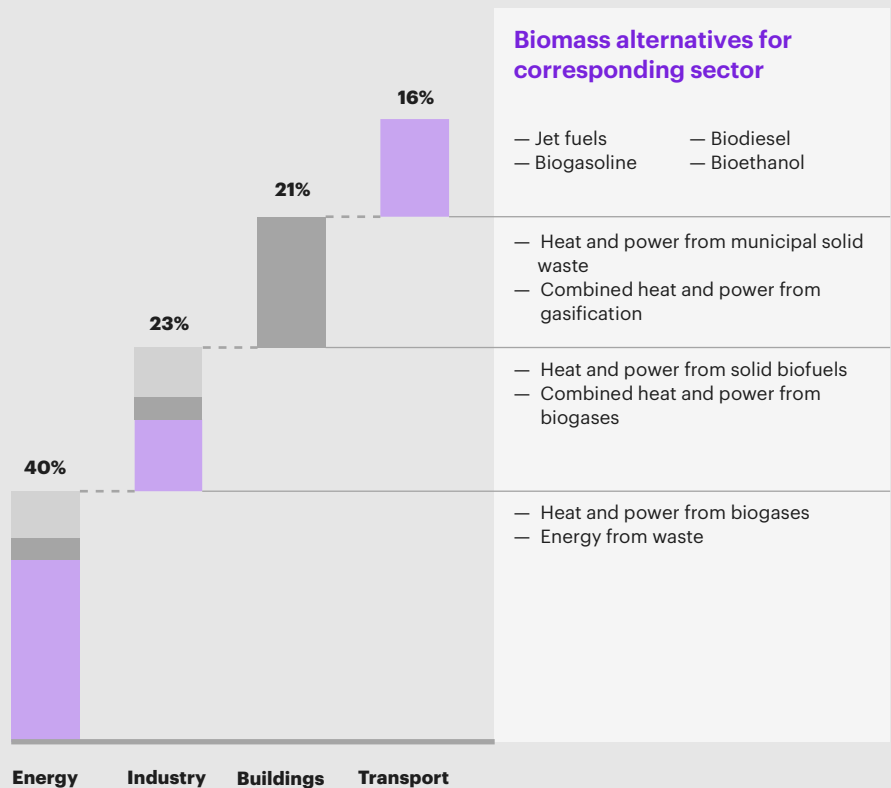
Applicability of bioenergy solutions

- Full
- Partial
- Very limited

¹ 16% 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 (www.ipcc.ch/report/ar5/wg3); Kearney Energy Transition Institute



Bioenergy must consider the sustainability constraints that apply to its feedstock production and collection and find the balance between environmental, economic, and social impacts to be sustainable.

The sustainability constraints depend on the feedstock and directly impact the biomass potential for bioenergy production. The scope of this FactBook is 2nd and 3rd generations of biomass feedstock as they lower the direct competition with food and respect more sustainability criteria.

Figure 3
Bioenergy sustainability performance has been improving over time

Sustainability constraints by advanced bioenergy generation

Generation	Feedstock source	Sustainability constraints			
		Direct competition with food	Land use change	Water use	Soil erosion
1st generation (-1990)	Oil crops, sugar and starch crops on arable land				
2nd generation (~2000)	Non-edible crops and waste with limited impact on food security				
3rd generation (~2015)	Micro or macro algae, which have high yields and limited land use impacts				
4th generation (Future)	Genetically modified crops to maximize yield and coupled with CCS technologies				

- High constraint
- Medium constraint
- Low constraint
- No constraint

Source: Kearney Energy Transition Institute

Considering the sustainable potential of biomass, bioenergy could sustainably supply around 15 to 30% of the world energy demand in 2060

