IEA BIOENERGY REPORT 2023

How bioenergy contributes to a sustainable future

IEA Bioenergy
Technology Collaboration Programme

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Foreword

Between the social foundation and the ecological ceiling: the safe and just space for humanity

The sustainable use of biogenic resources to provide food and feed, building materials, chemicals, textiles, and energy services is known as the bioeconomy. The bioeconomy has played a major role throughout history in helping humanity secure the resources necessary for its social foundation. An important element of the bioeconomy is bioenergy. Bioenergy, based on the further development of effective strategies and technologies, can support a just transition to renewables and the transformation of the energy system, leading to achievement of the Sustainable Development Goals (SDGs).

The safe and just space for humanity lies between the resources needed to secure the social foundation and an ecological ceiling—the planetary boundaries—that defines the limits within which human beings can develop, survive, and thrive.

Historically, human progress has developed hand in hand with the resources consumed. Technological advancements have considerably broadened the availability of resources and their efficient deployment, especially over the course of the last century. In turn, however, the population has grown significantly, as has the resource demand per capita, and thus overall resource consumption.

Today, there is overwhelming evidence that current rates of resource consumption have already resulted in negative and potentially irreversible impacts on the planet, a pattern that is set to continue. Overshoot of the planetary boundaries is, among other things, causing climate change and biodiversity loss and will ultimately halt and reverse human progress. A phase-out of the use of fossil resources, a circular use of minerals/materials, and the utilisation of regenerative/renewable resources and energy are key to staying within the planet's ecological limits. Resource utilisation will need to be improved and the carrying capacity of the planet respected.

Bioenergy is one of the important and necessary elements in combating climate change. Climate change, however, is not the only driver of bioenergy deployment. The COVID-19 pandemic demonstrated the risks inherent in global supply chains and—triggered by rising energy prices—the value of a diversified supply that is more regionally based. With energy security having again become a critical issue, bioenergy is able to improve the resilience of societies around the globe by providing greenhouse gas emission reductions, regional energy supply, income to rural communities, and energy system flexibility.

This report presents an evidence-based assessment of the status of bioenergy around the world. The assessment is based on work conducted by some 200 experts, active within the Tasks of the Bioenergy Technology Collaboration Programme (TCP) of the International Energy Agency (IEA). The aim of IEA Bioenergy is to advance technologies and provide factual input to evidence-based decisions. The report's goal is to reinvigorate awareness and interest in bioenergy, address concerns that arise in the public debate, and demonstrate the synergies between bioenergy and other renewables. The report also seeks to point out opportunities that can be seized by IEA Bioenergy member countries, most of which have a strong bioenergy strategy already in place, and also by countries outside the IEA Bioenergy membership.

The information provided here is complemented by information from other multilateral initiatives such as the International Renewable Energy Agency (IRENA), the Food and Agriculture Organisation (FAO) of the United Nations, and the Global Bioenergy Partnership (GBEP): these organisations focus on emerging economies and developing countries and, for instance, on topics such as phasing out the traditional use of biomass and replacing it with clean cooking options.

The report is divided into two parts: Part A "Strategic View on Biomass and Bioenergy" deals with bioenergy and its contribution to a sustainable future. Part B "Technologies for Sustainable Bioenergy" describes the status and perspectives of different bioenergy technologies.

Sustainable development is a two-sided coin: i) to avoid shortfalls in providing a minimum social foundation for all, while ii) making sure not to overshoot the ecological ceiling. These two sides are intended to be diametrical and must therefore be balanced—which is ultimately a political issue. The IEA Bioenergy Technology Collaboration Programme aims to provide knowledge on possible ways of achieving this balance, with a focus on the link between humanity and the biosphere.

Summary

Bioenergy, an important element in combating climate change, securing energy supply, and providing income through regional biomass-supply chains, is today the largest source of renewable energy. Types of biomass can be used to produce power, heat, cooling, to transport biofuels, and as intermediate bioenergy carriers, such as renewable gas. Biomass can be used as a substitute for fossil energy carriers and thus reduce energy-related greenhouse gas (GHG) emissions.

On its own, however, bioenergy cannot achieve the required transformation and decarbonisation of our energy system. It is part of a circular bio-based economy and complements not only other renewable energy sources but also efforts to increase energy efficiency and reduce energy demand.

Sustainability is a key issue to consider in all human activities. Acting sustainably means meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability is a broad policy concept and is thought to consist of at least three main dimensions or “pillars”: the environmental, economic, and social dimensions.

GHG emissions, the emission of local air pollutants, biodiversity, land and water use, etc., all come within the purview of environmental sustainability. There are ways of sustainably managing forests and agricultural landscapes so that they can deliver biomass for bioenergy to reduce GHG emissions while also maintaining or improving biodiversity, carbon sinks, and species abundance. In many regions, bioenergy has to comply with strict sustainability criteria and standards so as to assure effective GHG emission reductions; moreover, there is a growing awareness that preserving stocks of carbon in the soil, as well as biodiversity conservation, should be important elements in all our activities.

The term economic sustainability encompasses the supply of sufficient quantities of biomass feedstocks at reasonable prices. Being price-competitive with other (fossil or renewable) energy carriers is one of the biggest challenges for bioenergy. Significant quantities of biomass can be supplied at low cost, for example, straw from food/feed crop production or used cooking oil; but when larger quantities are extracted, costs increase. Costs for biomass feedstocks and bioenergy carriers vary regionally and also depend on their intended use and what competition there is from other market actors for the same feedstocks.

Creating a huge demand for biomass feedstocks may lead to overexploitation of ecosystems or to land use change, with negative consequences for biodiversity and the soil carbon stock. It is essential to carefully manage the mobilisation of biomass to safeguard the environment; biomass—being a limited resource —should also be used wisely. Wherever basic energy needs are already being met, a cascading use of biomass feedstocks is becoming a requirement.

Social sustainability, finally, deals with how sustainability affects people, their health and well-being, and their ability to make a decent living. The 17 Sustainable Development Goals (SDGs), which all United Nations Member States have adopted and aim to achieve by 2030, balance the three dimensions of sustainability—environmental, economic, and social—and aim for a just transition to a sustainable future. Today, about 2.8 billion people globally still lack access to clean cooking solutions, relying on traditional burning of biomass over open fires to heat their food.

This traditional use of biomass is problematic, as open fires are inefficient and expose people (particularly women and children) to emissions of harmful air pollutants, which can lead to respiratory disease. There is consensus that the traditional use of biomass should be phased out as soon as possible. Modern bioenergy, namely the use of commercial solid, liquid or gaseous biomass-based fuels in efficient appliances can play an important role in achieving the SDGs, directly contributing, for example, to better health and well-being, affordable and clean energy, and action against climate change. Modern bioenergy offers the opportunity to use domestic resources more efficiently to provide energy and create income.

Bioenergy supports the transition to a low carbon economy in many ways and offers multiple benefits to society. Bioenergy acts as a substitute for fossil fuels and thus reduces GHG emissions. Bioenergy and biofuel installations can act as point sources of biogenic CO2 for carbon capture and storage or use; in specific cases, they even offer the opportunity to achieve net negative CO2 emissions.

Biorefineries split biomass into disparate fractions that can be processed into a variety of products, including materials, chemicals, animal feed, pharmaceuticals, and energy. Intermediate bioenergy carriers, such as torrefied pellets and pyrolysis oils and other biocrudes, can be used to store energy, making transportation of the energy carrier more efficient. Bioenergy installations can provide heat and electricity on demand, cover baseload and peak demands, or shift energy provision between seasons. Solid, liquid, and gaseous bioenergy can be used in applications that are otherwise hard to decarbonise, such as high-temperature heat production for industry or for long-distance aviation, heavy-duty transport, and international shipping.

The most important bioenergy technologies include combustion, anaerobic digestion, gasification, pyrolysis, and hydrothermal liquefaction. This wide range of technologies provides bioenergy to the transport, heat, and electricity sectors, as well as ample opportunities to combine different feedstocks and technologies to produce a range of products in biorefineries. The technologies are, however, at various technology-readiness levels, from lab-scale research to large-scale demonstration and market maturity. While they are efficient at reducing GHG emissions, they come with costs that are often higher than those of competing technologies. Further research and development are needed to bring all such technologies to the market; policy frameworks will play an important role in facilitating the deployment of new technologies in a sustainable manner.

Despite its many benefits, bioenergy is still not globally implemented at the high level of sustainable capability needed for the desired energy transition. The wide range of bioenergy value chains with their many different biomass feedstocks, conversion processes, and possible applications make bioenergy a complex topic. Moreover, there can be competition between different services from biomass, and the supply potential, although large, is essentially finite. Governance systems are needed to assure sustainable sourcing of biomass feedstocks, their efficient conversion to renewable energy, and their deployment. Biomass trading is also required to connect biomass supply and end markets.

Policymakers have a crucial role to play in facilitating the energy transition, by giving it priority, creating markets for sustainable, low-carbon technologies, and promoting research and development.

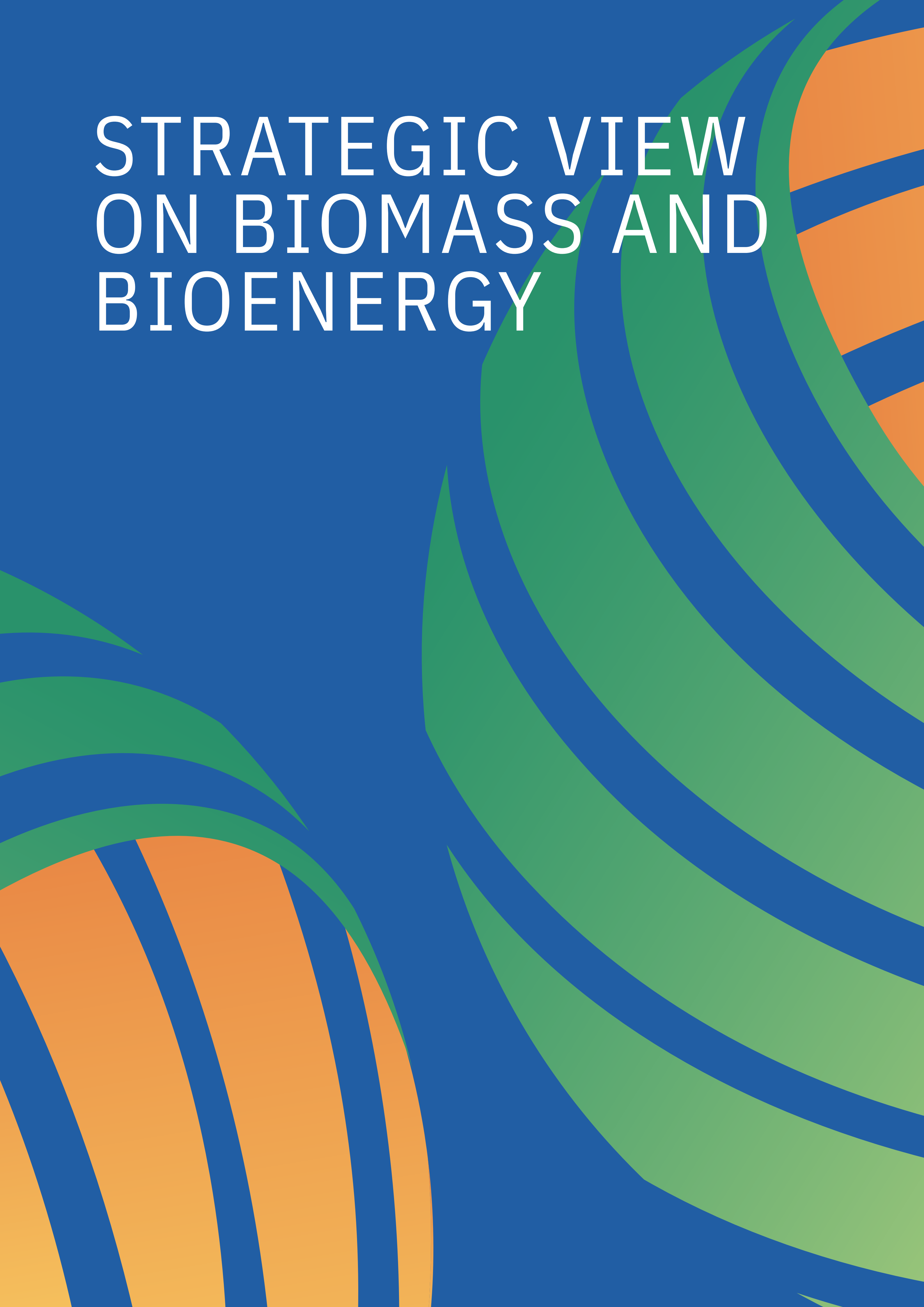
This report presents an evidence-based assessment of the status of bioenergy around the world. The assessment work was carried by some 200 experts, active within the Tasks of the IEA Bioenergy, which aims to advance technologies and to provide factual input to evidence-based decisions. The information presented is intended to reinvigorate awareness and interest in bioenergy, address concerns arising within the public debate, demonstrate the synergies between bioenergy and other renewables, and point out opportunities that can be seized by many countries around the globe.

Sustainable production of biomass for bioenergy—or any other bio-based product for that matter— can have significant positive environmental, socioeconomic, and health impacts for people and their communities. (Photo credit: Shutterstock / Makhh)

STRATEGIC VIEW ON BIOMASS AND BIOENERGY

TECHNOLOGIES FOR SUSTAINABLE BIOENERGY

STRATEGIC VIEW ON BIOMASS AND BIOENERGY



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Transitioning towards sustainability

We need to act urgently on climate change. Only the adoption of sustainable strategies can maintain our planet "liveable" (Photo credit: Unsplash/ Markus Spiske)

CHAPTER 1.1

Defining climate and sustainability targets and the global action needed to reach them

Although climate scientists around the world have been issuing warnings about climate change since the 1980s, actions to counteract it are still far from being on track

Without immediate and bold action, we will see a dramatic increase in the global average temperature. As a result, entire populations will be forced to adapt or—where adaptation is not possible—to abandon their homes. Based on scientific advice, most countries in the world have agreed on climate targets to counteract this dramatic warming trend; however, progress is slow. Renewable energy, including sustainable bioenergy, is needed to transform our energy systems, economies, and society as a whole. The good news is that we have the knowledge, technologies, and strategies to achieve this.

The current commitments to limit global warming

Probably the best-known commitment to combating climate change is the Paris Agreement, a legally binding international treaty on climate change, adopted by 196 Parties at the 21st Conference of the Parties (COP 21) to the United Nations Climate Change Framework Convention held in Paris in 2015. The goal of the Paris Agreement is to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. To achieve this, countries aim to reach global peaking of greenhouse gas emissions as soon as possible, and thus achieve a carbon-neutral world by mid-century. By 2020, countries submitted their action plans for reducing GHG emissions in accordance with the goals of the Paris Agreement. Countries also communicated their future resilience-building strategies to help them adapt to the impacts of rising temperatures.

The most recent commitment to climate goals was made at the 26th Conference of the Parties (COP26) held in Glasgow in November 2021. COP 26 led to the adoption of the Glasgow Climate Pact, which aims to turn the 2020s into a decade of climate action and support. As adaptation to the impacts of climate change is now deemed to be of equal importance to emission reductions, a work programme on climate change adaptation has been developed.

Moreover, with this in mind, governments of developed countries have committed to providing 100 billion US dollars annually to developing countries. Nations also agreed to work to reduce the gap between existing emission reduction plans and the measures required to actually reduce emissions to meet the 1.5°C global warming target. Most importantly, the Glasgow Pact calls upon nations to phase out unabated coal power and inefficient subsidies for fossil fuels.

Further commitments to an even faster transition to renewable energies can be expected in the near future. This is in response to recent geopolitical events that have brought energy security and diversity of energy supply chains back into focus.

Roadmap to decarbonise global economy

Currently, of the 33 sectors monitored by the International Energy Agency (IEA), only two (electric vehicles and lighting in buildings) are on track to reach the climate targets; more efforts are needed in renewable power, hydrogen, and many other sectors; more than half the sectors, including transport biofuels, aviation, and international shipping, are significantly lagging behind.

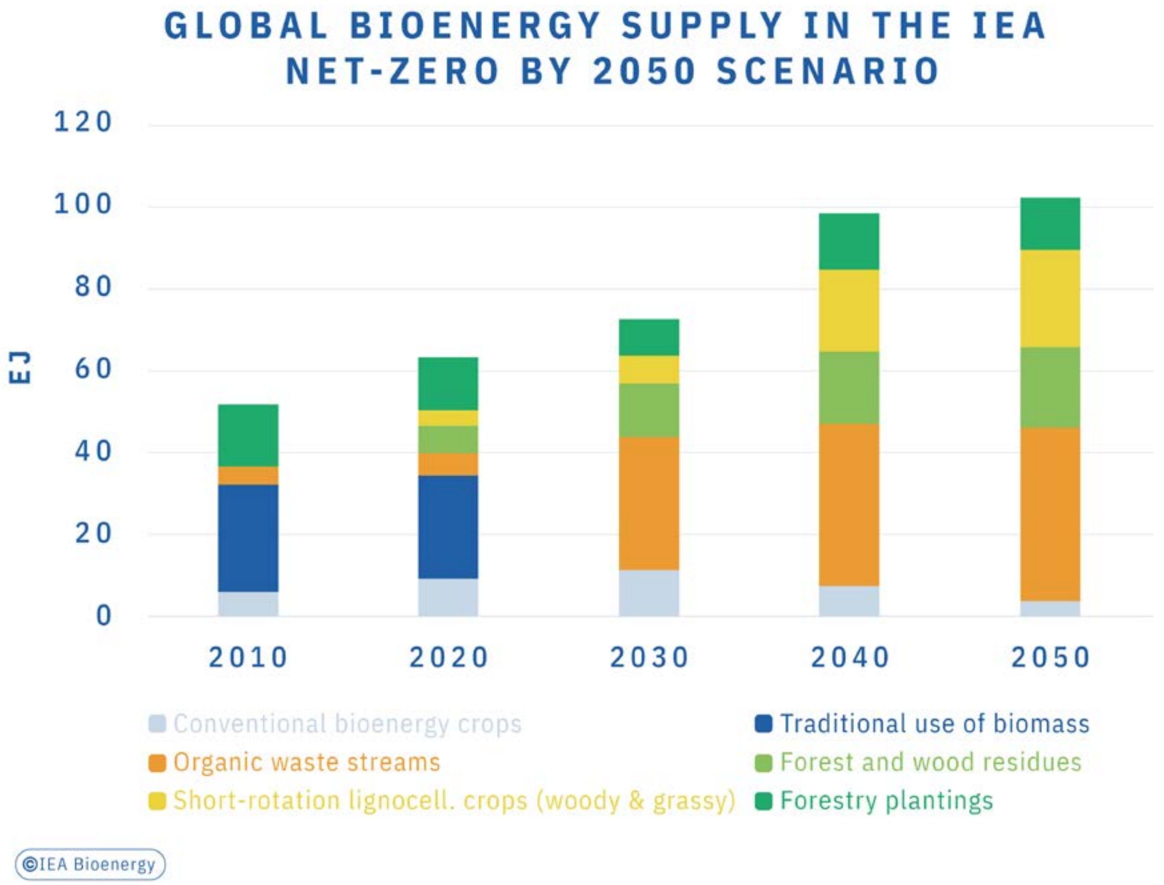
In the IEA "Net Zero by 2050" Roadmap for the global energy sector, published in May 2021, leading IEA analysts set out more than 400 milestones for what needs to be done—and by when—to decarbonise the global economy in just three decades.

Net Zero by 2050 builds on comprehensive computer modelling of energy systems by the IEA, with valuable inputs and contributions from various experts in academia, industry, and governments, including the IEA Technology Collaboration Programmes (TCPs).

The way forward presented in the report is one of several possible futures pathways to carbon-neutral energy provision by 2050, while ensuring stable and affordable energy supplies, providing universal energy access, and enabling robust economic growth. Although the focus is on reducing CO2 emissions from the energy sector, pathways also incorporates concrete action on the energyrelated SDGs which aim to achieve universal energy access by 2030 and to deliver a major reduction in air pollution. The way forward represents a cost-effective and economically productive strategy for a clean, dynamic, and resilient energy economy.

According to the IEA, the world needs to shift rapidly away from fossil fuels, and the energy sector—being the major source of global fossil emissions—has a key role to play in this. The energy sector needs to be transformed to increase energy conservation, use energy more efficiently, produce and use a greater amount of renewable energy, and deploy carbon capture, utilisation, and storage (CCUS) to avoid carbon emissions to the atmosphere.

Key energy carriers are sustainably produced electricity, biofuels, and hydrogen. The active involvement and engagement of citizens in deploying these low-carbon technologies as well as behavioural changes can strongly contribute to emission reductions.

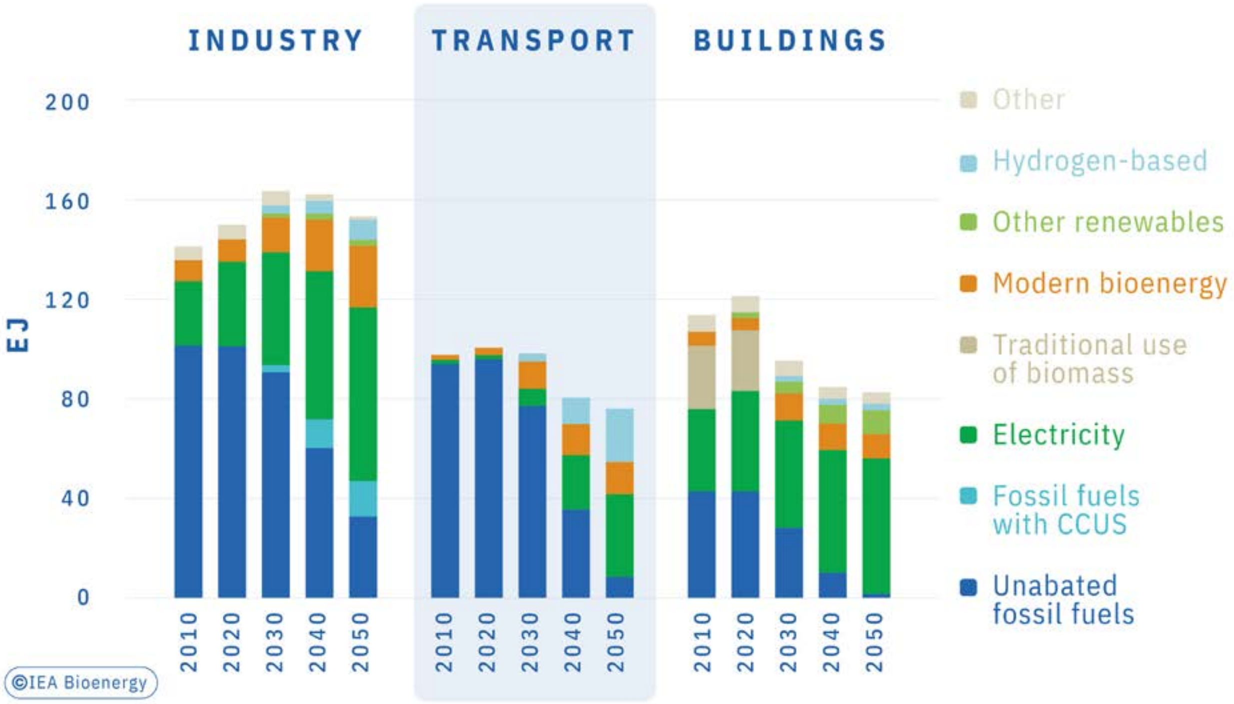


Sustainable bioenergy should provide 100 EJ of energy in 2050 (Source: IEA Net Zero by 2050 Roadmap)

Although renewable electricity will predominantly come from photovoltaic, wind, and hydro, bioenergy itself will have to grow in all energy application areas (power, heat, transport, and industry) to reach the values set out in the Net Zero Emissions (NZE) scenario of the IEA. Sustainable bioenergy can reduce emissions in three major ways: i) through the use of low carbon intensity fuels for planes, ships, and other forms of transport; ii) by replacing natural gas in dedicated applications with renewable biomethane to provide heating and electricity; and iii) by offering clean cooking solutions to 2.6 billion people who, as of 2021, still lacked them. Furthermore, carbon capture and utilisation and storage technologies can be applied in bioenergy installations to create net zero or even negative GHG emissions to offset the GHG emissions that remain.

In the scenario that leads to net zero CO2 emissions from the energy sector by 2050, the energy analysts of the IEA expect bioenergy to represent 18% of the total energy supply in 2050. The year 2050 will also see bioenergy providing 15% of energy consumption in industry (mainly high temperature heat), 16% of transport energy consumption, 10% of energy consumption in buildings (direct use), as well as negative emissions through bioenergy carbon capture and storage (BECCS) of 1.3 billion tonnes CO2 per year.

This, however, is not a self-starter scenario. It will require massive efforts to scale up deployment of sustainable bioenergy to the required levels.



Modern bioenergy will play an essential role in providing low-emissions energy to all sectors in 2050 (Source: IEA Net Zero by 2050 Roadmap)

A long path towards consensus: IPCC, the Paris Agreement, and the Sustainable Development Goals

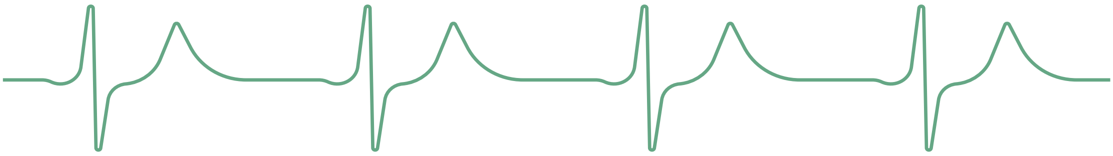
Intergovernmental action to address climate change began in 1990, when several hundred scientists involved in preparing the “Climate Change” report for the Intergovernmental Panel on Climate Change (IPCC) stated with certainty that a natural greenhouse effect was warming Earth to a greater than normal extent and that emissions resulting from human activities were causing a substantial increase in the atmospheric concentrations of the greenhouse gases carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide. Such increases would enhance the greenhouse effect, resulting overall in an additional warming of Earth’s surface.

> **Scientists state with certainty that emissions resulting from human activities are substantially increasing atmospheric concentrations of greenhouse gases**

In response to this warning by scientists, in 1992, the “Earth Summit” was held in Rio de Janeiro, bringing together political leaders, diplomats, representatives of academia, the media, and non-governmental organisations from 179 countries in a massive effort to focus on the impact of human socio-economic activities on the environment.

The Earth Summit led (among other things to) the Convention on Biological Diversity (CBD) and to the foundation of the United Nations Framework Convention on Climate Change (UNFCCC),as well as the adoption of the Kyoto Protocol in 1997 and the Paris Agreement in 2015. The ultimate objective of all these efforts was to stabilise GHG concentrations in the atmosphere at a level that would "prevent dangerous human interference with the climate system, in a time frame which allows ecosystems to adapt naturally and enables sustainable development" (UNFCCC Secretariat).

Through the Kyoto Protocol, which was adopted in 1997 and entered into force in 2005, industrialised countries and economies in transition committed to an average 5% reduction in emissions compared to 1990 levels over the period 2008–2012. In 2012, the Doha Amendment to the Kyoto Protocol was adopted for a second commitment period, running from 2013 to 2020, and was finally ratified by 2020. Even though the Kyoto Protocol did not greatly reduce global GHG emissions, it paved the way for the Paris Agreement to limit the global temperature rise to well below 2°C above pre-industrial levels, and thereby avoiding tremendous economic, social, and environmental disruption and costs.



Every bit of warming matters

The scientific evidence of global warming continues to strengthen further and to confirm the impact of human activities on the mean temperature of Earth. In its 6th Assessment Report (AR6) on adaptation (Working Group II) and mitigation (Working Group III), the IPCC describes the current negative impacts of climate change, deforestation, land use change, and pollution on people and the planet. The authors of AR6 stress the urgency of immediate action to address climate risks that goes well beyond current ambitions. They emphasise the pressing need for systemic transitions in a number of areas: energy; land and water ecosystems; urban and rural areas; infrastructure; industry; and society.

The contributions of Working Groups II and III recognise the important role of the bioeconomy within these urgent and deep transitions. The report stresses: "Bio-based products as part of a circular bioeconomy have potential to support adaptation and mitigation, with sectoral integration, transparent governance and stakeholder involvement key to maximizing benefits and managing trade-offs". (IPCC_AR6_WGII_FinalDraft_FullReport.pdf)

In an urban environment this could see the integration of waste and energy streams, while in a rural environment, agroecology would become more important: "Agroecology can support long-term productivity and resilience of food systems by sustaining ecosystem services such as pollination, soil organic carbon, pest and weed control, soil microbial activity, crop yield stability, water quality and biodiversity." (WG2AR6_FD_TS_FINAL (ipcc.ch))

The report also sees a substantial role for bioenergy: "Strategic integration of appropriate biomass production systems into agricultural landscapes can provide biomass for bioenergy and other biobased products while providing co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, flood regulation, pollination and biological pest and disease control." (Climate Change 2022: Mitigation of Climate Change (ipcc.ch)) However, the report also raises concerns regarding bioenergy and its land use as part of a carbon dioxide removal (CDR) technology (i.e., BECCS) and regarding the potentially inappropriate development of bioenergy that could accompany large-scale implementation.

In its special report "Global Warming of 1.5°C" scientists continue to provide evidence that human activities have already caused approximately 1.0°C of global warming above pre-industrial levels and that this has already caused irreversible damage to ecosystems and livelihoods around the world. Impacts include: i) increase in mean temperatures in most land and ocean regions; ii) hot extremes in most inhabited regions; iii) heavy precipitation in several regions; and iv) the probability of drought and precipitation deficits in some regions. Limiting warming to 1.5°C is not impossible, but it will require unprecedented transitions in all aspects of society. There are clear benefits to keeping warming to 1.5°C compared to 2°C or higher, as frequencies and intensities of temperature-related extremes increase with increasing global warming—every bit of warming matters. (Foreword — Global Warming of 1.5 ºC (ipcc.ch))

Another IPCC report, "Climate Change and Land" investigated the utilisation of land for food, feed, and bioenergy; it found that the land we are already using for cultivation could feed the world in a changing climate and, at the same time, provide biomass for material applications and renewable energy. This would require early and far-reaching action to be taken across several fronts, including improved crop management, reduced deforestation, measures for removing CO2 from the atmosphere, and people shifting to plant-based diets. Better land management can play its part in tackling climate change, but it cannot do everything.

Another strand of intergovernmental collaboration, brought up at the UN Conference on the Human Environment in Stockholm in 1972, and further strengthened through the 1992 Earth Summit, is the striving for peace and prosperity among all people and for the planet, both now and into the future. Eradicating poverty in all its forms and dimensions, including extreme poverty, is a global challenge and an indispensable requirement for sustainable development. Following several summits of the United Nations, in 2015 the 2030 Agenda for Sustainable Development was adopted by all United Nations Member States. At the core of this agenda are the 17 Sustainable Development Goals (SDGs). These goals and the 169 targets within the agenda are integrated and indivisible and in balance with the three dimensions of sustainable development: economic, social, and environmental. All efforts to combat climate change should be undertaken in the light of the SDGs and should aim for a just transition into a sustainable future.

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CHAPTER 1.2

Modern sustainability avenues

Moving towards establishment of a greater number of integrated biorefineries can be an important step in transitioning to a more circular bioeconomy (Photo credit: Gettyimages/ BanksPhotos)

The different energy pathways to sustainability in a world in transition—from a circular bioeconomy to renewable carbon and green hydrogen

In the transition to a sustainable future, several different energy carriers will become more important, as will the concept of a circular economy. Bioenergy will play an important role in achieving net zero CO2 emissions by substituting renewable carbon for fossil carbon. Biomass supply is, however, limited.

Transition to renewable carbon, circular material use, and green hydrogen

The rapidly closing window of opportunity for reaching the Paris 2015 climate goals and for halting the dramatic decline in numbers and abundance of species are the most visible dimensions of the urgent need to achieve sustainability. Paradoxically, however, the pressing need to open avenues to sustainability is at odds with ambitious biodiversity targets.

At the same time, many regions are desperate to further develop their economies and societies by providing universal access to clean energy and public goods and services, including those related to food, water, and health.

The challenge is to close the gaps in energy provision, while at the same time decreasing GHG emissions. Several routes to achieving sustainability are currently being discussed both within the scientific community and at the policy level. Different successful and promising pathways and strategies have also been identified and pursued in different world regions.

Renewable carbon

Sustainable biomass can be a substitute for fossil fuels in a number of difficult-to-decarbonise sectors such as transport and industry. Countries like Brazil and the USA, for example, have long been embarked on a pathway to scale up biofuels. Moreover, the chemical industry will always be in need of carbon as an input—ultimately, this carbon either has to be captured from the atmosphere or come from renewable and sustainable biomass, as fossil resources continue being phased out.

The maximum impact of renewable carbon avenues will, however, be limited by the overall availability of biomass.

A recent example of the role of biomass in a net zero emissions European Union (EU), a report by a sustainability consultancy, indicates that under current policy plans, pathways of biomass for material and energy use would require 40–100% more biomass than is likely to be available in Europe. In its conclusion, the report urges EU policymakers to carefully consider biomass use in the context of its highest value; this is also reflected in the EU's Fit for 55 package, which includes a proposal to amend the Renewable Energy Directive to cover the cascading use of biomass. The cascade chain would allocate high-quality woody biomass first to long-lived products, such as building materials, then to refurbishment, and eventually to reuse and recycling, before ending up in an energetic use. Residues (low quality) from biomass processing (e.g., dust from sawmilling) can be used for direct energetic conversion, if there are no other options for their material application.

Circular bioeconomy

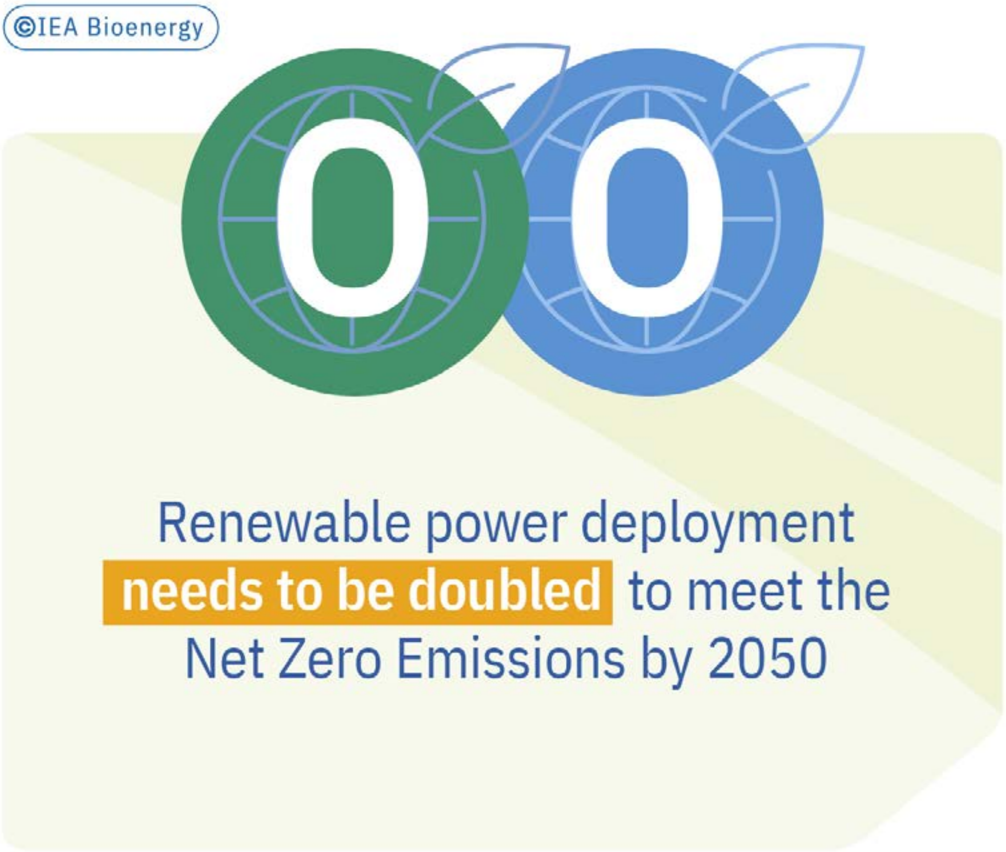
The understanding of circular bioeconomy (CBE) as an essential part of a wider circular economy can differ across stakeholders, countries, and even among scientists. A recent review of a number of bioeconomy clusters found that they are increasingly using residues and wastes, moving towards more integrated biorefineries production models (see also IEA Bioenergy Task 42: Biorefining in a Circular Economy), and focusing first on material and higher-value applications of biomass.

While these are signs of a trend towards a CBE, circular product design, recycling, and cascading are marked by large research gaps. Recent research identifies implementation policies and regulations, costs, and the current small size of bio-based markets as key challenges for a CBE. Furthermore, when shifting to CBE or any other new pathway such as hydrogen or a cascading system, trade-offs need to be considered, as other existing biomass usages might be more sustainable (in terms of net GHG emissions savings). Presently, the social aspects, cascading, circular product design, and aspects related to product use are especially underrepresented in the CBE literature.

Expansion of solar PV and wind

According to recent IEA assessments, renewables have grown rapidly in recent years, driven by policy support and sharp cost reductions for solar photovoltaics (PV) and wind power in particular. Yet, electricity accounts for only a fifth of global energy consumption, and the role of renewables in the transportation and heating sectors remains critical to the energy transition.

In 2020, renewable electricity generation rose by 7%, with wind and solar PV technologies together accounting for almost 60% of this increase. However, according to the IEA's Net Zero Emissions by 2050 scenario (NZE), renewable power deployment as a whole still needs to expand significantly to achieve Net Zero Emissions by 2050. This pathway would require growth, from a share that is presently 27% of power generation, to a share of more than 60% by 2030.



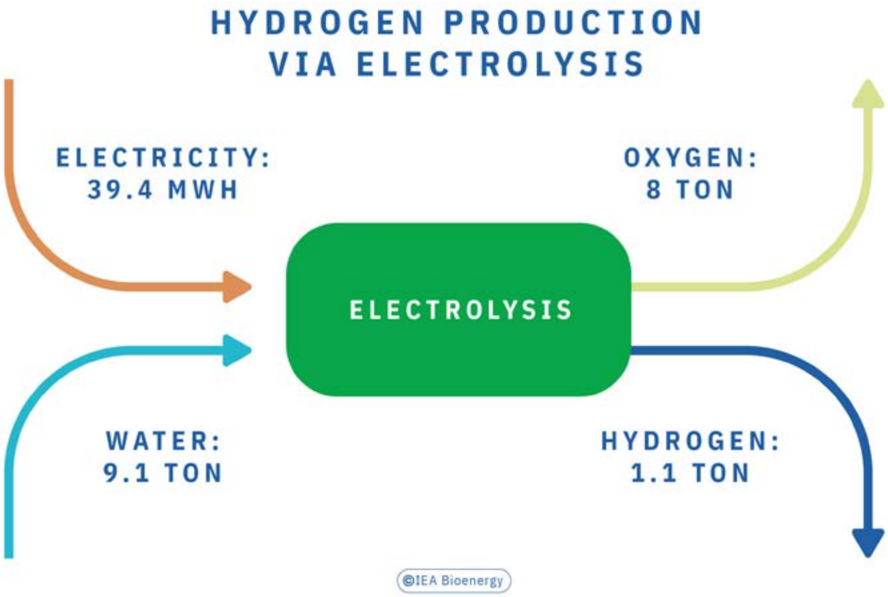
In a significant majority of countries worldwide, solar PV is becoming quite an important economic option in terms of adding new electricity generation capacity, especially amid rising natural gas and coal prices; its importance is also due to improved storage and reduced spare capacity needs to make up for the intermittency of PV. Meanwhile, policy initiatives in China, India, and the European Union are boosting the deployment of commercial and residential PV projects. To reach Net Zero Emissions in the energy sector by 2050, however, PV would need to see an almost fivefold increase in annual deployment until 2030, according to the IEA. This will require much greater policy ambition and more efforts from both public and private stakeholders, especially in the areas of grid integration and the mitigation of policy, regulation, and financing challenges—and particularly in emerging and developing countries.

The IEA World Energy Outlook for 2021 states that clean electrification is a central element of decarbonising the energy sector, including all sustainability avenues and energy pathways, but it is not possible to electrify everything. In the IEA Net Zero Emissions scenarios, although overall electricity production increases impressively by a factor of 2.5 compared to current levels, it still comprises less than 50% of total final energy consumption in 2050. This means that liquid, gaseous, and solid fuels of various types will continue to make major contributions to the global energy mix through to 2050.

Renewable hydrogen

Another route that has enjoyed a wide push by a large variety of policies and initiatives across the world has been towards renewable hydrogen. According to IEA statistics, 23 governments plus the EU have published low-carbon hydrogen strategies and more than 20 countries are already developing them. While these strategies focus mainly on targets for hydrogen supply, attention is increasingly being paid to the policies needed to stimulate demand for both renewable hydrogen and hydrogen-based liquids, including ammonia, methanol, and other synthetic liquid hydrocarbons with very low emission intensities.

While green hydrogen (from renewable sources) can be produced through electrolysis, this is still quite a costly route. Thus, the transition from fossil fuel–based hydrogen production to renewable hydrogen production is also likely to include other low-carbon energy carriers. In the IEA's Net Zero Emissions scenario, around half of low-carbon hydrogen production in 2030 is from electrolysis and the remainder is from coal and natural gas equipped with CCUS (although this ratio varies considerably among countries).



Hydrogen production scheme through electrolysis of water, resulting in very low GHG emissions if renewable electricity input is considered (e.g., from biomass, wind, or solar PV).

Choosing between different options

Biomass, while available in limited supply, is renewable and can serve all sectors (industry, power, heat, transport). Hence, its use has to be targeted at where it creates the highest value, not only economically, but also in terms of reducing net carbon emissions, while also respecting other SDGs.

Rather than choosing between different options, a complementary approach is needed—tapping into biomass for renewable carbon, moving further towards a circular economy to maximise the use of a limited resource, and helping mitigate climate change/reduce GHG emissions.

> **Biomass use has to be targeted at where it creates the highest value, not only economically, but also in terms of reducing GHG emissions and advancing other SDGs**

Different regions will choose different strategies for doing this. For example, as fuel costs make up the bulk of current production, Russia, the Middle East, and North America have a head start in fossil-based (grey) hydrogen due to low gas prices. Other regions may become more important during the transition to green hydrogen because of their abundant availability of solar energy, wind, or hydropower.

Biomass availability, national policies, regulatory frameworks, existing infrastructure, trading conditions, and carbon intensity will all play decisive roles in determining how much countries will be able to substitute renewable carbon for fossil energy and how circularity can further increase this ability.