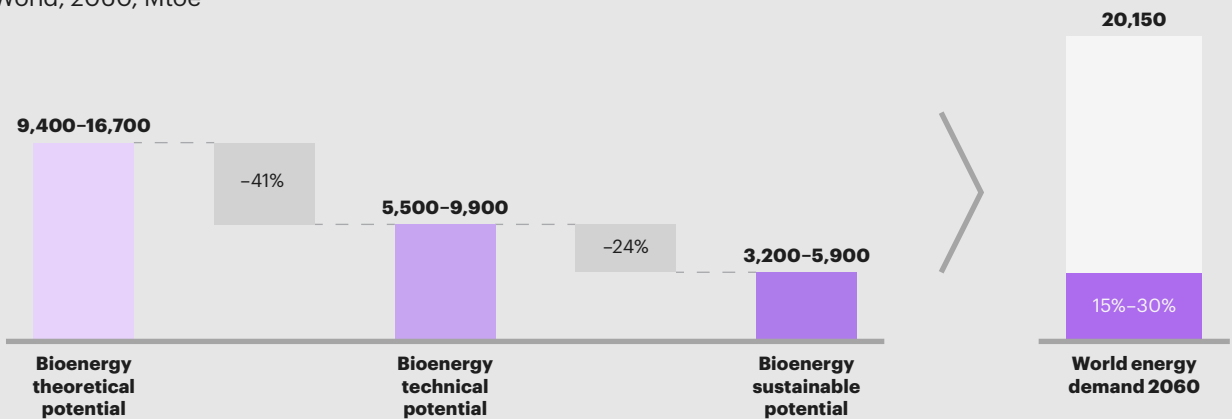
Figure 4

Bioenergy could sustainably supply 15 to 30% of the world energy demand in 2060

Feedstock supply being limited, its allocation in the biomass-to-bioenergy needs to be focused on decarbonizing sectors with no other renewable alternatives options

Bioenergy potential vs. world energy demand¹

World, 2060, Mtoe



¹ Potentials calculated in this section account for the "raw" energy embedded in the feedstocks. A more accurate comparison would require consideration of 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 conversion feedstock-to-biofuel is characterized by a complex value chain with a broad set of options

Advanced biomass transformation pathways are numerous. First, a broad range of feedstocks can be used: agricultural residues, forestry residues, animal waste, municipal solid waste, energy crops, and algae. The feedstock is conditioned, pretreated, and converted into biofuels through mechanical, chemical, thermal, or biological processes.

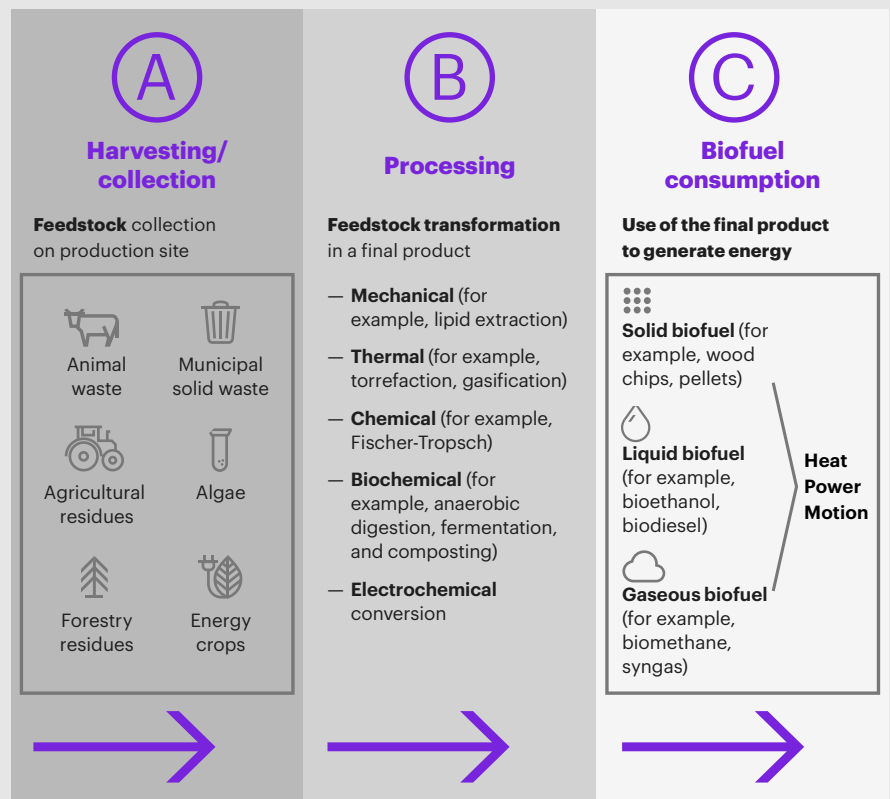
The multiplicity of possible routes comes with an increasing complexity of the value chain but also a strong diversity in the biofuels produced. Bioenergy can be produced from the combustion of solid (charcoal, wood pellets), liquid (liquid hydrocarbons, alcohols), or gaseous (biogas, biomethane, syngas, H₂) biofuels to produce power, motion, and heat.

Biomass processing includes multiple routes for each feedstock

To be converted into bioenergy, the feedstock is conditioned to reduce its size and moisture and increase its energy density. It is pretreated to break down the building blocks of the biomass into simpler compounds of interest (carbohydrates, lipid content) and then transformed into the targeted biofuel. Hydrolysis allows the extraction of carbohydrates (sugar content) from the ligno-cellulosic structure of the feedstock, which are upgraded into alcohols through fermentation.

Pyrolysis or hydrothermal upgrading separates the carbon content between three phases: a solid one that gives biochar; a gaseous one that gives syngas which can be directly used or further upgraded in biogas through fermentation, Fischer-Tropsch, or refining; and a liquid phase called pyrolysis oil that can be refined into liquid hydrocarbons (renewable diesel, biogasoline, bio jet fuels). Anaerobic digestion produces biogas from any type of feedstock (see figure 6 on page 7).

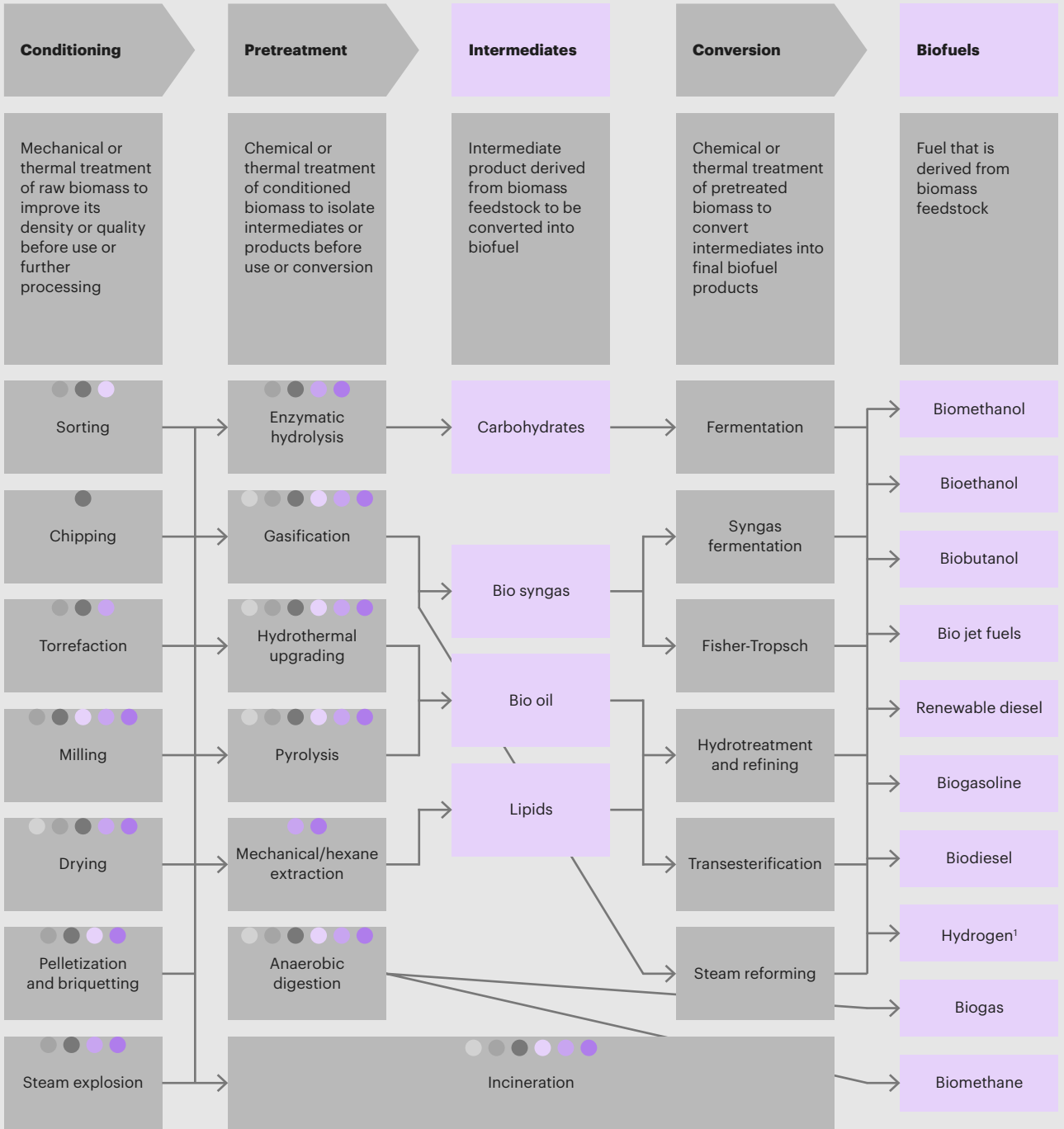
Figure 5
Conversion of biomass to energy and consumption generally follows three main steps



Source: Kearney Energy Transition Institute

Figure 6

Bioenergy relies on multiple possible combinations of feedstock and conversion pathways



Feedstock compatibility

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

¹ Hydrogen value chain is assessed in another 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