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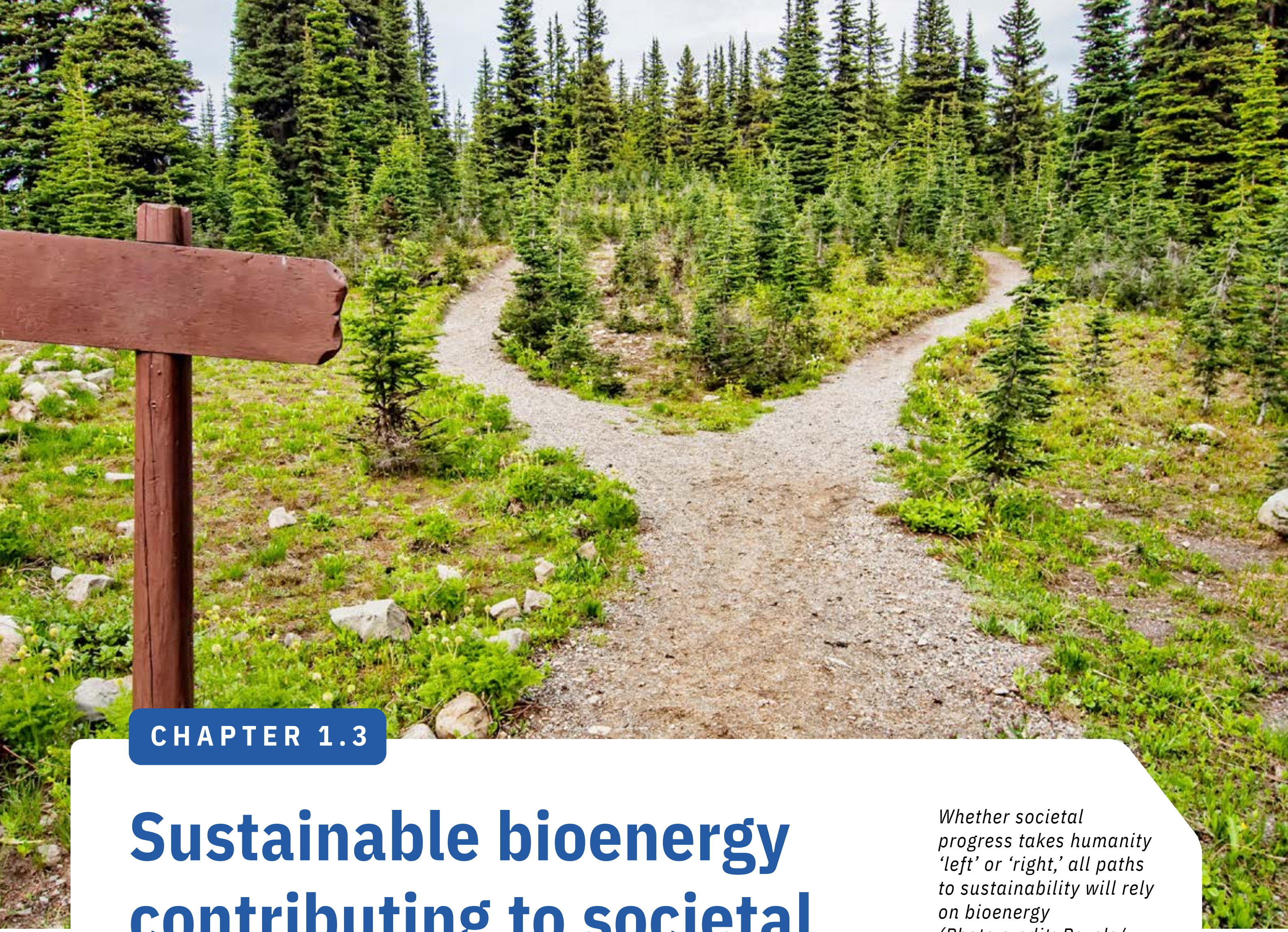


CHAPTER 1.3

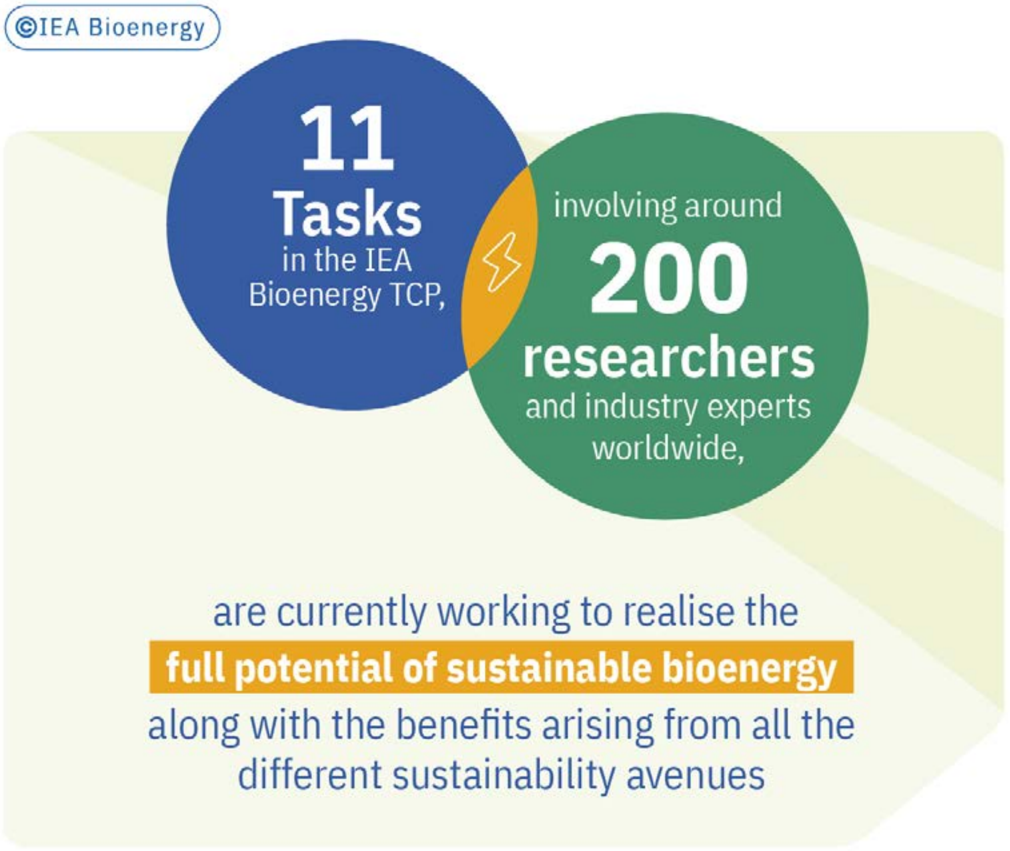
Sustainable bioenergy contributing to societal progress in the 21st century

Whether societal progress takes humanity 'left' or 'right,' all paths to sustainability will rely on bioenergy (Photo credit: Pexels/ James Wheeler)

No matter which sustainability avenues are chosen, modern bioenergy will be part of the picture

Modern bioenergy is not only part of the solution; it is also extremely versatile and will contribute to the required transformation in different ways that will, even themselves, change along the transition to our future energy system. Subject to the condition that biomass is sourced from sustainably managed land, bioenergy not only offers quick solutions for decarbonising existing infrastructure, but also supports ecosystems, creates socio-economic benefits, provides for clean cooking, and stabilises an energy system in transition.

As different world regions will pursue different sustainability avenues, technology and organisational focus will depend on various factors: for example, which resources are available locally, what local cultural preferences are, and the influence of international communities of states on the process. That is why sustainable bioenergy use will have many roles to play, depending not only on different political agendas, but also on various phases of the transition processes.



11 Tasks in the IEA Bioenergy TCP, involving around 200 researchers and industry experts worldwide, are currently working to realise the **full potential of sustainable bioenergy** along with the benefits arising from all the different sustainability avenues

Different pathways may be pursued, yet the exceptional benefits of sustainable bioenergy must not be overlooked - no matter which scenario we decide to pursue.

Significantly improving the room for manoeuvre

To tackle the grand challenges of the 21st century and to counter the myriad uncertainties related to them, the top priority must be to implement and diversify sustainable solutions. Furthermore, given the time pressure caused by rapid increases in atmospheric GHG concentrations, the high technological readiness level (TRL) of many sustainable solutions, including modern bioenergy, must be acknowledged. High technological readiness goes hand in hand with established infrastructure, know-how, and experience that is already being—and should continue to be—deployed to ensure the complete phasing out of fossil fuels.

Supporting ecosystems, preventing forest degradation, and contributing to biodiversity

GHG intensity is the extent to which a service contributes to atmospheric GHG concentration. The reduced GHG intensity of modern bioenergy compared with that of fossil fuels has always been the major argument for the provision of heat, electricity, and fuels from biomass. Meanwhile, initial applications of carbon sequestration and storage have been providing negative CO2 emissions, in other words, they are actually removing CO2 from the atmosphere, for example through bioenergy carbon capture and storage (BECCS). Negative emissions are not only achievable through central, large-scale bioenergy plants and storage solutions; they can also come through decentralised, nature-based sequestration and storage, for example, afforestation. Furthermore, emissions can be retained for a foreseeable period through the circular use of biogenic CO2. Related practices can improve soil conditions and restore land, for instance biogas slurry being used as a biofertiliser or solid biomass gasification by-products being applied as soil conditioners (e.g., biochar).

Over the last decade, the debate has matured as to how biomass can be provided for energy in a sustainable and regenerative way that supports primary ecosystems and sources. With respect to agriculture and forestry under climate change stress, the term ecosystem services means, for example, the restoration and sustainable management of forests to prevent forest fires and mitigate pest infestations. Demand for sustainable biomass sources will shape not only sustainable forestry management but also sustainable agriculture. The provision of bioenergy, and the sustainability conditions required for its sourcing, will thus contribute to concerns for the biosphere being incorporated more responsibly into all human activities, including food and material provision.

No matter which sustainability avenue is taken, the exceptional benefits of sustainable bioenergy must not be overlooked

Creating socio-economic benefits, supporting local producers, and generating jobs

Regional value creation is key to counteracting urbanisation and the rural exodus. The participation of the local population in bioenergy supply chains is already high; this is due to their multiple production and processing steps and also to different decision-making processes at different levels of governance—spanning from local communities, to districts, to the national and international levels.

At the same time, regional markets are being challenged by economic scaling effects and vertical supply chains (where the producer equals the consumer), by international markets, and by commodity markets in general. The economic feasibility of smaller producers and local supply chains can be particularly jeopardised when confronted with international prices. Both commoditisation and trade can, however, support the formation of efficient regional markets if shareholder diversity is incentivised. Allowing for, and encouraging, the participation of a broader cross-section of society in the supply chains can create socio-economic benefits. This would bring to the fore the impressive decentralisation potential, particularly in biomass sourcing and processing—supporting energy and resource democratisation and generating jobs.

Stabilising an energy system in transition

Over the next 10–20 years the rapid expansion of photovoltaic and wind power is expected to also lead to significant temporary surpluses and shortages in power provision in many countries. Imbalances in the power grid could be tackled over hours and days with battery and pump hydro storage. As bioenergy can be stored over longer periods, its importance will increase in the context of seasonal shortages, providing, for example, residential heating in wintertime when photovoltaic power for heat pumps is scarce. Furthermore, surpluses can be valorised, for example through the upgrading of biogas with hydrogen from excess renewable electricity.

In the longer run, bioenergy flexibility options for the power grid can also be supplemented with product flexibility, for example, combined heat and power or biomethane for industrial process heat, which can also be used as a chemical raw material. The unique versatility of possible applications for bioenergy technologies, their established supply chains, and their infrastructure will be decisive in terms of reacting to changing needs during the transition.

Supporting cleaner cooking solutions

About 2.8 billion people globally still lack access to clean cooking solutions and thus rely on traditional use of biomass in open fires. This traditional use of biomass is problematic, as open fires are inefficient and expose people (in particular women and children) to emissions of harmful air pollutants that can lead to respiratory diseases. Moreover, irresponsible gathering of wood can result in deforestation. Assuring access to cleaner cooking solutions is an integral part of a just transition and is addressed in Affordable and Clean Energy (SDG7), the goal of which is the phasing out of traditional open fire bioenergy by 2030.

Modern biomass stoves, bioethanol, and biogas are among several options for cleaner cooking. Compared to other cleaner cooking solutions, such as natural gas, liquified petroleum gas (LPG), or electricity, the use of biomass not only offers health benefits; it can also create income from biomass cultivation and ethanol production and enable the diversion of waste biomass to biogas production. Multilateral organisations such as the International Renewable Energy Agency (IRENA), the Global Bioenergy Partnership (GBEP), and the United Nations Industrial Development Organization (UNIDO) are actively involved in the roll-out of biomass-based clean cooking solutions.

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02

Environmental sustainability

CHAPTER 2.1

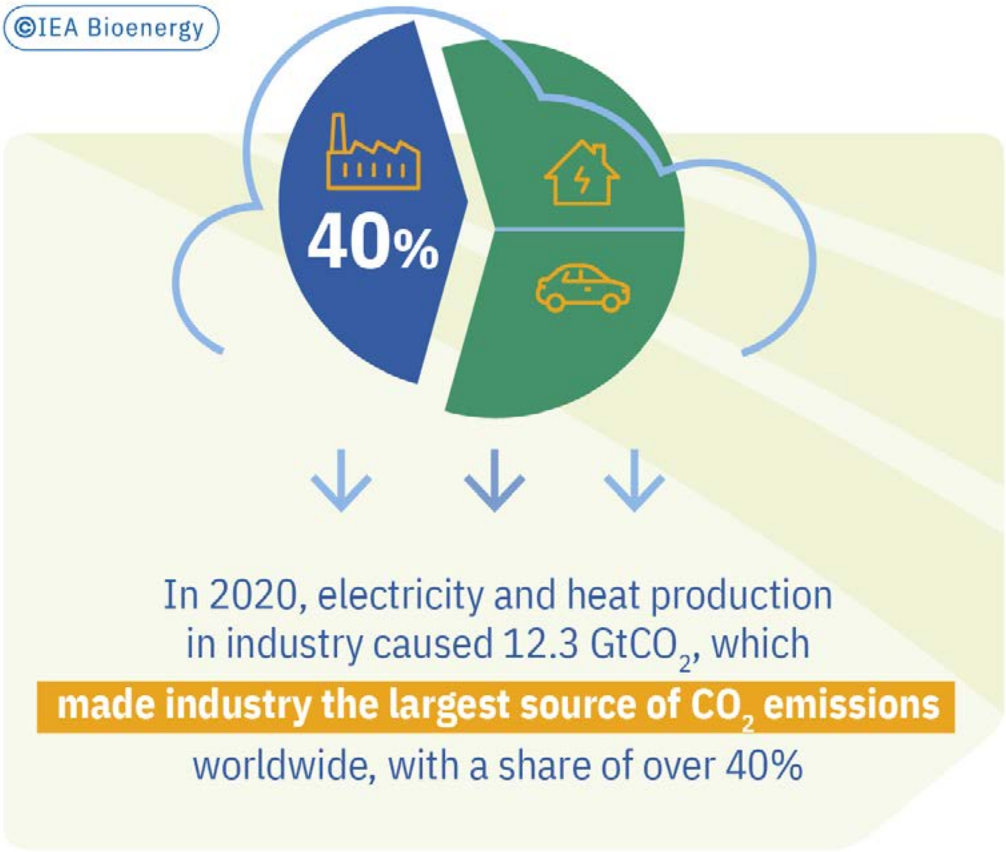
Reducing greenhouse gas emissions through fossil fuel substitution

Sustainable forest management allows the biogenic carbon cycle to be leveraged to help decarbonise the economy and achieve the climate goals (Photo credit: Pixabay/Marcin Jozwiak)

Sustainable bioenergy can support the decarbonisation of all energy sectors

Projected to represent one-fifth of total energy supply in 2050, sustainable bioenergy is expected to continue playing a key role in decarbonising all energy sectors, and by extension, the global economy. Bioenergy replaces fossil fuels in energy production, thereby reducing GHGs. It is, however, crucial to source biomass from sustainably managed forests and agricultural lands, as well as to apply governance systems to ensure sustainable operations.

The fossil-dominated energy sector is responsible for around three quarters of GHG emissions today and holds the key to averting the worst effects of climate change. In 1990, global energy-related CO2 emissions were estimated at 20.5 Gt, and reached 31.5 Gt in 2021. This contributed to CO2 reaching its highest-ever average annual concentration in the atmosphere of 412.5 parts per million in 2020— around 50% higher than at the start of the industrial revolution in the mid-1700s.



In 2020, electricity and heat production in industry caused 12.3 $GtCO_2$, which **made industry the largest source of CO_2 emissions** worldwide, with a share of over 40%

Bioenergy is the main source of renewable energy today, and its role in climate change mitigation should not be underestimated. The IEA Net Zero by 2050 Roadmap estimates that the supply of modern bioenergy needs to triple to achieve net zero energy-related CO2 emissions by 2050.

Today, bioenergy covers approximately 10% of the global overall energy demand and is the main source of renewable energy, with modern bioenergy accounting for 50% of global renewable energy consumption.

Bioenergy contributes to energy used in power generation, heat for industry and buildings, and transport fuels. Sustainable bioenergy can effectively reduce fossil fuel use in the short term, and can contribute to phasing out fossil fuels altogether. Furthermore, bioenergy is the only renewable energy source that can remove CO2 from the atmosphere, when combined with carbon capture and storage (CCS) (namely, bioenergy with carbon capture and storage [BECCS]).

> **Bioenergy can replace fossil fuels and remove CO2 from the atmosphere when combined with carbon capture and storage**

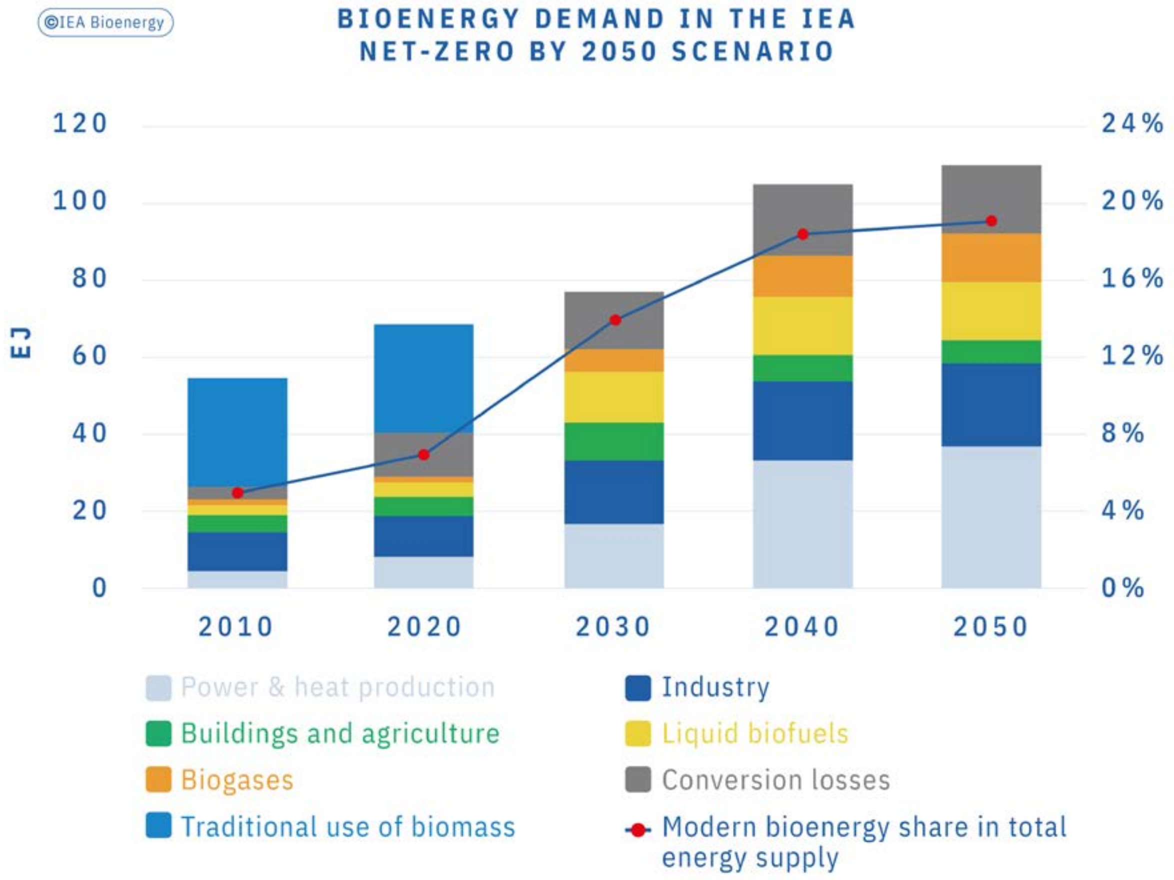
In the field of **electricity production** and storage, biomass can be used for co-firing or in existing combined heat and power (CHP) plants. Moreover, as the contributions from solar and wind power increase, bioenergy can support grid stability by complementing other balancing options, such as battery storage and reservoir hydropower.

The electrification of the **transport sector** will require a substantial increase in electricity supply, including electricity produced by sustainable (and potentially even carbon-negative) bioenergy. In hard-to-abate transport sectors, such as aviation and shipping, liquid biofuels can be used to replace fossil fuels. When combined with CCS, negative emissions can be generated during the biofuel production process.

In the **building sector**, district heating systems in densely populated areas and small-scale combustion technologies in rural areas (boilers and stoves) can provide heating and domestic hot water supply. Biomass-based CHP plants can provide both heat and electricity supply.