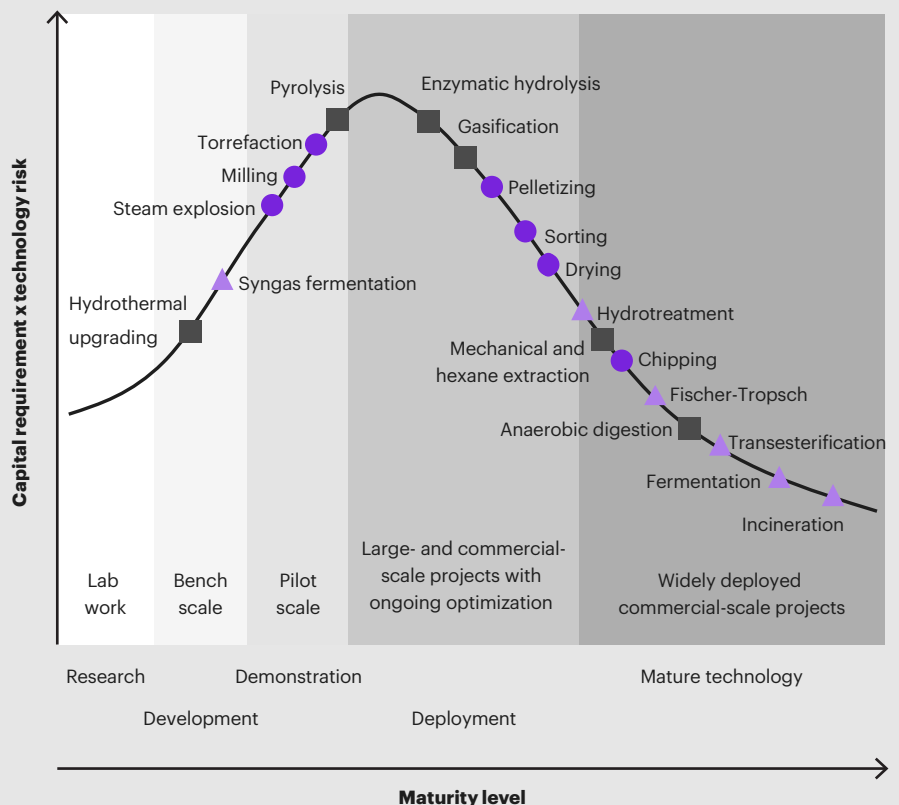
The maturity of bioenergy products displays large disparities—some promising biofuels are still in early stage or deployment phase and require improvements in the technology and supportive changes in policy environment

Efforts are required to lower the cost of biofuels to compete with fossil fuels, especially with the recent abrupt decline of oil prices due to the COVID-19 crisis. For traditional use of bioenergy (cookstoves, heat), efficiency improvements are needed and health issues that come with this use (indoor flue gases, air pollutants) must be mitigated.

Figure 7
Today, technologies also used to transform conventional resources are more mature than those mainly applicable to biomass

Technology maturity curve for bioenergy processing methods

- Conditioning
- Pretreatment
- ▲ Conversion



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

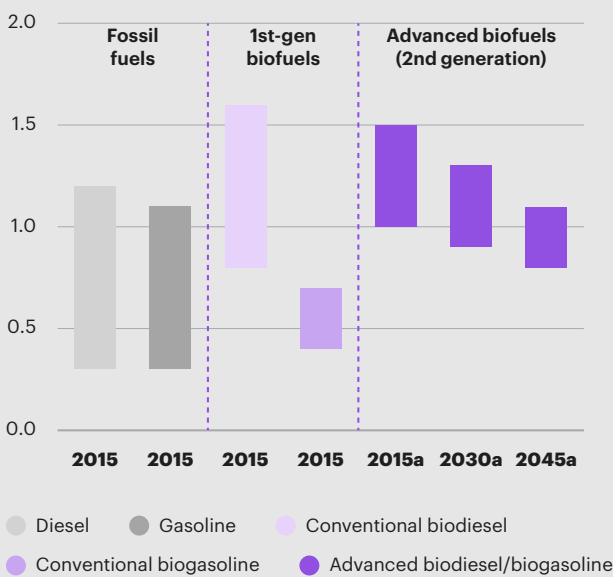
Biomass-to-biofuel or biomass-to-biogas are likely to remain more expensive than fossil fuels, and their opportunities are driven by country regulation

To be competitive with fossil fuels, liquid and solid advanced biofuels must improve their economics with optimized production, collection, and transport of the feedstock; better yields; better efficiency (use of combined cycle or catalysts); increased size of plants to reach economy of scale; valorization of the by-products; and support from regulation and incentives.