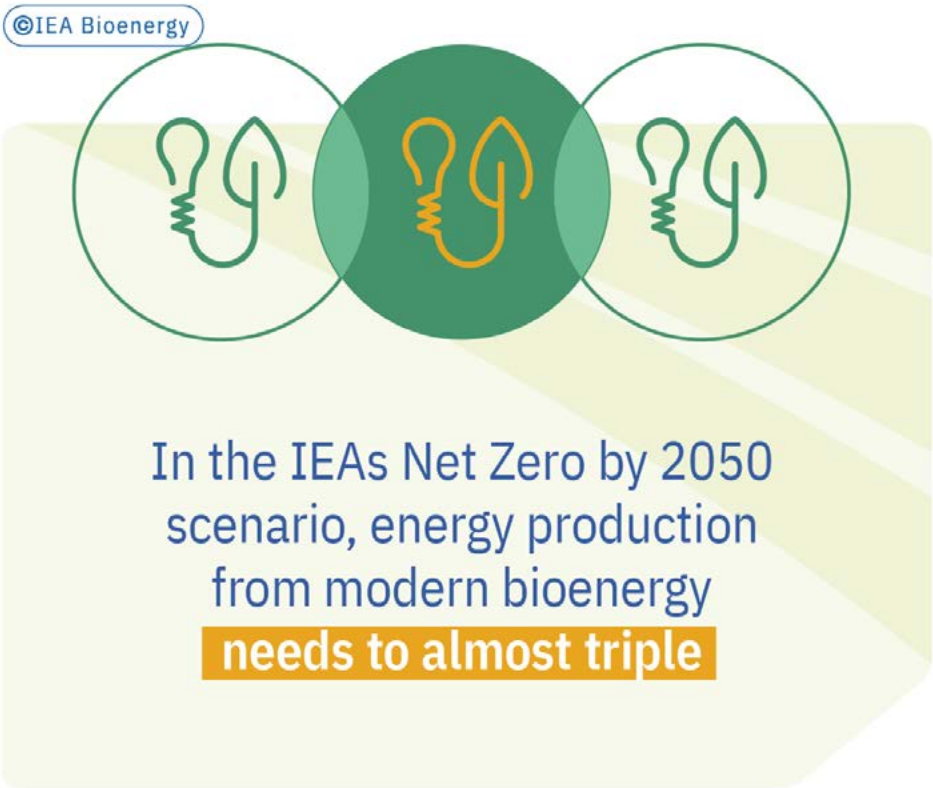
In the **industry sector**, the main application of bioenergy is currently in biomass-processing industries that use their own residues to cover their energy demand (e.g., wood processing, pulp and paper). With industry being more and more motivated to reduce GHG emissions, biomass can increasingly be a substitute for fossil fuels in other sectors, as well as providing high-temperature process heat (e.g., steel production).

Increased deployment of sustainable bioenergy is part of the Nationally Determined Contributions (NDCs) of many countries that have made commitments under the Paris Agreement.



Global bioenergy supply in the IEA Net Zero by 2050 Scenario (Source: IEA Net Zero by 2050 Roadmap)

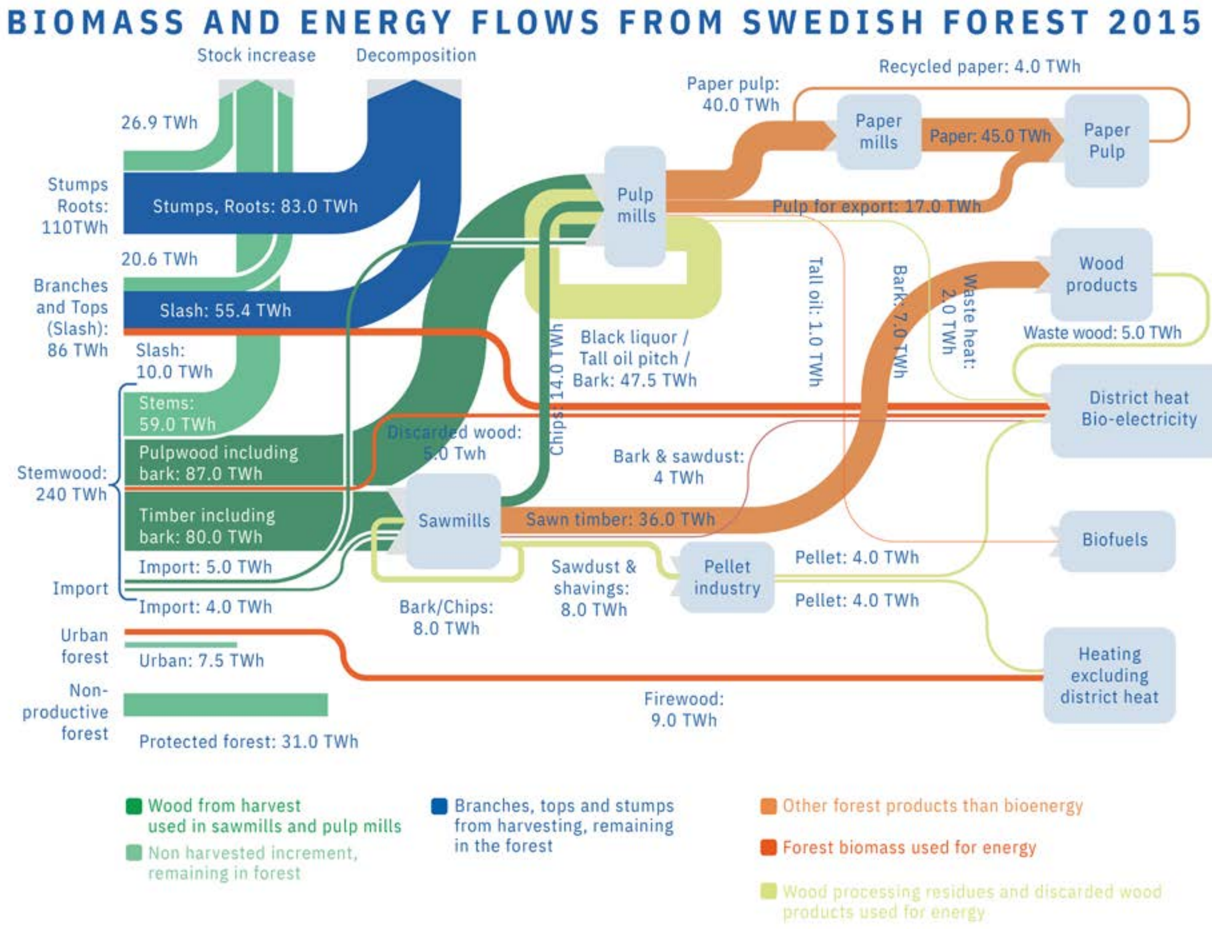
The IEA Net Zero by 2050 Roadmap proposes an approach for transitioning to a net zero energy system by 2050. Along with other measures, such as the increased use of other renewable energies and higher energy efficiency, the energy analysts of the IEA have estimated that the global biomass supply of modern bioenergy needs to rise from approximately 37 EJ in 2020 to around 100 EJ in 2050—an almost threefold increase in under three decades. The intention is for this biomass to be used to produce bioenergy, representing 18% of total energy supply in 2050 (15% of the energy consumption in industry, 16% in transport, and 10% in building). IRENA foresees an even larger role for bioenergy (150 EJ of biomass primary supply).



An increased use of bioenergy needs to be supported by an increase in available feedstock. The IEA Net Zero by 2050 Roadmap estimates that this will be possible thanks to an increased use of forest and wood residues as well as short-rotation woody and grassy crops. In addition, organic residues and waste streams will provide significant amounts of bioenergy (e.g., to replace the traditional use of biomass in developing countries).

As actual GHG emission savings need to be assured, it is important to assess GHG emissions of bioenergy systems at the landscape level across the full life-cycle. Discussions on the climate effects of forest bioenergy have recently involved particular controversy. To understand these, including the temporal and spatial system boundaries and reference scenarios used in the assessments, several factors need to be taken into account. A recent paper ("Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy") points out that forest bioenergy should not be assumed to be carbon-neutral by default—forests managed according to sustainable forest management principles and practices can contribute to climate change mitigation by replacing GHG-intensive materials and fossil fuels and by storing carbon in the forest and in long-lived forest products. Bioenergy systems operate within the biogenic carbon cycle. This implies a fundamentally different influence on atmospheric CO2 concentrations over time compared to fossil fuels; fossil fuel use transfers carbon out of the ground and into the atmosphere, causing a permanent increase in atmospheric CO2.

The consistent application of effective sustainability governance measures ensures that forest biomass used for energy contributes not only to mitigating climate change, but also to broader environmental and socio-economic objectives, such as the UN Sustainable Development Goals.


BIOMASS AND ENERGY FLOWS FROM SWEDISH FOREST 2015

Bioenergy systems are commonly integrated within forest and agriculture systems that produce food, feed, lumber, paper and other biobased products. Figure shows biomass flows in the Swedish forest sector (Based on IRENA (2019), Bioenergy from boreal forests - Swedish approach to sustainable wood use)

Bioenergy and forest carbon balance

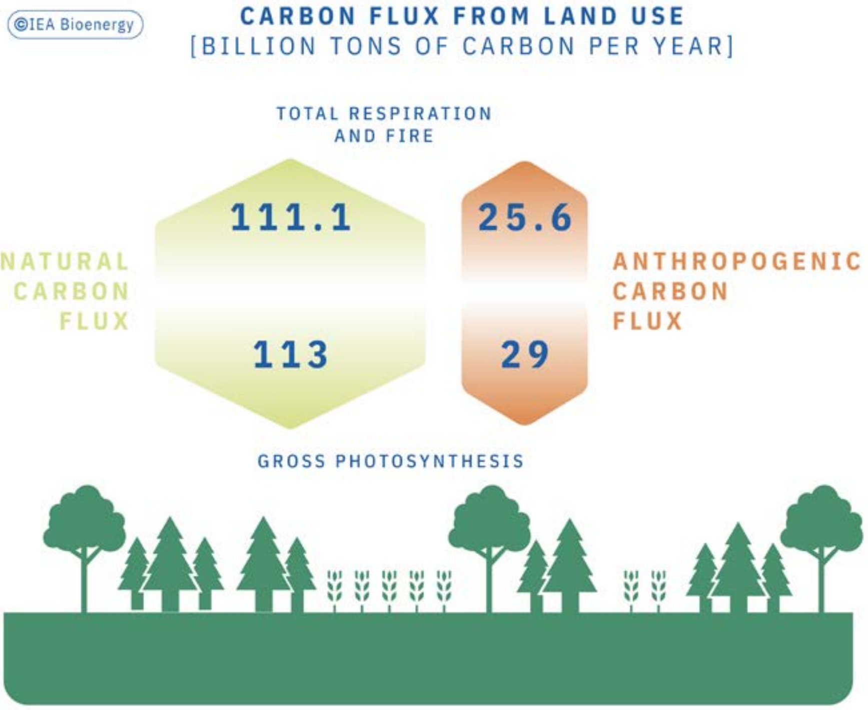
A widely discussed topic related to bioenergy and its sustainability is that of “foregone carbon sequestration” resulting from use of forest biomass. The concept refers to a trade-off between the objectives of storing carbon in the forest and the harvesting of wood to produce forest products.

Forests managed for production of wood products, including bioenergy, may have lower carbon stocks than unharvested forests. This gap is sometimes referred to as foregone carbon sequestration. In the absence of forest management and harvest, however, forest growth rates decline and disturbance risks increase as trees become mature. While old and unharvested forests can thus hold large amounts of carbon per hectare, they also have a lower sink strength and may become carbon sources instead of sinks.

Sustainable harvesting of trees and the management of stem densities and species composition of the forest help maintain net forest growth (i.e., carbon sinks), allowing sustainable harvesting. The carbon stock at a regional or national level can, in fact, increase simultaneously with increases in harvesting. A recent study shows that, for example, in Sweden, and other boreal countries, under fairly intensive forest management, the standing volume of forests (hence, the carbon stock) and its rate of carbon sequestration has increased over the past decades, at the same time as annual harvest has increased.

Scientists from IEA bioenergy Task 45 have explained that sustainably managed long-rotation forests are not primarily harvested for bioenergy products, but produce bioenergy feedstock along with sawlog and pulpwood production for material applications; such applications can create substitutes for more carbon-intensive building materials such as concrete, steel, and aluminium. Residues from such forestry operations (including larger branches, damaged stem sections, and thinning material) and wood processing residues (including e.g., sawdust, bark, and black liquor) tend to be used for bioenergy. These biomass sources have a high likelihood of reducing net GHG emissions when they are substituted for fossil fuels; it is also widely accepted that their use for bioenergy enhances the climate change mitigation value of forests managed for wood production.

While forests, both managed and unmanaged, take up large quantities of carbon through photosynthesis, a major part of that carbon is emitted back to the atmosphere through decomposition or fires. If part of this material is used to provide an energy service, climate benefits are likely. Furthermore, extraction of lower quality biomass (e.g., resulting from pest and disease impacts or overstocking) that would otherwise be left in the forest to decompose, can reduce the frequency and severity of wildfires and the associated loss of forest carbon and release of non-CO2 GHGs; this further enhances the benefits to the climate.



Good forest management can increase biomass growth and reduce the loss from fires or other disturbances. Increased growth can supplement carbon stocks in soil and vegetation(Source: Adapted from IPCC AR6—Carbon Fluxes)

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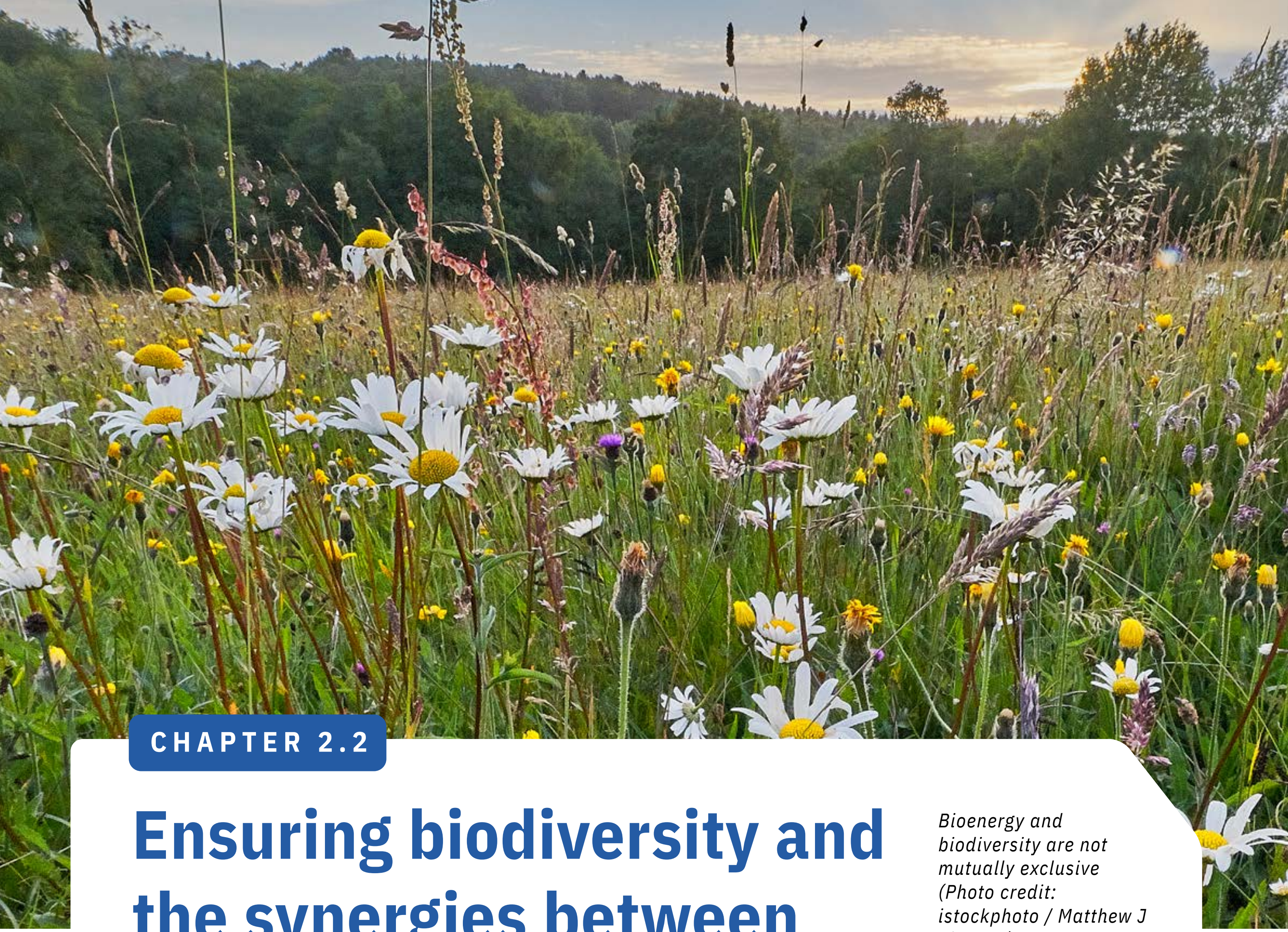


CHAPTER 2.2

Ensuring biodiversity and the synergies between agriculture and bioenergy

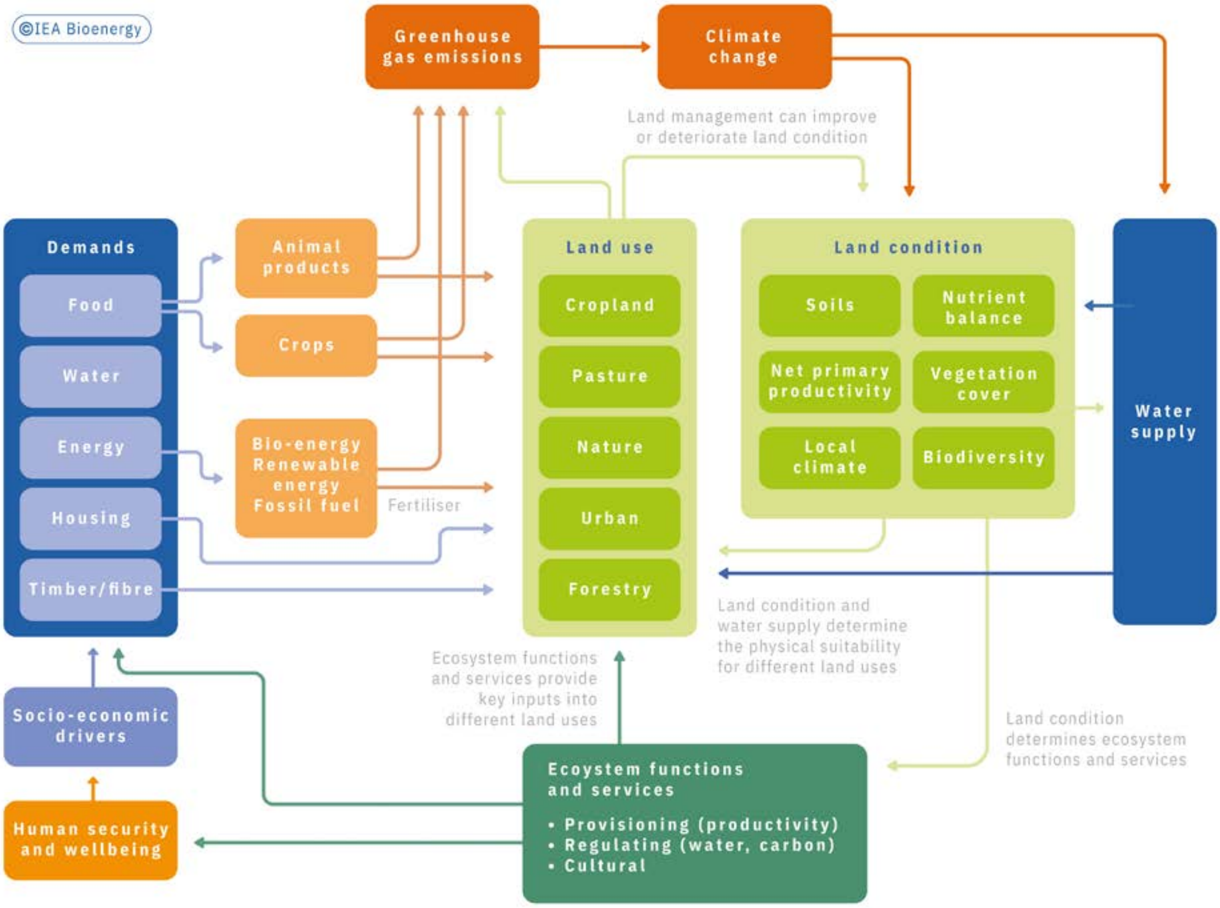
Bioenergy and biodiversity are not mutually exclusive (Photo credit: istockphoto / Matthew J Thomas)

Biodiversity is an important criterion for assessing the value of nature conservation areas, but is also of substantial importance for humans

Modern technologies and optimisation of existing agriculture and food processing industries enable synergies between biofuels and food and feed production without jeopardising biodiversity. These synergies can be realised through sustainable intensification of land use, the use of marginal and degraded lands, improved agronomic practices (increased yields), and by a shift to integrated production systems that combine production of food, feed, and fuels, for example, in crop rotations, intercropping, multiple-cropping, or agroforestry systems.

Land is a limited resource and has to be managed sustainably: this includes soils and water reserves as well as biodiversity. Given the growing demand for energy and food and the importance of environmental protection, optimising land use is more important than ever.

Land management plays a key role in achieving goals related to climate change, biodiversity, desertification, and land degradation and is linked to several Sustainable Development Goals (no poverty, zero hunger, gender equality, clean water and sanitation, affordable and clean energy, responsible consumption and production, climate action, and life on land).



Interlinkages between key themes in global land systems (Source: Exploring future changes in land use and land condition)

Land Use Change (LUC) and the related effects

As land is a limited resource, increasing the use of bioenergy can result in land use change, both directly and indirectly.

- Direct Land Use Change (DLUC) refers to the direct conversion of a specific land area from one use (e.g., forest, agricultural crop cultivation for food/feed) to another (e.g., crop cultivation for biofuels). DLUC can be observed and measured.
- Indirect Land Use Change (ILUC) is an unintended consequence of a land use decision taken elsewhere. Bioenergy production that uses feedstocks grown on arable and pasture land can cause ILUC via market mechanisms; for instance, they can cause increased demand for food and feed, resulting in increased crop prices. This incentivises the conversion of additional land

to agricultural use. Converting land with high natural carbon stocks to agricultural use can lead to significant GHG emissions.

ILUC effects cannot be measured directly and are therefore modelled using market-equilibrium models: these models employ, for example, information on land use provided by landowners. Calculation of ILUC effects is complex, and taking a holistic approach to assessing the range of impacts and effects should be considered, for instance, the impact of ILUC on biodiversity and access to land and land use rights.

The effects of ILUC also need to be accounted for when environmental sustainability is the goal, as they can have a significant negative impact on the GHG balance of bioenergy. To calculate ILUC-related GHG emissions from biofuels, it is vital to analyse the additional biofuel demand and the additional land demand and displacement due to biofuels. ILUC-related GHG emissions are influenced by several parameters, such as, for example, which crops were previously grown on the land and the overall use the land has been put to, the biofuel pathway, technology, the world region in focus, the yield projections, and stakeholder reactions to changing markets. After more than a decade of biofuel growth, actual changes in land use can also be assessed and used to continuously improve modelling.

While it is important to know the magnitude of ILUC effects, the model-based ILUC factors calculated are not fixed values, but depend on market dynamics and local circumstances. Policy is divided on whether to handle ILUC effects using a risk-based approach, for example, to limit crops/farming practices that have potentially high ILUC impacts (EU REDII, Canada CFR (currently under revision), or to add an estimated value for ILUC to the GHG emissions values calculated for biofuels (US RFS2, California LCFS, ICAO CORSIA).

Assessing land availability for biomass potential

The potential of agricultural biomass for energy production largely depends on the available land. Several contextual and science-based methods have been developed to assess the availability of suitable land and related factors for improved land management and sustainable bioenergy production. Examples include Global Agro-Ecological Zoning (GAEZ)—a concept developed by the International Institute for Applied Systems Analysis (IIASA) and the FAO (Food and Agricultural Organization), as well as the FAO Bioenergy and Food Security (BEFS) which fosters sustainable bioenergy while ensuring food security.

This type of methodology makes it possible to identify promising areas for growing biomass for energy based on climate, soil, landform, etc., so as not to interfere with the production of food and feed. High-risk areas in terms of potential damage to ecosystems and biodiversity must be excluded from bioenergy production to ensure biodiversity conservation. Existing agricultural production and infrastructure has to be identified and mapped, and good communication with local stakeholders is critical to confirm data integrity and provide necessary context.

Synergetic development of agriculture and bioenergy

Growing biomass for energy on abandoned, degraded, or marginal lands limits the competition with food and feed. If done in a sustainable way, it restores or improves soil quality and enhances carbon sequestration. However, biomass from abandoned, degraded, or marginal land would be more costly to produce due to increased demand for fertilisers, irrigation, etc. Moreover, the benefits from soil improvement and carbon sequestration would need to be valued economically. A substantial increase in the use of bioenergy crops is thus likely to rely on the use of arable land.

> **Growing biomass for energy can improve soil quality of degraded lands**

Biomass for energy may also be produced on good quality agricultural and pasture lands without jeopardising global food and feed supply, as long as agricultural land use efficiency is increased or multi-cropping combinations are implemented. Increased demand in the agricultural sector has encouraged farmers to increase their yields through improved agronomic practices and better seed varieties (e.g., drought- and insect-resistant). The increased demand for crops—partially triggered by biofuels—can positively affect farm income and health and provide income-earning opportunities for women and poor households.

Food, fibre, and bioenergy crops can be grown in integrated production systems; agricultural crops for food and biomass residues for bioenergy are harvested from the same land. This is mitigating displacement effects and improves the productive use of land.

Links between biofuels and food security are complex, and biofuel production can deliver both risks and opportunities. This complexity underlines the importance of the role of sound and science-based assessments, such as FAO´s Bioenergy and Food Security Approach, or feedstock sustainability certifications. Such assessments will assure the long-term positive impacts of biofuel production and use that do not distort the food and feed markets or negatively affect biodiversity.

Future outlook on land use for bioenergy

According to the IEA Roadmap to Net Zero by 2050, over 60% of global bioenergy supply is projected to come from waste and residue streams, such as agricultural residues or municipal organic waste, thus avoiding the need for dedicated land use. This projection does not, however, fully account for the potential competing uses of residues for bioenergy, fertilisers, animal feed, etc. The remaining 40% of bioenergy supply is projected to be supplied by short-rotation lignocellulosic crops, sustainably managed forests (outside existing forest land), and agroforestry (integrated production of agricultural crops and tree planting). These activities can be implemented on cropland, pasture, or abandoned/marginal lands. No additional arable land is required for bioenergy in this roadmap. Projected land use for bioenergy is estimated to be around 140 million hectares globally; this is below estimated ranges of potential land availability, taking into account sustainability constraints and the Sustainable Development Goals on biodiversity and land use. Nevertheless, certification of bioenergy feedstocks/products and the strict control of additional land use is crucial to avoid land use conflicts and biodiversity losses.

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CHAPTER 2.3

The water and nutrient footprint of bioenergy

Maintaining soil fertility is important for any cultivation of biomass, regardless of whether the intended use is food, feed, or bioenergy (Photo credit: Pexels/ Greta Hoffman)

What are the water implications of bioenergy production in the context of a circular economy-based agricultural system?

Bioenergy can have multiple positive impacts on society, beyond its crucial role in helping to supply sustainable energy and mitigating climate change. To succeed in its important roles, bioenergy feedstock production from agriculture and forestry needs sufficient and sustainable water and nutrient supplies as well as appropriate management.

Water

The United Nations Environment Programme (UNEP) together with IEA Bioenergy Task 43 produced a joint report on the bioenergy and water nexus in 2011; this report considered bioenergy and water to be inextricably linked. In other words, water availability affects the availability of sustainable bioenergy. As bioenergy is largely dependent on biomass production (as dedicated energy crop, or as residue of other agricultural or forest products), expected growth trends will lead to increasing competition for, and pressures on, water resources. These pressures may be attenuated if the sustainability criteria for bioenergy production, advances in technology, and the use of different feedstocks are adhered to.

Bioenergy is not the only part of the energy sector that has impacts on water resources. Energy and water are deeply inter-related, although different energy sources have different "water footprints". Furthermore, concerns raised here with respect to increasing water scarcity are not unique to bioenergy, but are examples of larger, systemic issues in agriculture, industry, land use, and natural resource management. As a steadily growing sector, however, bioenergy can serve as a high-profile leverage point to raise awareness of water-related issues and to stimulate the implementation of best management practices where this might not otherwise occur. Bioenergy also offers synergy options with other sectors, which need to be further explored.

Water demand, bioenergy water footprint, and related policies

Water use occurs throughout the bioenergy production cycle, including feedstock production and conversion. Quantifying the impacts of bioenergy production on water resources is, however, complicated because of the feedstock diversity and the fact that biomass production happens concurrently for multiple applications (food, feed, materials, energy). Variability in site-specific conditions and the conversion processes also have a role to play. Particularly for policymaking, this large number of influencing factors requires an understanding of the advantages and limitations of each factor and their impact on bioenergy production and related water demand. Inventories provide values for the "water efficiency" of different bioenergy pathways.

A recent study reports large differences among the water footprints of the different feedstocks used for bioenergy, and also the technologies (i.e., chemical, biochemical, thermochemical technologies), as well as the consequences of applying these in future energy mixes. The report shows that residues are the most favourable bioenergy feedstocks in terms of water use. The total water footprint does not increase when residues are applied for energy purposes. When crops are grown primarily for energy, however, the water footprints are clearly larger, and this should be particularly taken into account in regard to river basins with increasing water scarcity.

To avoid a negative impact of bioenergy production on the water balance, targeted policy instruments are needed to address the water implications of bioenergy production. They should be designed to help avoid long-term adverse consequences while maximising potential benefits (e.g., new rural jobs and new options for sustainable land and water use). Bioenergy-related water policy instruments need to be designed for coherency with instruments in related policy sectors and with existing water policy instruments, including those concerned with irrigation and other agricultural practices and industrial water use. Such policies can include incentives for enhanced soil moisture conservation measures, including rainfall capture, conservation tillage, and precision agriculture.

Recommendations for implementing and ensuring a sustainable bioenergy–water nexus

In 2016, the Global Bioenergy Partnership (GBEP) and IEA Bioenergy joined forces to collect information and carry out analysis on "Positive Bioenergy and Water Relationships". Inter alia, the following key messages for positive examples that could well work as role models for various locations and regions were identified:

- Consider location-dependent conditions, when applying integrated water planning and management;
- Design and implement effective water-related policy instruments that address the impacts of biomass and bioenergy production on water availability and quality, and at the same time carry out effective monitoring of the competition between sectoral uses of water;
- Disseminate best management practices and support capacity building among farmers and NGOs in the field;
- Consider a comprehensive socio-ecological perspective, including ecological functions in agricultural and natural landscapes and broader livelihood and development implications; promote sustainable land and water use.

Given the crucial role of the bioenergy-water nexus, IEA Bioenergy together with the United Nations Environment Programme (UNEP) and Oeko Institut recommend the following key strategies in their report:

- Take a **holistic approach** at the appropriate geographic level and consider a long-term perspective through application of integrated water planning and management at the watershed level: namely, consider location-dependent conditions; apply life cycle perspectives; and account for potentially synergistic effects (e.g., for food and fuel production, irrigation, etc.);
- **Base decisions on scientific impact assessments** to ensure sustainable water management by considering a comprehensive socio-ecological perspective, including ecological functions in agricultural and natural landscapes and the broader livelihood and development implications;
- **Design and implement effective water-related policy instruments** that address the impacts of bioenergy production on water availability and quality; carry out effective monitoring of the competition between sectoral uses of water.
- **Establish/support appropriate institutions and processes**, including inter-ministerial task forces; ensure stakeholder engagement from the planning through the implementation phases;
- **Disseminate best practices and promote new technology** through upgrading of extension services and promotion of special training through certification schemes.
- **Intensify dialogue on the topic of the bioenergy-water nexus and on capacity building**, inter alia, with groups and organisations working on the issue; build the capacity of the different groups in emerging economies and developing countries to include decision makers.
- **Conduct further research, fill data gaps, and develop regionalised tools**, for example, by supporting international cooperation in research into the impacts of bioenergy development on water, as well as by further developing regionalised tools, given that life cycle impact assessments (LCIA) and water footprint (WF) are inadequate without the differentiation of localised impacts.

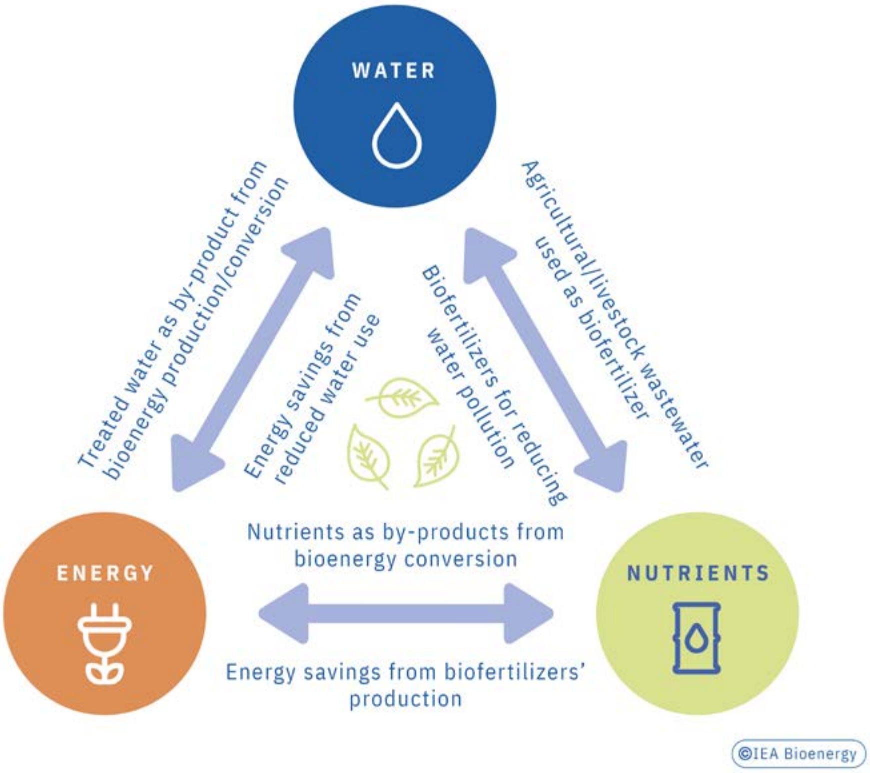
Bioenergy and soil nutrients

The bioeconomy—which includes bioenergy—relies on a continuous supply of biomass. The soil conditions especially play an important role in the production of this biomass. Biomass not only contains carbohydrates but also nutrients. Some of these nutrients will be extracted from the soil during biomass production and harvesting, and some will be lost during the further processing of the biomass. The soil needs to be kept in good condition to maintain sufficient biomass production. Some of the nutrients that are harvested with the biomass can be retained within the residues for bioenergy production. These residues from bioenergy production (e.g., digestate, compost, biochar) can be fed back to the soil as a fertiliser by-product.

The growth and removal of biomass from soils has impacts both on the soil organic matter content and on the nutrient balance. The more biomass harvested, the less biomass is available to return to the soil to maintain soil organic matter levels. Scientists explain that the utilisation of residues from bioenergy production, like digestate or biochar, can help to maintain soil organic content, while the use of cropping residues for bioenergy reduces the return of organic material to the soil.

The Water–Energy–Nutrients Nexus

A recent research study explains that water, energy, and nutrients are the main pillars in the design of a circular economy-based agricultural system. There are various correlations and links between these pillars, and these create technological bases for sustainable economic and social development.



Potential synergies between water, energy, and nutrients in agriculture (Source: https://www.mdpi.com/1996-1073/14/1/159/htm)

Scientists state that closed-loop (or circular) agriculture is one of the most promising solutions for minimising the use of resources throughout crop and livestock production processes.

In contrast, fertilisation using synthetic fertilisers is among the most energy- and cost-consuming field operations, as well as having an adverse environmental impact. According to the research study, this is the key reason for so much attention being devoted to nutrient circularity applications and avoidance of the use of synthetic fertilisers as much as possible.

Sustainable nutrient management for biomass production and bioenergy

A comparative study in the United States shows that without soil amendments, typical row crop agriculture such as maize results in a net removal of nutrients and carbon from the soil. A harvest in one location removes plant material rich in nutrients for consumption by animals or humans in another. This annual removal of nutrients can be compensated for by fertiliser application. Manufacturing of synthetic fertilisers and application to row crops, however, has several adverse environmental consequences. Production of fertiliser is energy-intensive, and its production and use contribute significantly to CO2/N2O emissions and nitrate leaching.

The authors of this study argue that the conversion from traditional row crops (for energy) to other cropping and harvesting practices (e.g., intercropping, shifting to perennial grasses, etc.) may reduce many negative environmental consequences associated with nitrogen fertilisation. For example, it appears that miscanthus, a promising energy crop, requires minimal nitrogen fertilisation on fertile soils.

Nitrate leaching under developing perennial grasses drops dramatically and perennial grasses (miscanthus, switchgrass, etc.) have the potential to build soil carbon and nitrogen pools, providing additional ecological benefits in addition to displacing fossil fuels.

There is also growing evidence to suggest that perennialisation on degraded lands has a large potential for restoration, particularly as additional ecosystem services can be provided simultaneously. Sustainable biomass production systems based on perennial plants can simultaneously deliver climate mitigation (lignocellulosic biomass replacing fossil resources), animal production (intensive rotational grazing), and biodiversity conservation (natural ecological succession). Perennialisation has substantial promise for restoring fertility to degraded croplands, thus helping to meet future food security needs.

Example of a modern tool to optimise soil nutrients in bioenergy systems

Dutch scientists have developed the BioESoil tool to assess the impacts of bioenergy on soil quality. The tool can help users, including bioenergy producers and certification organisations, to determine the impact of bio-energy production on soil fertility and soil organic matter. It can also help NGOs and other organisations to create awareness of nutrient recovery options in bio-energy production and use.

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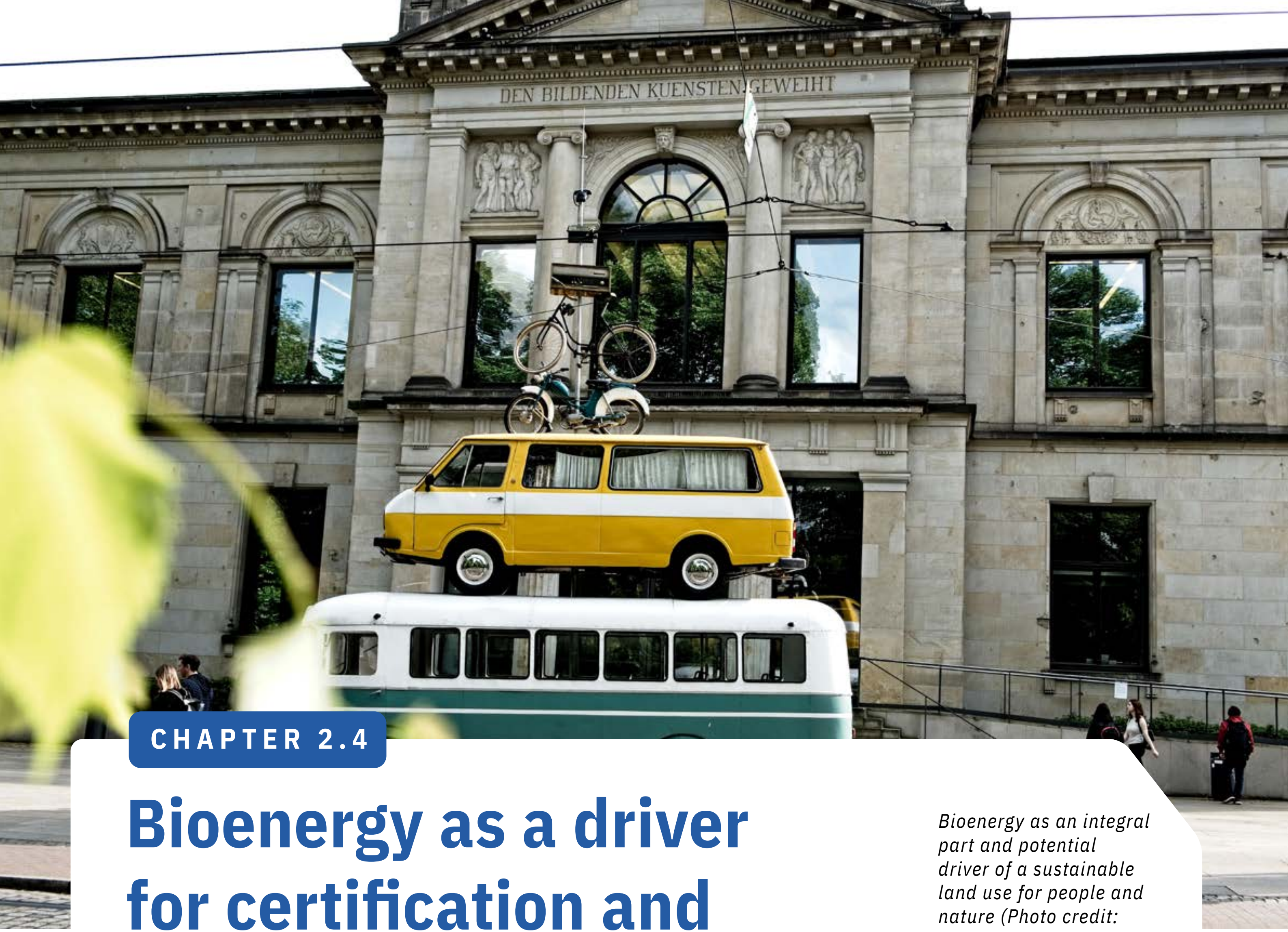


CHAPTER 2.4

Bioenergy as a driver for certification and conservation

Bioenergy as an integral part and potential driver of a sustainable land use for people and nature (Photo credit: Unsplash/Moritz Kindler)

How can bioenergy help in the transition to a more sustainable management of land?

Bioenergy can be a driver and gate opener for transition towards higher sustainability and sound land use practices. This is particularly so when ambitious sustainability regulations and biodiversity conservation requirements are in place and strictly enforced during the procurement process by the demand side of bioenergy production and final consumption. Sustainably sourced biomass for biofuel/bioenergy generation is expected to make an important contribution to supporting the SDGs— including for example, 7, 8, 9, and 12.

Bioenergy can be a powerful driver for sustainable land use and biodiversity conservation; this is shown by a series of recent studies on the potential of biomass for bioenergy that specifically consider environmental sustainability criteria and high biodiversity areas. Thoughtfully produced biomass need not have a damaging impact on biodiversity and sustainability goals.