Figure 8

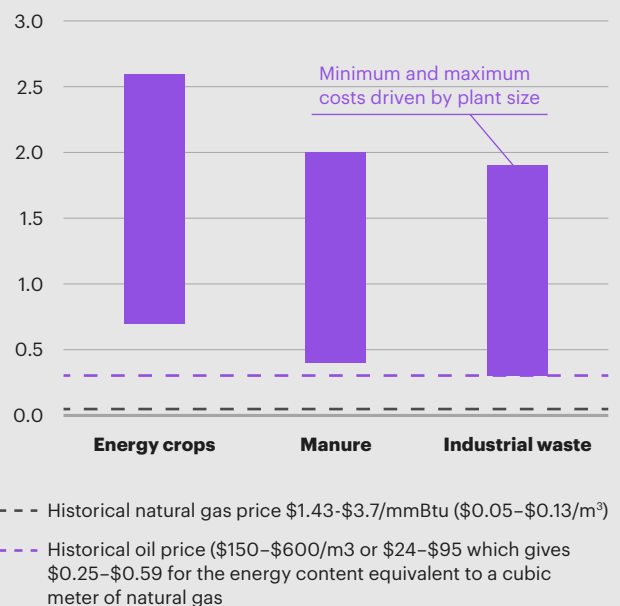
Biomass-to-biofuel or biogas is likely to remain more expensive than fossil fuels—opportunity-driven by country regulation

Projected biofuel production cost (\$/l)



Source: Kearney analysis

Biomethane production cost (\$/m³)

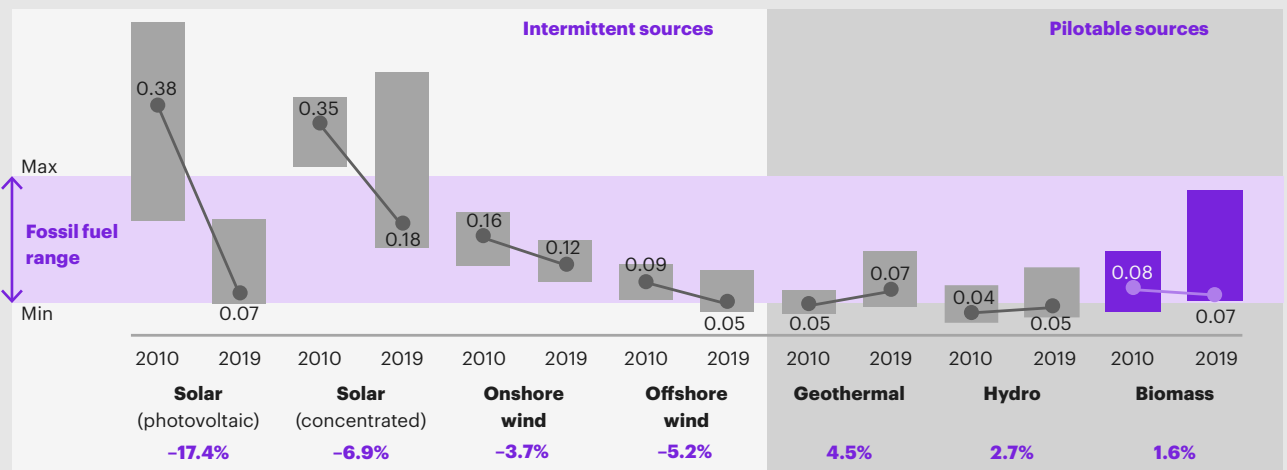


Biomass-to-power is competitive with other renewables and in the price range of fossil fuels

Figure 9

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

LCoE by renewable energy source¹
Global, USD/kWh, 2010–2019²



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

¹ LCoE is levelized cost of energy; outliers not considered in max/min but included in weighted averages.

² kWh is kilowatt hours

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

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

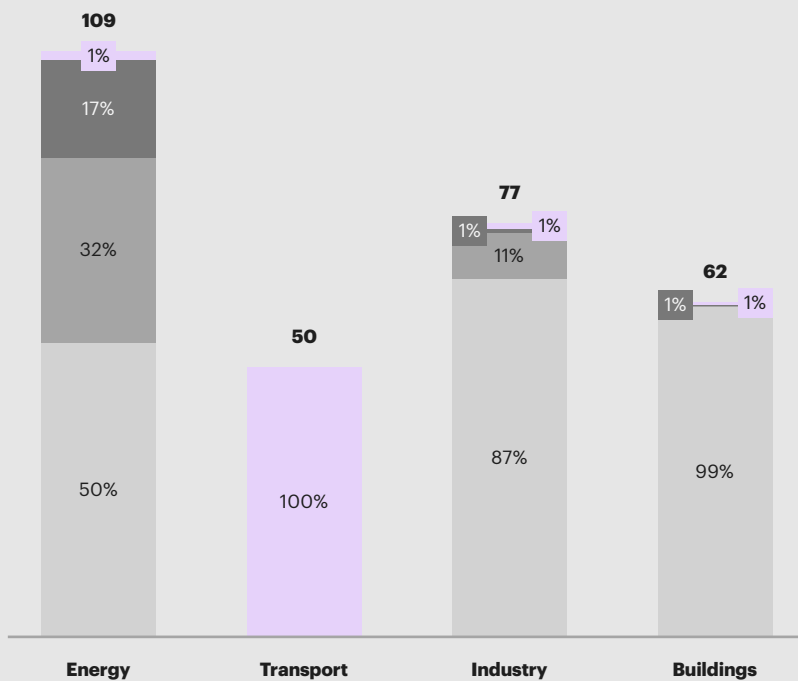
OECD countries are the ones where “advanced biofuels” are the most developed; the reliance on solid biofuels is even more significant at the global level.