Positive examples of certification systems, labels, and schemes are, inter alia, RSB (on bioeconomy), ISCC (sustainable feedstocks), SBP (forest biomass), the Bonsucro initiative on sustainable sugarcane production, and the efforts of the Roundtable on Sustainable Palm Oil (RSPO) for the certification of sustainable palm oil production. The latter two were initiated because of concerns over the sustainability of transport biofuels produced from these resources, but the schemes are also having a positive impact on food production.

On the one hand, there are global schemes that particularly consider biodiversity, including the UN Convention on Biological Diversity (CBD) and the Sustainable Development Goals (SDGs). On the other, there are regional schemes, for example, for the EU, including the Common Agricultural Policy (CAP) and the Renewable Energy Directive (RED, REDII), that include specific regulations with respect to the origin of biomass for bioenergy production. Accordingly, bioenergy feedstock cannot be obtained from land with high biodiversity, such as primary forests or highly biodiverse grasslands.

If such restrictions and considerations of biodiversity protection are not followed, biomass production could have a negative impact on biodiversity and sustainable land use. In the case of the EU, risks associated with biomass trade are addressed by requiring that bioenergy and bioenergy feedstocks used in the EU comply with the mandatory sustainability criteria in the RED/RED II in order to benefit from public financial support and to count toward the overall renewable energy targets—irrespective of geographic origin. Compliance can be proved through either national or EU-wide recognised voluntary certification schemes.

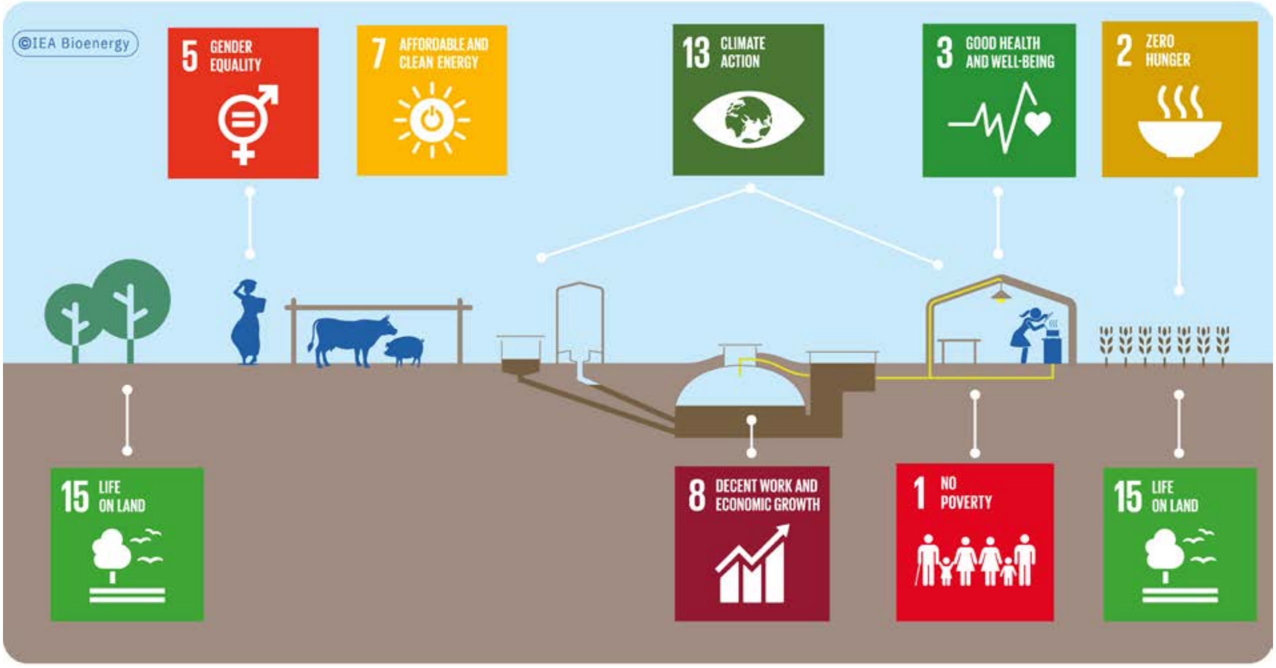
Carefully produced biomass need not negatively impact land use and biodiversity

In the sustainable land management context, restrictions with respect to biodiversity and sustainability criteria seem to be particularly important for biomass production from grasslands, which are considered highly biodiverse. Experts caution to rely only on the approach of identifying high biodiversity areas (must be protected) and land that is marked as “available” for sustainable biomass/bioenergy feedstock production. This is because the correct designation for bioenergy production might be difficult to characterise.

Moreover, indirect land use effects could have negative impacts on neighbouring plots or even across countries and continents. When it comes to sustainable bioenergy feedstock production, science recommends a combination of safeguards—top-down (including global biodiversity programs) and bottom-up (including national and/or subnational lists of plant habitat types)—to ensure compliance with the strict land use policies in place combined with clear sustainability criteria and indicators (e.g., through recognised certification systems).

Carefully developed and science-based sustainability policies could lead to (a demand for) bioenergy to become a positive driver for the introduction of improved sustainability criteria for biomass production, sensible land use policies, and biodiversity protection; this is particularly so considering the importance of bioenergy for climate change mitigation. In such cases, bioenergy would become a positive driver for a transition towards sustainable land use, with the achievement of biodiversity being a top priority.

Certainly, the actual influence of bioenergy production on sustainable land use and biodiversity protection, and vice versa, will depend on the real-world implementation of the relevant regulations, and these will vary by region. In this regard, scientists recommend a learning-by-doing approach to identify the merits and pitfalls of biomass deployment and to improve understanding of the prospects for achieving higher levels of sustainable biomass production for bioenergy.



The direct and multiple contributions of a biomass-based biodigester to the United Nations Sustainable Development Goals. Image, courtesy Hivos

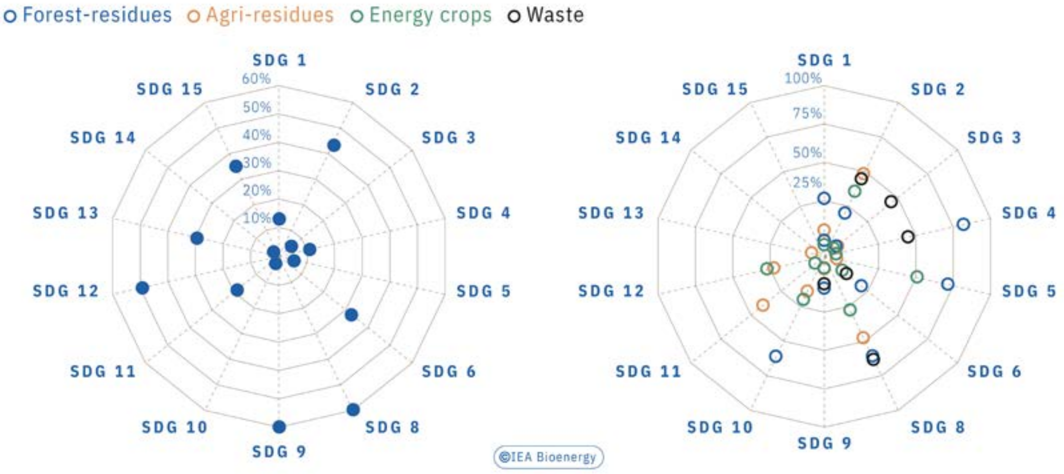
Scientists and industry experts behind IEA Bioenergy documented and analysed a total of 37 case studies from every continent with a range of feedstocks, supply chains, and end uses; their aim was to learn if and how biomass supply chains contribute to sustainable development (see also chapter 4: Social sustainability and the need for a just transition).

In particular, bioenergy contributes to sustainable land management, restoration of degraded lands, and improved economic opportunities in rural areas.

The study concludes that sustainably sourced biomass for bioenergy generation can play an important role in supporting sustainable development. While biomass supply for bioenergy generation directly contributes to Affordable and Clean Energy (SDG 7) and Climate Change Mitigation (SDG 13), it can also make meaningful contributions to many other SDGs.

37 case studies around the world confirm that **bioenergy contributes to a broad range of SDGs,** most notably, Decent Work and Economic Growth (SDG 8) and Responsible Production and Consumption (SDG 12)

For example, while agricultural supply chains (i.e., energy crops and residues) are more likely to positively impact Zero Hunger (SDG 2) and Clean Water and Sanitation (SDG 6), waste and forest supply chains are more likely to positively impact Life on Land (SDG 15). Biomass supply for bioenergy generation was also found to indirectly contribute towards socio-economic development such as No Poverty (SDG 1), Quality Education (SDG 4), Gender Inequality (SDG 5), and Reduced Inequalities (SDG 10). At least half of the 37 case studies reviewed contributed towards Decent Work and Economic Growth (SDG 8), Industry, Innovation, and Infrastructure (SDG 9), and Responsible Production and Consumption (SDG 12), with differences in contributions across supply chains.



Visualisation of the contributions of case studies to the SDGs. Percentage of (a) total cases contributing to each SDG and (b) cases by biomass supply chain type contributing to SDGs. Source: [Contribution of Biomass Supply Chains for Bioenergy to Sustainable Development Goals](#))

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03

Economic considerations

CHAPTER 3.1

Making biomass available to meet long-term market demand

Although we naturally expect agriculture and forestry to be responsible for the biomass supply, we can enhance its availability by making use of waste streams and industry residues (Photo credit: Peter Oslanec)

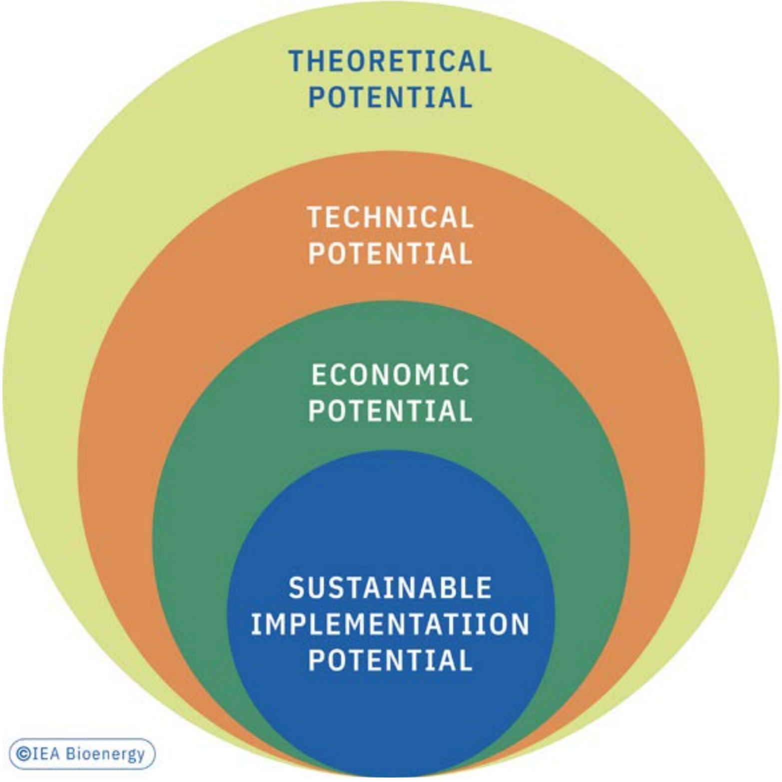
How can we ensure and enhance biomass availability?

Availability of suitable, sustainable biomasses in sufficient quantities at reasonable prices is crucial for implementing successful and sustainable bioenergy businesses. Enhancing biomass availability can be challenging due to differences in regional and individual characteristics of biomass resources. Appropriate legislative frameworks, creation of markets for biomass commodities, and technological innovations can support biomass mobilisation.

Biomass potential

Numbers are often confused when the quantities of biomass that could be made available for bioenergy use are discussed. While availability means the amount of biomass actually available on a market in a specified region, biomass potentials are estimated amounts of biomass. Biomass potentials are based on assumptions, and we distinguish between theoretical, technical, economic, and sustainable implementation potentials.

The theoretical biomass potential describes the amount of biomass that is theoretically usable in a certain geographical area for a certain period of time. The technical potential is the part of the theoretical potential that can be gained, taking into account a number of limiting factors such as technical limitations regarding biomass supply, harvest, and conversion. The economic potential is the share of the technical potential that meets economic profitability criteria within a given framework. This depends on different parameters, for example the biomass production costs. The sustainable implementation potential describes the part of the economic potential that can be used in a certain time frame considering socio-political framework conditions and restrictions such as sustainable practice and sustainability regulations.



Distinction of biomass potentials

Biomass potentials are difficult to estimate. Most estimates of future biomass potential for bioenergy rely on the scenario approach; this is based on different scenario parameters that have an impact on the target value. Thus, the overall range between biomass potential estimates is extremely wide: in the most extreme scenario, the theoretical biomass potential for bioenergy reaches over 1,500 EJ per year. This is equivalent to almost three times the present global primary energy supply. The sustainable implementation potential is estimated at between 60 and 120 EJ per year (corresponding to 9–18% of the total world energy supply).

Available biomass feedstocks

Currently available biomass feedstocks include dedicated energy crops from sustainable agriculture (preferably produced on abandoned, degraded, or marginal lands), residues from forestry and agriculture, various organic residue streams from wood and agro-food industries, as well as organic fractions of municipal waste. As a biological resource, algae could potentially provide a sustainable contribution for biomaterials and bioenergy production in the future.

Algae could contribute to the bioeconomy, with bioenergy being a by-product of high value biomaterial production.

Residue feedstocks from various agriculture sectors come in the form of i) primary crop residues such as rice husk, wheat straw, or manure; ii) sugar/starch and biofuel crops such as sugarcane, corn, rapeseed, soy, oil palm, or iii) lignocellulosic crops, such as short rotation coppice or energy grasses. Besides agriculture, forestry is the major biomass supply sector. Woody biomass from forests includes residues that otherwise would remain in the forest after harvests, (parts of) trees (thinnings, badly shaped stems, diseased trees) that are of no interest to conventional wood processing industries or as actual wood processing residues in these industries. Secondary residues are those from food, feed, and material production processes. Tertiary residues (e.g., post-consumer material such as demolition wood and scrap pallets) are another important feedstock source in terms of cascading use.

When using these biomass resources, we must also consider ecological criteria and the balance with carbon sinks.

Biomass demand for energy production

Of all renewable energy resources, biomass contributes the highest share to the global energy supply. Bioenergy, including the traditional use of biomass (burning of woody biomass or charcoal and agricultural residues in simple and inefficient devices in developing and emerging economies), contributed an estimated 12%, or 45.2 EJ, to total final energy consumption in 2018. This is equivalent to only 50% of the estimated mean sustainable biomass potential (90 EJ). Modern bioenergy, which excludes the traditional use of biomass in simple and inefficient devices such as three-stone fires without chimneys, provided an estimated 19.3 EJ—or 5.1% of total global final energy demand—in 2018.

In the stated policies scenario of the IEA global bioenergy demand assessment, the demand for solid biomass for traditional use will decrease to 23 EJ until 2040. In contrast, the demand for solid biomass for modern use will increase to 39 EJ. The 2040 demand for biofuels will increase to 9.4 EJ and for biogas, including biomethane, to 6.3 EJ. More ambitious pathways, however, that strive for net zero CO2 emissions by 2050, include the phasing out of traditional bioenergy completely by 2030, thereby partly amplifying the need for modern bioenergy.

Hence, it is important to enhance sustainable long-term biomass availability.

Dynamic factors defining biomass availability

In practice, the availability of biomass for energy will be influenced by population growth, diet, water availability, farming and forestry practices, agricultural density, nature conservation, and (changing) climatic circumstances. No matter what type of sustainable biomass is considered or where it comes from, strategies for biomass availability would generally cover the following considerations:

- An agile and flexible large-scale biomass business case will be able to adapt to multiple sources of feedstocks, and continually move up the technological learning curve through learning-by-doing;
- Understanding of the biomass supply including the amount, locations, and quality;
- Realisation of the best value by connecting the biomass to the right market and use; and
- Scaling and integration with existing supply chains.

However, the availability of biomass resources and residues is mainly determined by future developments in agriculture and forestry. Aspects include availability of land for agricultural crops, agricultural practice, forestry practice, and demand for bio-based products with related biomass residues. Policy incentives and restrictions, such as sustainability requirements, will have a major impact.

Agricultural biomass is seasonal

If year-round bioenergy production is desired, this will usually lead to large amounts of biomass (or processed biofuels) needing to be stored for a significant time period. A better understanding of biomass degradation in storage is thus required. Furthermore, apart from sugars/starches or oils, agricultural biomass resources such as straw or other lignocellulosic materials are usually characterised by low densities and low heating values.

These challenges can be partially addressed by innovative supply chain design. There could, for example, be a focus on establishing transport and storage systems for various types of agricultural biomass resources, or supply chains could also be managed through adapted technology solutions, for example, processing biomass to make it compatible with existing infrastructure.

The future supply of agricultural biomass is further limited by the biomass yield levels that can be obtained from the available land and what crop is chosen, the sustainability constraints imposed on bioenergy crop production and population growth, and the resulting food and feed demand.

To ensure future sustainable supply of agricultural residues as well as energy crops, the efficiency of feedstock provision processes and logistics, including the efficient collection of residues, should be optimised. There should also be a focus on modernisation and technology development in agriculture, including productivity increases and technology exchange, as well as the improvement of production of short rotation forestry and bioenergy crops (such as energy grasses and reeds) on marginal lands.

Agricultural crops and agricultural residues provide biomass for bioenergy (Photo credit: ETA-Florence Renewable Energies)

Forest biomass supply is inherently complex

Different types of biomass need to be accorded an appropriate value market. If there is a well-planned supply chain management, specific local market needs can be met, and risks of failure can be decreased if local conditions are considered. Forest biomass supply chains need to continuously adapt to changing conditions such as the opening and closing of saw mills or pulp and paper mills, as well as to catastrophic circumstances.

Pre-processing solutions can contribute to upgrading the value of under-utilised forest biomass by managing moisture content, limiting contamination, and ensuring homogenisation of the biomass resources. This increases biomass cost but leads to savings on transport cost. The impact of pre-processing solutions on the carbon footprint should also be taken into account. Locating the upgrading operations close to trimodal transportation opportunities (road, rail, and water) can significantly reduce the logistical cost. For local supply chains, the required pre-processing is placed either at the point of harvest, at decentralised logistic hubs, or within the facility of the final energy producer, depending on the water content of the substrate. The processing of other (industrial) biomass residues differs substantially from harvested biomass. Hence, enhancing the availability of these other biomass residues demands adapted solutions.

Waste materials

For used cooking oil (UCO) or organic municipal solid waste (MSW), the core logistical challenge is the collection and management of these wastes. Consumer awareness and behaviour play an important role in facilitating the set-up of such biomass value chains. Finally, safety and hygiene, and regulatory aspects must also be considered. The growing global demand for FAME biodiesel and Hydrogenation-Derived Renewable Diesel (HDRD or HVO), coupled with policy incentives to use waste feedstocks, have significantly improved UCO collection in some regions such as North America and the EU.

Algae biomass

In future, there may be potential to establish aquatic biomass (algae) and other wet sources of biomass. There is a great opportunity for research and development regarding the supply of these biomass resources and logistics, with innovative technology solutions and uncertainties being needed to serve new markets.

Algae are currently used primarily by the food and chemical industries, with new applications emerging in the areas of food and feed, nutraceuticals, pharmaceuticals, biofuels, biomaterials, and bioremediation services. Macroalgae are harvested from wild stocks or produced in aquaculture systems, while microalgae are cultivated in open systems (e.g., raceway ponds) or closed systems (photobioreactors and fermenters). Further research is needed to evaluate the full impact of algae use in terms of water, energy, and land use, changes in sedimentation rates, and structure of local communities; potential pollution and the risk of releasing invasive species into the environment must also be considered.

Biomass mobilisation - Possibilities for enhancing biomass availability

More development is needed to mobilise biomass potentials and to address risks and uncertainties associated with feedstock costs, its quality and quantity, as well as supply chain efficiency. IEA Bioenergy scientists and industry experts agree that this requires focus on legislative frameworks, technological innovation, and market creation.

The **legislative framework dimension** explores the current policy landscape and connects the different policy strategies, blueprints, roadmaps, action plans, and funding schemes. Multi-level governance concepts provide a framework for acknowledging the interactions between the different spatial or organisational resolutions. Participatory processes in governance will be decisive in terms of social acceptance. The remarkably high societal participation potential for circular bioeconomy supply chains must be acknowledged to empower energy democracy and harness multiple societal benefits.

> **To empower energy democracy and harness multiple societal benefits, we need to acknowledge that the potential for societal participation in circular bioeconomy supply chains is remarkably high**

The **market creation** dimension focuses on market catalysts for wastes, residues, post-consumer products, and secondary raw materials. Moreover, market platforms such as bio-hubs should be addressed.

Bio-hubs are making a variety of biomass types available at a single location. The key advantages of bio-hubs include the streamlining of processing, storage, and transportation, reduction in administrative costs, providing an opportunity for suppliers of biomass products to continue producing in the off-season (e.g., in the summer, when residents or building occupants do not require heat), and providing a place for companies to connect and trade with one another. Bio-hubs also provide a sales point for local biomass residues.

Biomass supply via bio-hubs as an alternative to the conventional supply route provides opportunities to manage quality, support new production, and develop critical logistical mass through biomass uniting and pre-processing hubs. As bio-hubs have the potential to improve the security of biomass supply, they would be able to mobilise less profitable biomass and take this market to the next level.

Moreover, bio-hubs may serve as entry points for emerging, innovative players in the bioeconomy that, although frontrunners in novel conversion technologies, have limited knowledge or experience of secure biomass supply chains.

To minimise risks related to the operation of bio-hubs, it would be advisable to either start small or to build on the existing business cases or facilities. This approach would still allow businesses to grow to a larger-scale operation with multiple suppliers and a diversified portfolio of products, depending on the location.

Mobilisation level “**technological innovation**”, refers to quite specific developments such as mobile and portable pre-treatment processes and precision farming/forestry based on planning and harvesting supported by geographic information (GIS) systems; this includes models, services, and start-ups. Science and evidence-based integration of bio-based supply chains with other renewable energy sources—that is, in a broader sustainable economy—will provide resilience for an economic metabolism under changing framework conditions.

Pre-treatment of biomass residues can improve and enable supply chains for thermochemical conversion. Pre-treatment results in fuels with better defined specifications and increased energy densities. Through pre-treatment steps, such as washing, drying, sieving, leaching, or thermal pre-treatment, the characteristics of lower-grade biomass can be significantly improved and, in some cases, will also more closely mimic the characteristics of the fossil fuel for which it is being substituted. Increased volumetric energy density decreases feedstock transportation costs and logistical challenges. The IEA Bioenergy report “Biomass pre-treatment for bioenergy” has analysed five individual case studies, including biomass torrefaction, pre-treatment of woody residues, treatment of municipal solid waste (MSW) to produce solid recovered fuel (SRF), steam explosion for co-firing, and leaching of herbaceous biomass.

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CHAPTER 3.2

Residues as resources—bioenergy instead of decomposition

This is a home. Imagine what using biomass residues for sustainable bioenergy on an industrial scale could achieve (Photo credit: Lenka Zdunderova)

Biomass residues are globally under-utilised and can contribute to climate change mitigation efforts

Large amounts of annual agricultural and forestry residues are still unused, left to decay naturally, or burnt off in open fields. Residues brought into a sustainable bioenergy value chain can substitute for a large share of fossil fuel and thereby significantly reduce GHG emissions. Modern streams of biomass residues are being used for the production of fuels and chemicals, as well as for the provision of heat and power to the residential, commercial, and industry sectors.

There are different sources of biomass residues: those remaining from the harvest of trees, agriculture residues left in the field after harvesting or pruning, those discarded during the processing phase (for instance, olive pits and nutshells), residues from wood and food industries, farming and livestock manure, the organic part of municipal solid waste, and sludge from sewage treatment plants. The common practices of natural biomass waste decomposition or the open field burning of agricultural residues can cause unhealthy air pollution as well as high risks of fire escaping into forests and endangering health and life.

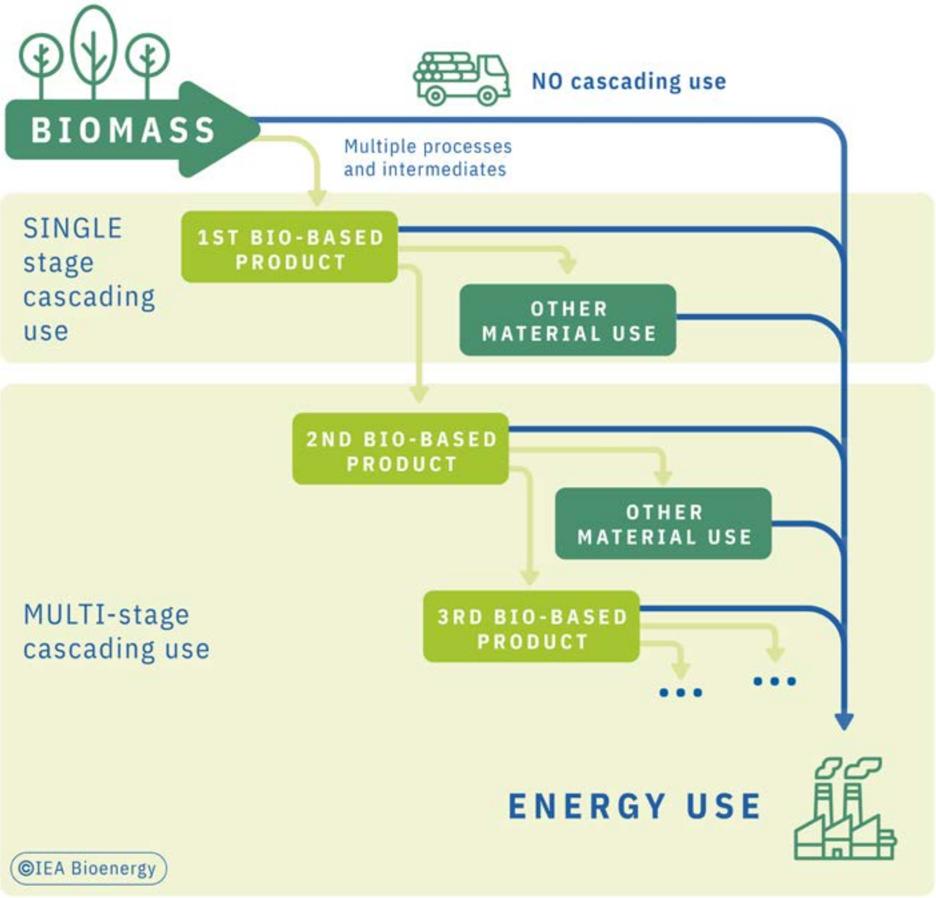
In India and other Asian countries, farmers often burn rice straw in the fields, with the aim of removing residues and preparing the field for the next crop. This practice leads to an uncontrolled combustion process which has a high impact on air quality, with emissions of particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), nitric oxides (NOx) and other pollutants.

South Africa, like many other countries in the African continent, discards over 90% of municipal solid waste and industrial biomass onto the land, without any effective recycling of materials or resources.

Approaches to utilising biomass residues and waste fractions

Biomass residue streams and waste fractions are potential feedstocks for a variety of products, including biofuels for transport, chemicals, and construction materials.

In well developed economies, a cascading use of biomass is at the core of a circular economy, which means that residues and recycled materials are used efficiently to extend total biomass availability within a given system. The cascade chain would allocate high-quality woody biomass first to long-lived products, such as building materials, then to refurbishment, and eventually to re-use and recycling, finally putting it to energetic use before it ends up in landfill disposal.



In most developed countries, biomass residues are managed using a cascadic chain approach, in which the use of biomass in bio-based products has priority over energy use

Improving the cascading and resource-efficient use of biomass requires interventions throughout the whole value chain. There is no one-size-fits-all solution to improve resource efficiency and implement the cascading use of biomass. Only a mix of coordinated approaches—tailored to the local specifics—will lead to full implementation. It should be noted that wherever access to biomass for priority services such as heating and cooking is low, the use of high-quality woody biomass for heating and cooking may still take priority over its use for products of higher economic value.

Biomass residues offer multiple possibilities at all stages of cascading so that landfill disposal can be minimised. Examples at the stages of reusing and recycling are:

- Solid recovered fuels are produced from individual or mixed streams of wastes from different sectors (municipal, commercial, industrial, construction, demolition). These streams include plastic, paper and cardboard, textile, and wood and biogenic fractions. Mechanical or mechanical-biological treatments are used to produce solid recovered fuels. These fuels are in high demand by energy-intensive industrial sectors (like the cement sector) as substitutes for fossil fuels. Solid recovered fuels may have great potential in countries that have to manage high annual amounts of wastes (such as China and India) while also satisfying their internal energy demand.
- Manure and sewage sludge can be reused as fertilisers or for the recovery of highly valuable phosphorus via advanced processes. Care needs to be taken, however, not to contaminate farmland with heavy metals and pharmaceutical residues from the sludge.

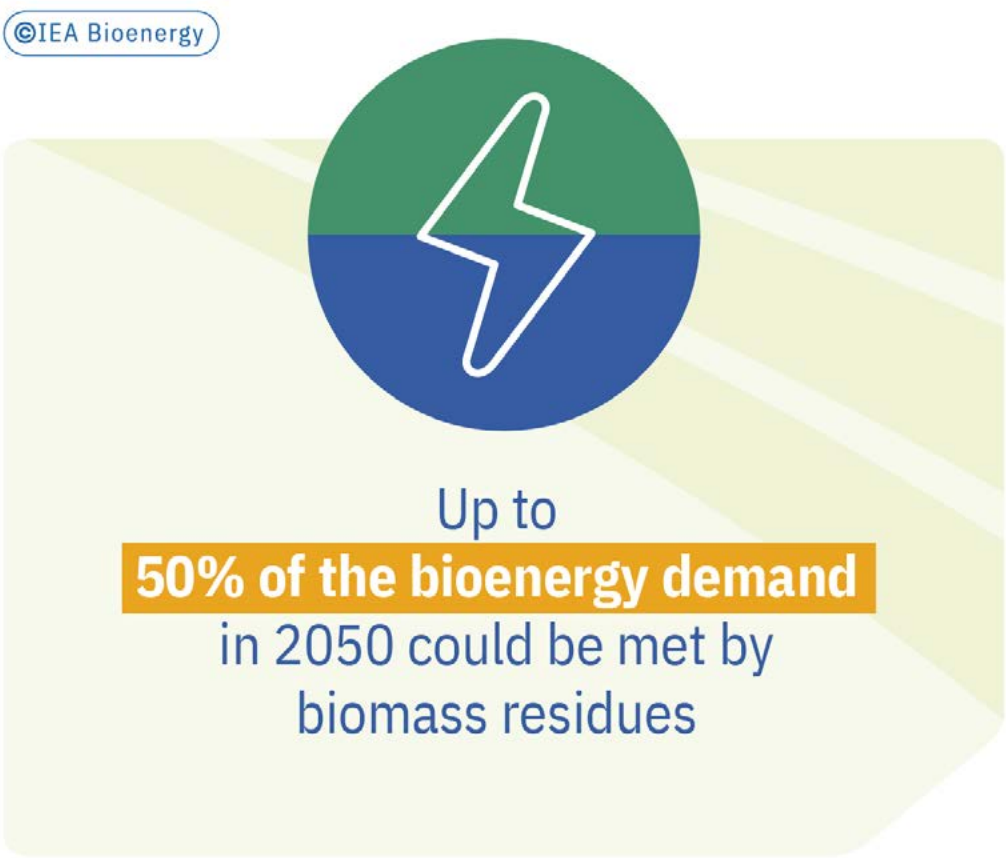
At the stage of energy valorisation, the main established processes for converting biomass residues into bioenergy are combustion and biological treatment.

- Combustion of biomass residues from forestry and agriculture produces heat and electricity. For example, in district heating systems, locally produced woody residues (wood chips and sawdust) are combusted to supply heating and domestic hot water to communities.
- Anaerobic digestion of manure, organic industry waste, and a separately collected organic fraction of municipal solid waste produce biogas which is used either directly for heat and/or power generation, or upgraded to biomethane and further fed into the gas grid. The second product of the process is a digestate that can be used as a biofertiliser.

Moreover, in the last decades innovative technological approaches have been developed to convert biomass residues into energy, fuels, and chemicals.

- Biomass residues such as straw and corn cobs can be fermented into ethanol for use as transport biofuel. While the production of ethanol from sugar and starch crops has reached maturity, technologies for producing ethanol from forestry and agricultural residues and waste materials are currently under development.
- Gasification converts solid materials (biomass, as well as other fractions of municipal solid waste such as paper, cardboard and textiles) into a combustible gas (syngas). This gas can be used for the synthesis of fuels (such as hydrogen, methane, and others), for chemical products, or to generate heat and/or electricity. When applied to biomass-based materials, gasification can produce energy with low carbon intensity, as successfully demonstrated at several plants in Europe. Researchers in the scientific community are working to further improve the process and to explore new pathways for the production and use of biofuels and chemicals.

- Pyrolysis is used to produce liquid oil that can be either directly combusted to produce heat or upgraded into transport biofuels. Additional products of pyrolysis are gases and also biochar.
- Biomass residues can also be liquified by hydrothermal liquefaction to produce a liquid "bio-crude" that can be upgraded into transport biofuels or valuable chemical products.



Biomass residues are valuable feedstocks that can help contribute to climate change mitigation by displacing substantial amounts of fossil fuels and carbon-intensive materials, thus reducing GHG emissions. The IEA Net Zero by 2050 Roadmap estimated that biomass residues could provide an energy supply of around 65 EJ/year by 2050 (20 EJ from wood processing and forest harvesting and 45 EJ from agricultural and food processing residues, as well as industrial and municipal organic waste streams). Another study analysed quantities of biomass residues supplied for energy and their sensitivities in harmonised bioenergy-demand scenarios and found that residues could meet 7–50% of bioenergy demand towards 2050 (depending on different scenarios).

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CHAPTER 3.3

Biomass feedstock costs and prices

Raw material costs of bioenergy production differ over regionsand can be quite volatile

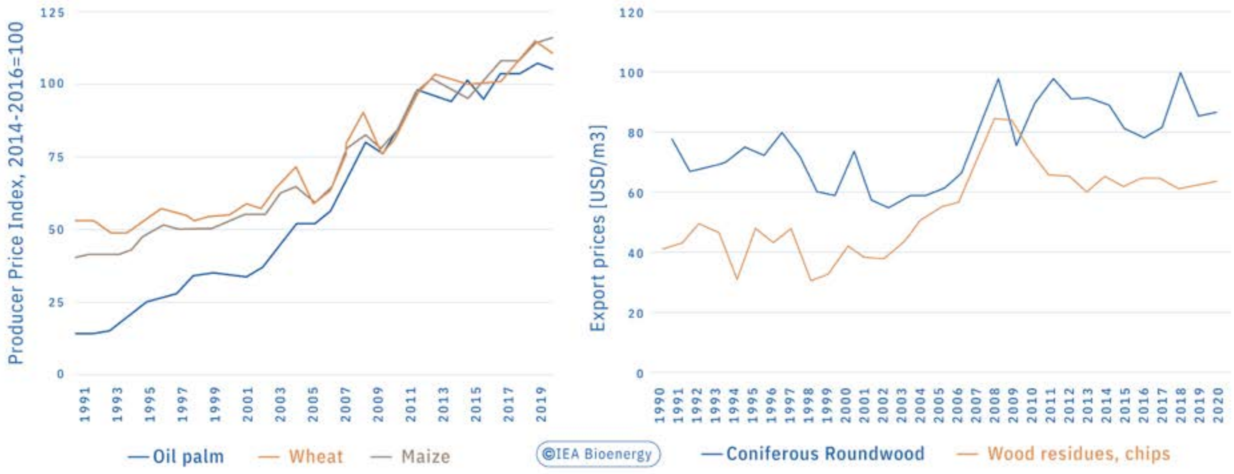
Woody biomass from forests, such as parts of trees that are not suitable for conventional wood processing industries, could be used as feedstocks for sustainable bioenergy production, contributing to the bioeconomy(Photo credit: Alexander Schimmeck)

The cost of biomass feedstocks is one of the main barriers to wider bioenergy deployment. With increasing demand, prices are expected to rise. Approaches such as the cascading use of biomass and integrated biorefineries can prevent biomass prices from exploding. The total costs of bioenergy technologies vary significantly by technology, country, and also by which feedstock can be used. Hence, cost, quality, and quantity of biomass available will determine the amount of bioenergy that can be produced in a sustainable way.

Biomass costs

Reliable supply of affordable biomass feedstocks is crucial for the development of sustainable bio-based businesses. It is needed to reduce financial, technical, and operational risk to biomass supply and conversion investments. The additional risks associated with the long-term supply of affordable biomass feedstock having to meet appropriate sustainability criteria, are a significant complicating factor for financing bioenergy projects.

Biomass feedstock costs are dependent on biomass types, location, yield, harvesting systems, collection methods, storage, and transportation distances.



Left side: Producer Price Index, 2014-2016=100 of Palm oil, Wheat and Maize (global average) from 1990 to 2020, Source: FAO

Right side: Nominal coniferous roundwood and wood residues, chip export prices in $/m3 from 1990 to 2020, Source: FAOSTAT

The costs of biomass feedstock break down as follows:

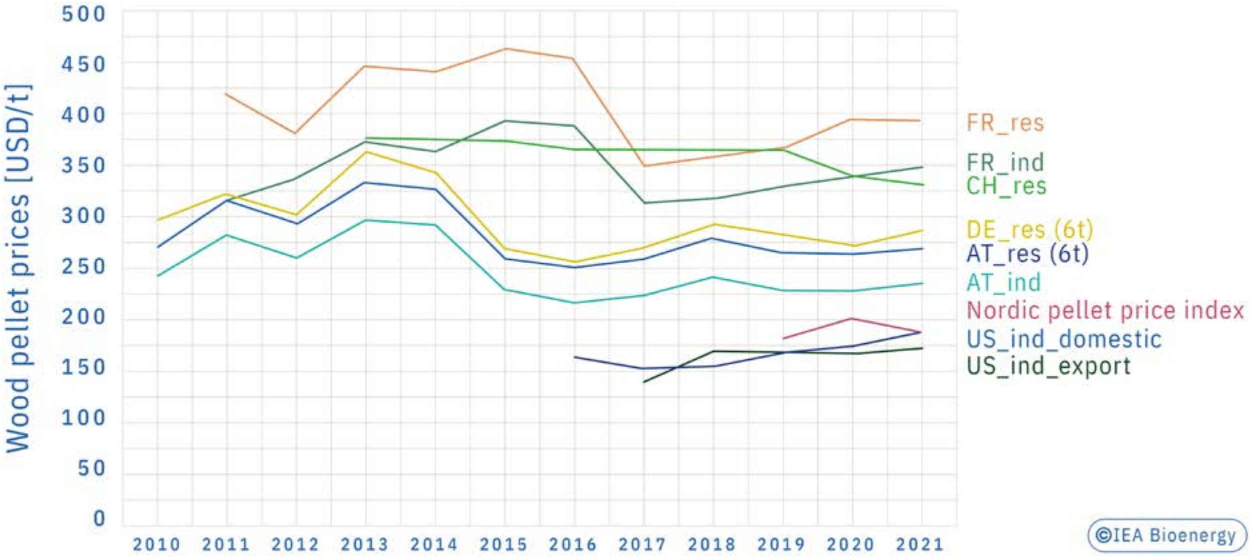
- Cultivation costs such as seed, fertiliser, irrigation water, labour and machinery time, etc. The costs depend on the biomass and the regional economic, topographical, and climatic conditions. If residues are used, cultivation costs can be disregarded.
- Costs for harvest and collection, storage, pre-processing, transportation and handling.

Harvesting, transportation, and handling costs for biomass in its different forms vary due to individual characteristics of different biomass feedstocks, quantities removed, distance to the using/storage facility, terrain, road condition, and other considerations. There is a tremendous variation in these factors within different regions. Biomass harvesting, transportation, and delivery systems must therefore be designed to meet constraints at the local level. Improvements in feedstock productivity and biomass harvesting, processing, and logistic systems could further reduce the biomass production cost. In addition, the economic efficient use of currently under-utilised biomass resources should be supported by the development of cost-efficient supply chains.

Biomass prices and markets

Whereas biomass production costs are expected to decrease due to biomass supply chain optimisation, biomass prices are expected to rise due to the following biomass market developments: i) the demand for biomass along well established value chains is increasing (e.g., demand for sawmill by-products); and ii) innovations and new technologies such as the production of biomethane and advanced biofuels are attracting new actors to enter the biomass market.

As a result, we see an increasing competition for biomass feedstock and, given that supply is limited, this is leading to rising prices. In addition, a higher demand incentivises suppliers to provide more raw materials. A simultaneous increase in raw material supply and demand can balance these effects, as prices are likely to decrease or stagnate, respectively.



Residential (res) incl. VAT and industrial (ind) excl. VAT wood pellet prices in US$/t. (Data Source: proPellets Austria, DEPI, EIA, pelletpreisCH). Prices depend on location, size of order, and competing demand. At the end of 2021 (and from 2022 onwards) price increases in line with the price trend in commodity markets can be observed

Naturally, industries strive to use the cheapest raw material possible. The competition, particularly for by-products and residues, is thus likely to increase further. Price dependencies are therefore of interest when it comes to assessing the extent of influences on the bioenergy production cost.

Biomass markets are usually interconnected through complex supply chains, and biomass prices can be quite volatile. To reduce the associated price risks, such as volatility spill-overs, there is a need for long-term supply contracts, together with stronger policy support and innovation; this will allow biomass consumption to be scaled up using innovative conversion technologies, in particular biomass resources that are currently under-utilised, such as agricultural residues.

Analysing and understanding biomass price volatility behaviour allows cost-effective supply chain management, including in the import and export trade. At the microeconomic level, biomass feedstock price volatility is relevant for the assessment of investment returns and capacities.

Although the price volatilities of woody biomass resources have increased in recent years, they are still lower than those of agricultural biomass commodities and fossil fuels. However, external shocks caused, for example, by wind storms, can quickly transmit to higher price volatilities.

Biomass market development

Increasing fossil fuel prices have made a growing number of agricultural feedstocks competitive as feedstocks for the energy market. The extra demand has resulted in a global rise in agricultural commodity prices. The demand shift from traditional agricultural commodities to agricultural residues such as straw and forest-based feedstocks for bioenergy production should, however, result in falling real prices.

There are two types of wood residue that are of particular interest as feedstock: logging residues and industrial by-products that are mainly provided by the sawmill industry. The availability of logging residues is limited by the amounts that need to stay in the forest to manage the soil nutrient balance; moreover, they are difficult to collect as they are spread across the forest; quality criteria, like ash or energy content, restrict their use in some applications. In contrast, sawdust, wood chips, and bark are sawmill by-products with no additional procurement costs.

Biomass from forest tree species can also be produced by intensive cultivation of fast-growing species (usually willow and poplar) in short rotation coppice (SRC). SCR has a shorter investment payback period. Due to intensive production, however, the presence of only one or a few genotypes and artificial regeneration, such plantations are more vulnerable to natural disturbances. Hence, higher discount rates need to be considered in economic analyses.