Figure 10

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

Bioenergy consumption by sector and fuel type
Mtoe, 2017, OECD countries

- Liquid biofuels
- Gaseous biofuels
- Energy from waste
- Solid biofuels



Note: Percentages may not resolve due to rounding.

Sources: IEA Renewables Information 2019 Database, World Energy Outlook 2019 (IEA); Kearney Energy Transition Institute

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

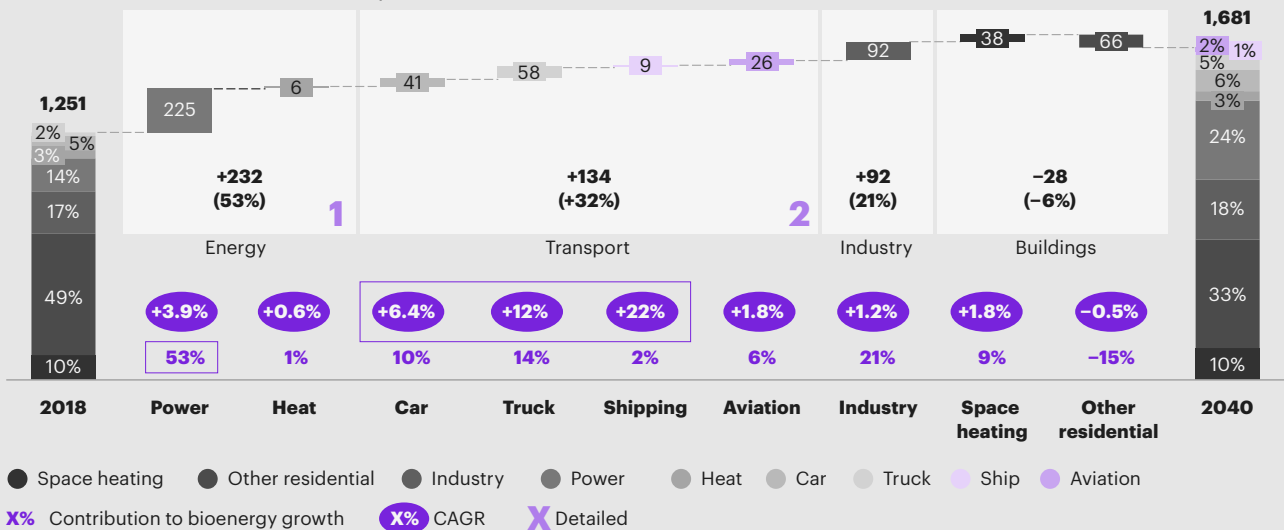
Bioenergy growth will be supported by the power sector (~50% total demand increase) but the highest growth rates are in transport (+22% per year in aviation and +12% in shipping).

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

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 and acceptance** drives the biomass market supply and the bioenergy demand (volume and price effect), the **technologies and 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) (see figure 12 on page 13).

Figure 11
Overall, energy and transport are the top two contributors to bioenergy growth forecast until 2040

World bioenergy consumption by sector
 Mtoe, 2018–2040, world – stated policies scenario¹



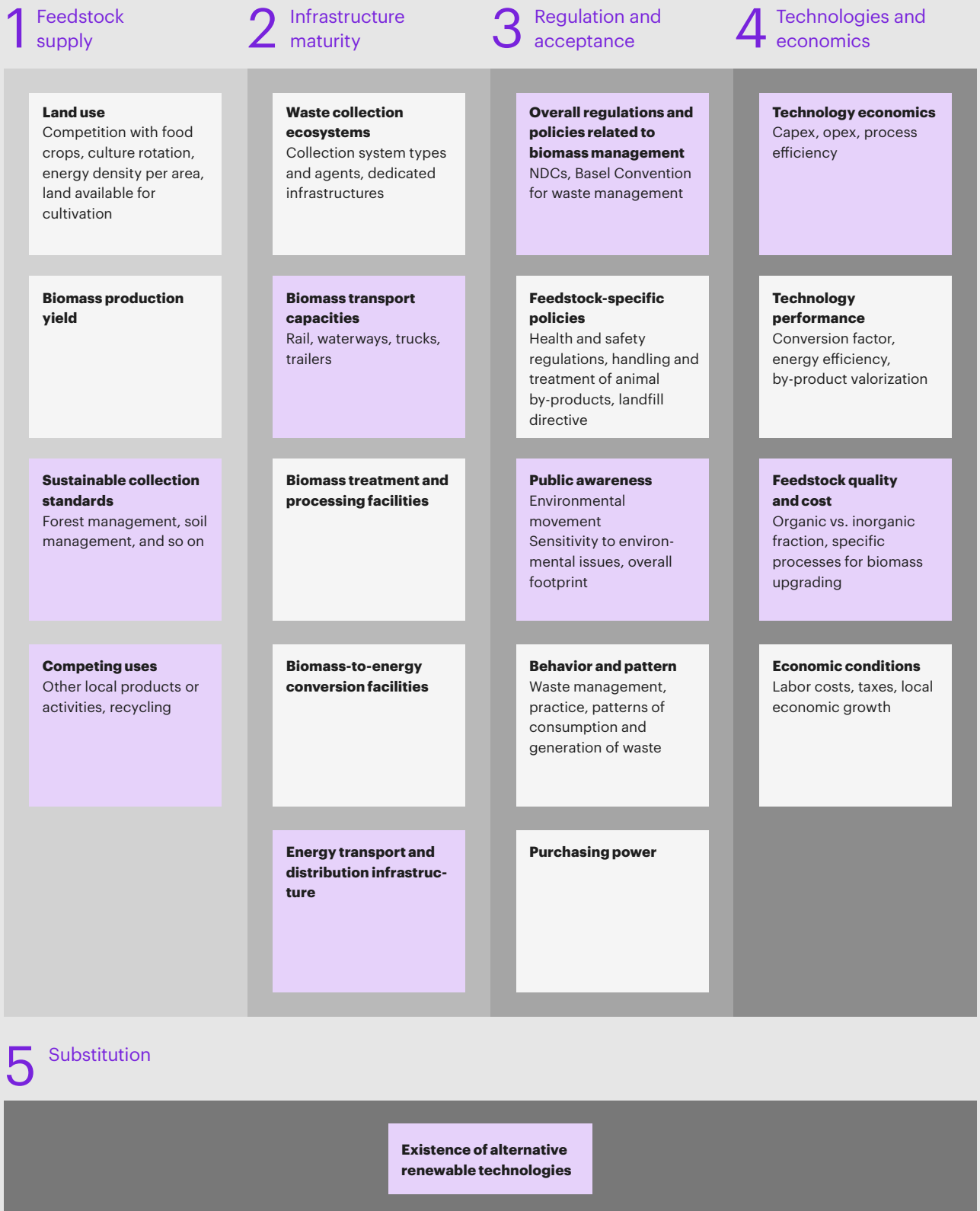
¹ Excluding "Other" which gathers the energy used for transformation activities (for example, energy industry own use) as well as the final energy used in sectors other than industry, transport, and buildings (-8% of total bioenergy consumption in 2018)

Note: Percentages may not resolve due to rounding.

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

Figure 12

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



○ Sub-driver ● Sub-driver detailed

Source: Kearney Energy Transition Institute

The demand for bioenergy is growing across the globe

“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

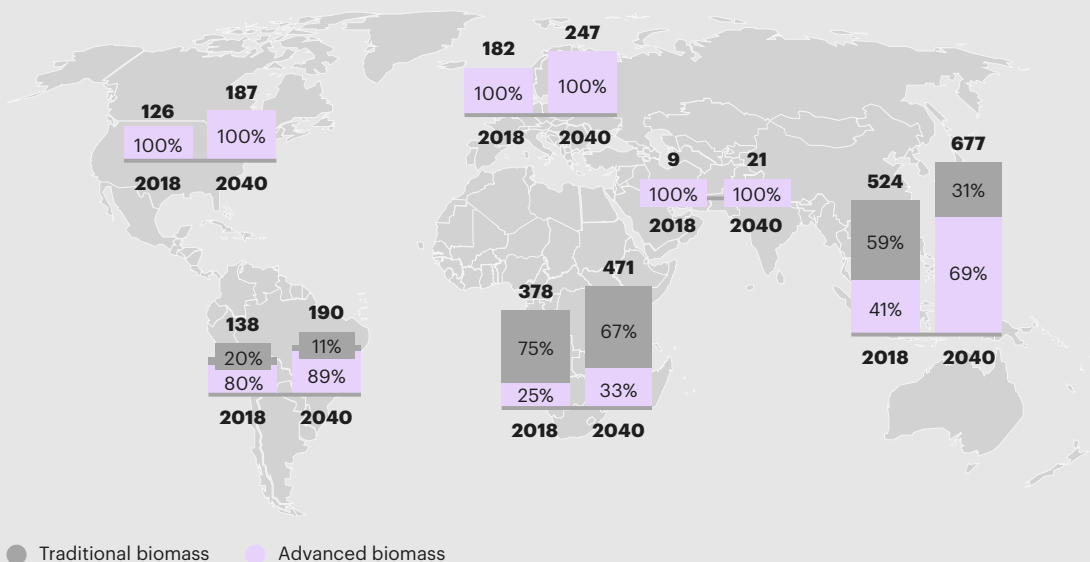
Biomass should focus on segments where they have competitive advantage to alternative decarbonization solutions

Biofuels compete with other low-carbon options across sectors to reach carbon neutrality. In **power**, biofuels compete for storage with other well-established low-carbon sources (for example, wind and solar). For **road transport and rail**, focus is mainly on hydrogen and electrification. Biofuels are one of the only alternatives to decarbonize **aviation and shipping**. Biofuels have potential as low-carbon feedstock in **petrochemicals** value chains, and biofuels and hydrogen could be an interesting combination in some sectors (see figure 14 on page 15).

Figure 13

The demand for bioenergy is growing across the globe

Bioenergy primary energy demand by continent
World, 2017, Mtoe, WEO – stated policies scenario



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

Figure 14

Bioenergy substitution matrix

Sector		Transport				Energy		
		Car	Truck	Aviation	Shipping	Power	Heat	CHP
Sector energy consumption (Mtoe, 2018)		1,124	740	326	251	4,294	113	1,086
Potential technologies to reduce CO ₂ emissions (2040 time horizon)	H2							
	Electrification (renewables and storage)							
	Carbon capture storage ¹							
Substitution score		+++	++	+	+	+++	+++	+++
Biofuels opportunity		↓	↑	↑	↑	→	↓	→
Biofuel potential by sector	Bioethanol	✓	✓	✗	✓	✗	✗	✗
	Biogasoline	✓	✓	✗	✗	✗	✗	✗
	Biodiesel	✓	✓	✗	✓	✗	✗	✗
	Renewable diesel	✓	✓	✗	✓	✗	✗	✗
	Black liquor	✗	✗	✗	✗	✓	✓	✓
	Bio jet fuels	✗	✗	✓	✗	✗	✗	✗
	Biomethane	✓	✓	✗	✓	✓	✓	✓
	Gas from waste	✗	✗	✗	✗	✓	✓	✓

Maturity of technologies

- Commercialized
- Pilot projects
- Research stages
- Not an option

Maturity of substitution options

- +++ Research stages
- ++ At least one pilot project
- + Ongoing R&D investment

Potential product-sector combination opportunity



¹ Use of CO₂ from CCS is not considered in the range of possible solutions.

Sources: IEA WEO 2019; Kearney Energy Transition Institute

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- Gas hydrates – Taking the heat out of the burning-ice debate
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- Negative emissions technologies – Towards a carbon-free world
- Carbon capture and storage – At a crossroads

Conclusion

Biomass is a major asset for pilotable renewable energy production that also offers the possibility to decarbonize applications, end uses, and sectors which have been traditionally difficult to tackle with other clean energy solutions. The biomass renewable resource versatility, abundance, and distribution makes it an interesting candidate to decarbonize power (combined with CCUS or not), progressively replace fossil fuels in industrial applications, and offer fuel alternatives to the transport sectors. This significant potential can contribute to energy and environmental objectives if it is developed and produced in ways that are sustainable—environmentally, socially, and economically.

Acknowledgements

The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Dr. Jean-Michel Commandré, program director at CIRAD, Head of Research Unit Biomass, Wood, Energy, Bioproducts, as well as Dr. Adnan Shihab-Eldin, Claude Mandil, Antoine Rostand, and Richard Forrest, members of the board for the Kearney Energy Transition Institute.

Main contributors: Thomas Vaillant, Romain Debarre, Prashant Gahlot, Céleste Grillet, Jean-Karim Intisar, Christian Tapolcai, and Jo Webster.

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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 in a rapidly changing energy landscape, exploring how businesses may both capture the opportunities that arise and address the challenges that face them in this complex and often uncertain shift. The Institute has developed deep insights in areas such as solar PV, hydrogen, negative emissions technologies, gas hydrates, carbon capture and storage, wind, smart grids, and energy storage and continues to address the most pressing emerging topics such as the impact of digitalization. The Kearney Energy Transition Institute is governed by an eight-member board and has access to a world-class scientific network comprising highly experienced individuals and academics. The Institute's independence fosters unbiased primary insights and the ability to co-create new ideas and insights with sponsors and relevant stakeholders.

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