With respect to using “biomass waste” as feedstock, a transition from waste to valuable resource can be expected, reducing the need to pay for disposal. The efficient use of currently under-utilised biogenic by-products, residues, and wastes plays a key role in a system using bioenergy. However, the market conditions are still rather immature compared to fossil fuels. To access this particular biomass potential, efficient supply chains need to be established and regulations must be clarified, such as the management of sustainability criteria.

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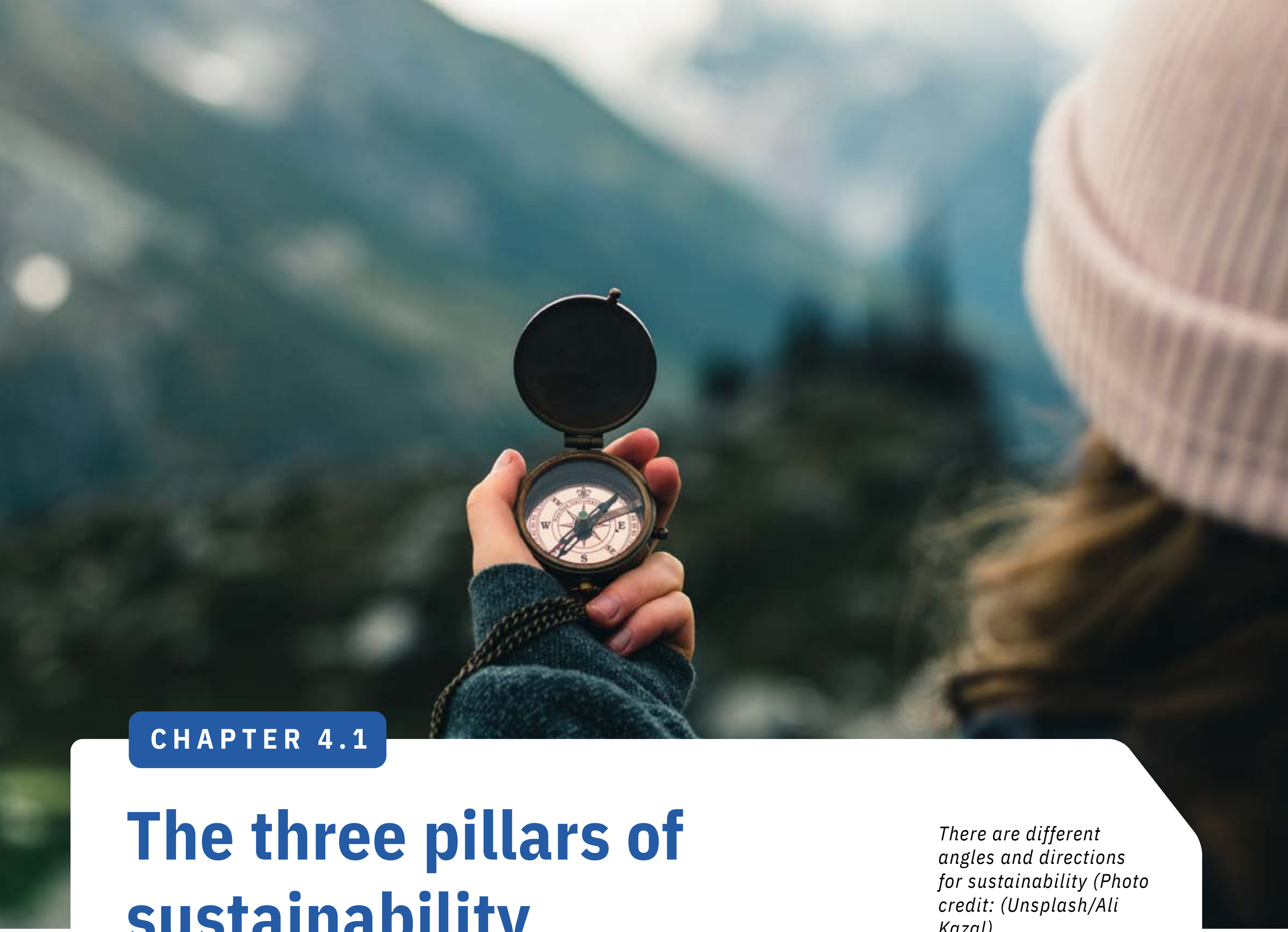
04

Social sustainability and the need for a just transition



CHAPTER 4.1

The three pillars of sustainability

There are different angles and directions for sustainability (Photo credit: (Unsplash/Ali Kazal)

Bioenergy strives to achieve an "inclusive sustainability" at the nexus of environmental, social, and economic sustainability

The original concept of sustainability was developed a long time ago. Today, the concept of sustainability—based around sustainable consumption and production—needs to be interpreted in a comprehensive and holistic manner. The term "sustainability" also needs to embody the concept of inclusiveness. While social and economic elements complement environmental sustainability in various dimensions, there are also "tipping points" which mark the ecological boundaries for human activities.

The origin of the sustainability concept

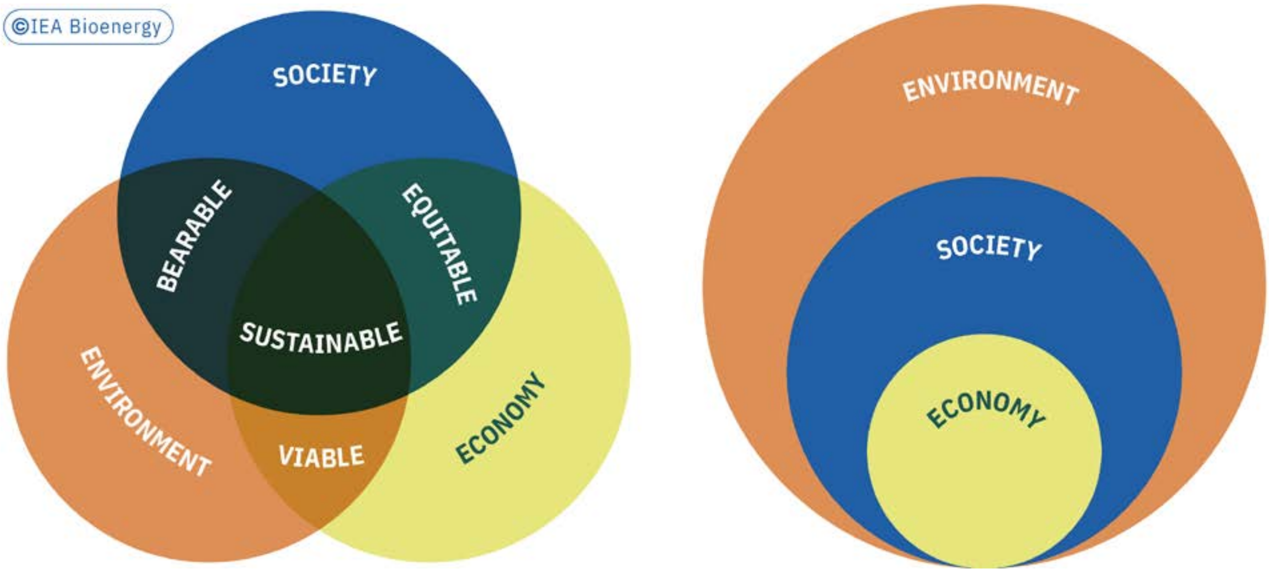
The original concept of "sustainability" comes from 17th century forestry. It means to use natural resources mindfully so that the supply never runs out, using timber resources purely for mining, construction, and heating or cooking. However, even many ancient cultures had traditions restricting the use of natural resources.

Modern definition and interpretation of sustainability

Nowadays, sustainability is a broad policy concept in the global public discourse and is thought to consist of at least three main "dimensions" or "pillars": the environmental, economic, and social dimensions. Modern concepts define it rather as a development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (see also Brundtland Report).

An overlapping concept is that of "sustainable development" where an important distinction is made between sustainability, often thought of as a long-term goal, and sustainable development which refers rather to the many processes and pathways towards achievement of sustainability. Sustainable development came to prominence through the United Nations Sustainable Development Goals (SDGs). The dominant issues that have been addressed in this context are related to environmental sustainability and include, for example, climate change, loss of biodiversity, environmental degradation, and pollution.

Complementing environmental aspects with the economic dimension and the crucial social pillar make sustainability an integrated and global concept that embraces our actions and our thinking.



Sustainability: Venn diagram (left side) opposed to the concentric circles diagram or nested approach for sustainability (right side) based on Giddings et al. (2002).

Integrated environmental, social, and economic sustainability

The integration of environmental health, social equity, and economic vitality is vital to creating thriving, healthy, diverse, and resilient communities for the present generation and those to come. Sustainability, as a concept, signifies inclusiveness, and the term is used as such by various institutions; see, for example, UCLA. Sustainability, as the concept that interconnects the environmental, social, and economic pillars and sectors, is highly complex, and any assessment of it requires a systems-based approach.

Different interpretation of the sustainability triad

One of the key observations with respect to the environmental, social, and economic sustainability pillars and how to evaluate them both singly and jointly, is that as systems grow, the number of feedback loops interconnecting different parts of the systems become particularly hard to capture and describe. In the traditional representation of these pillars as a Venn diagram, certain conditions are attained where pillars overlap. For example, if a system is optimised for sustainable societal and economic growth, equitable conditions are attained. If the conditions are optimised for the three pillars, sustainability is achieved.

It is argued that in the material reality, economic needs are nested within societal needs, which in turn must be nested within the needs of the environment, of which humans are only one component. The imbalance between the distribution of consequences clearly raises many ethical questions that need to be carefully addressed in policy design.

Limits of sustainability and the need of sustainable consumption and production

The capacity of the modern technological society to modify the environment has grown exponentially over the last century. Our capacity to restore natural systems to pristine conditions, however, remains rather limited. That limitation can be also attributed to a limited understanding of how complex natural systems behave, how they react to changes in physical, chemical, and biological conditions, and what their individual and collective tipping points or points of no return to stability are.

With humans consuming more resources than ever before, the United Nations Environment Programme (UNEP) emphasises that current patterns of development across the world are not sustainable. One of the key elements for achieving sustainable development is the transition towards Sustainable Consumption and Production (SCP). SCP is about fulfilling the needs of all while using fewer resources, including energy and water, and producing less waste and pollution.

This approach can contribute to almost all SDGs including, first and foremost, poverty alleviation and the transition to a low-carbon and green economy. This approach need to be holistic and collaboration between multiple areas and stakeholders is also required. Policies must aim not just at improving production, but also at encouraging consumers to move towards sustainable consumption choices. Thus, everyone in society has a role to play in this transition including governments, educators, the private sector, and the consumer.

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CHAPTER 4.2

The sustainable development goals shall ensure a just transition of the energy sector

Replacing traditional biomass use by modern bioenergy can improve living conditions dramatically and is key for implementing the UN 2030 Agenda (Photo credit: Shutterstock / Riccardo Mayer)

Resilient societies and the contribution of bioenergy to the SDGs

As well as its positive impact on climate change and the environment, the use of biomass can have various economic and social co-benefits, mostly in the form of cross-fertilising synergies. The bioeconomy sector is expected to play an important role in the implementation of the United Nations 2030 Agenda for Sustainable Development and for achieving its ambitious goals (SDGs). The different biomass supply chains contribute to the SDGs in a great variety of ways.

The important inter-linkages between the SDGs and the bioeconomy

The SDGs provide a normative framework for activating a sustainable world by 2030, fostering planetary peace, justice, and improved prosperity for all. A major role in the transition to sustainability is being played by the bioeconomy, including the bioenergy sector. Indeed, according to IEA Bioenergy, 15 of the 17 SDGs are directly or indirectly linked to the production and use of biomass. Given their inherent complexity and interconnected nature, the SDGs will not be achieved one by one but in an integrated manner. Sharing successful examples is one of the ways of accelerating progress.

The 17 Sustainable Development Goals. Source: UN Sustainable Development Goals

A bioeconomy-embedded bioenergy sector can achieve diversification of the energy supply and improve energy access. It can also support sustainable agricultural practices and forest management, reducing the risk of losses due to storms, insect infestations or wildfires, decreasing land and ecosystem degradation, boosting economic development in rural areas, improving waste management, and creating jobs (see also Chapter 2.4: Bioenergy as a driver for certification and conservation).

For these reasons, the wider bioeconomy, including the bioenergy sector, can play an important role globally in the implementation of the UN 2030 Agenda for Sustainable Development, and the achievement of the SDGs.

15 out of 17 SDGs are directly or indirectly **linked to biomass** and its production

The development of holistic policies that address environmental, social, and economic priorities is key to achieving sustainability. Sustainable production of biomass for bioenergy—or any other bio-based product for that matter—encompasses growth, harvest, collection, storage, transport, processing, and use, and it can also have significant environmental, socioeconomic, and health impacts for people and their communities.

Through 37 case studies from around the world, IEA Bioenergy researchers analysed how the most common biomass supply chains could be implemented to support bioenergy production while simultaneously contributing to the SDGs (see also Chapter 2.4: Bioenergy as a driver for certification and conservation).

Forest-based biomass residues and the SDGs

Insights from 10 international case studies including harvest residues such as treetops, branches, and unmerchantable stems, as well as wood processing residues such as wood chips, sawdust, and shavings:

Relevant SDGs: 3,4,6,8,9,11,12,13,15

- Biomass sourced from forests that are sustainably managed can ensure the protection of ecosystem services (e.g., water purification, soil stabilisation, biodiversity conservation).
- Biomass sourced through stand improvement techniques (e.g., thinning) can simultaneously increase growth rates, improve carbon sequestration, and reduce natural disturbances (e.g., wildfires, pests).
- Use of residues, if previously discarded as waste materials, can improve resource-use efficiency and help replace fossil-based energy generation.
- Use of biomass for bioenergy can improve energy security and resiliency, while also improving the share of renewable low-carbon energy.
- Biomass can provide new economic and job opportunities for communities and regions, as forest biomass supply chains typically require more labour than fossil fuel-based supply chains.

Residues from timber processing are a major feedstock for sustainable bioenergy production. (Photo credit: iStock / Richard Johnson)

Agriculture-based biomass residues and the SDGs

Insights from 11 case studies including biomass remaining after crops are harvested (e.g., wheat straw, rice straw, cane straw, and corn stover) and also including food- or feed-processing residues such as corn cobs, olive pits, or grape marc:

Relevant SDGs: 1,2,3,5,6,8,9,10,11,12,13,15

- Use of residues can improve resource-use efficiency, especially if sourced from waste and by-product streams of primary production, as long as enough residues are left to maintain soil health and productivity.

- Redirecting residues to bioenergy away from disposal piles and open-air burning can improve local air and water quality.
- Residues that would otherwise add to excess fuel loads can help reduce the destructive effects of pests and wildfires and support other perennial management goals.
- Use of residues for bioenergy can improve energy security and resiliency, while also improving the share of renewable energy.
- Mobilisation of residues in rural areas can support sustainable economic development and job opportunities related to perennial management and biomass collection, transportation, processing, and use.
- Removal of a portion of residues from high-yielding agricultural croplands can enable the use of no-till practices which would otherwise be impractical.

Agriculture-based energy crops and the SDGs

Insights from 12 case studies including crops purpose-grown for bioenergy production are listed below. Emerging energy crops are most often perennial and can be woody (e.g., poplar or willow) or herbaceous (e.g., switchgrass). Annual cover crops can also be used for bioenergy.

Relevant SDGs: 1,2,3,4,5,6,8,9,12,13,14,15

- Energy crops integrated into good farming practices or other land management practices such as landscape management, can improve ecosystem functioning by improving local soil and water quality, reducing and filtering agricultural run-off, reducing soil erosion, diversifying land cover, and increasing soil carbon storage.
- Energy crops can help to reclaim degraded land, restoring land and soil tilth and bringing nutrients and carbon back into soils.
- Energy crops can also provide new sources of incomes for farmers, land owners, and land managers on less productive lands; they can provide new economic and job opportunities in the community, given that growing, harvesting, transporting, and processing energy crops are frequently labour-intensive.
- Use of energy crops to improve the share of renewable energy can improve energy security and resiliency.

Biogenic waste and the SDGs

Insights from four case studies on waste of biological origin, which includes primarily animal (manure) and household, commercial, or municipal organic waste:

Relevant SDGs: 1,2,6,8,9,12

- Biogenic waste used for bioenergy can improve both resource use efficiency and waste management, while reducing methane emissions, solving waste problems, and providing value-added services such as bioenergy generation.
- Biogenic waste used for bioenergy can also create useful co-products, such as biochar or digestate that can be used in agriculture to reduce the use of synthetic fertilisers and to improve

the overall circularity of supply chains.
- Removing biogenic waste can reduce potential contamination of local/regional waterways.
- Biogenic waste used for bioenergy can not only improve energy security and resiliency of communities and regions but also improving their share of renewable low-carbon energy.

The Sustainable Development Goals strive for peace and prosperity for all people and the planet, now and into the future (Photo credit: Pexels/Mikhail Nilov)

Bioenergy-related GHG removal technologies and the SDGs

Bioenergy is currently the largest source of renewable energy globally. Demand for bioenergy is expected to increase as countries look to sustainable low-carbon energy alternatives to support their national climate change mitigation strategies. Long-term scenarios to reduce global warming include an important role for biomass and sustainable bioenergy in implementing negative carbon emission technologies. Land-based Greenhouse Gas Removal (GGR) technologies, including bioenergy, have a particularly strong and positive interaction with the environmental and social aspects of sustainability. Given its foreseeable importance, bioenergy combined with carbon capture and storage (BECCS), as well as biomass-based biochar production and use, will create further demand for biomass resources (see also Chapter 5.1).

Bioenergy combined with carbon capture and storage (BECCS) in the SDG context

In the case of BECCS, the production and use of bioenergy mainly raises issues about potential trade-offs between economic development and sustainability, as well as potential conflicts for land between energy and non-energy uses. BECCS delivers two primary functions: energy production and carbon sequestration. BECCS can be used to produce power and/or heat, refined liquids, hydrogen, and biomethane, all of which can be used in the provision of energy services. The BECCS system removes carbon from the atmosphere as plants absorb CO2 when they grow, and (part of) this carbon can be stored (i.e., not released back in the air), which reduces CO2 concentrations.

Relevant and positive contribution to SDGs, 1,2,3,6,7,8,9,11,12,13,14,15

- Biomass provision, energy production, and payments for carbon sequestration can provide additional options for local income creation for farmers and forest owners. If BECCS replaces fossil energy use, it can also reduce air pollution, as the carbon capture and storage component of the energy plant removes air pollutants as well as CO2.
- Large-scale production of biomass based on dedicated crops, and hence the potential additional fertiliser input, needs to be monitored to protect and maintain ecosystem services such as clean water and sanitation.
- Replacing fossil energy with BECCS can enhance affordable and clean energy through decreases in air pollution and CO2 concentrations and thus produce an additional positive impact on health.
- Sustainable feedstock production for BECCS both from forest and agriculture can create new income opportunities for rural land owners and the labour force, thus helping to support rural livelihoods.
- With 2.5 billion people in the world relying on agriculture and forestry for work, biomass production for BECCS can be expected to contribute to the creation of green jobs.
- If BECCS is developed carefully and sustainably, small-scale farmers and forest owners can also benefit.
- If BECCS is managed well (e.g., sustainable development of bioenergy cropping systems, sustainable and multi-purpose forest management, focus on sustainable biomass residues), negative impacts on ecosystems and their services and competition for land and food production can be avoided.

Biochar in the SDG context

Recycled agricultural and forestry biomass residues serve as feedstock for biochar—a solid product of biomass pyrolysis. Biochar has a greenhouse gas removal (GGR) potential that is similar to that of BECCS. Biochar production avoids competition for land when used in agricultural soils in the (sub)tropics due to the possible yield increases it provides. Biochar production from biomass residues also eliminates the need to set aside dedicated land for its production, thus contributing to the self-sufficiency of communities. Biomass feedstock residues for biochar can come from forests, mills, crop residue, or urban wastes.

Relevant and positive contribution to SDGs: 1,2,3,6,7,8,9,10,11,12,13,15

- Biochar brings reduced costs and dependency on external resources, together with increased crop productivity, that would help farmers be self-sufficient while increasing incomes.
- Food security will benefit from higher food crop yields and higher agroecosystem resilience.

- Biochar application to soils can increase crop yields, aid soil remediation and water purification, and thus contributes significantly to people's nutritional health.
- Biochar can adsorb soil pollutants, thus reducing leaching and thus water pollution.
- The high recalcitrance of the organic C in biochar, together with the decrease in N2O and CH4 emissions from soils amended with biochar (through mobilisation/incorporation into new plant matter biomass or microbes etc.) contribute to climate regulation.

Bioenergy systems can provide food, feed, fibre, and fuel and thus support implementation of the Sustainable Development Goals (SDGs) (Photo credit: Pexels/Kelly)

Final considerations with respect to bioenergy and the SDGs

There will always be a need for carbon in society, in the long term, too, but this must be renewable carbon, which can be provided by regenerated biomass. There are impacts and potential risks associated with biomass (including potential non-sustainable production, direct and indirect land use change, etc.). These, however, can be managed in a sensible way through sustainability governance that will ensure no net loss of carbon from the biosphere (soils, forests, vegetation) into the atmosphere.

The implementation of sustainability governance is based on the fact that bioenergy systems are commonly components in value chains or production processes that also produce other bio-based products, such as food, feed, and fibre. An assessment of the biomass value chain, and particularly its bioenergy aspects, need to be based on a holistic perspective that recognises a multitude of societal objectives and should promote options that contribute positively to the implementation of the SDGs.

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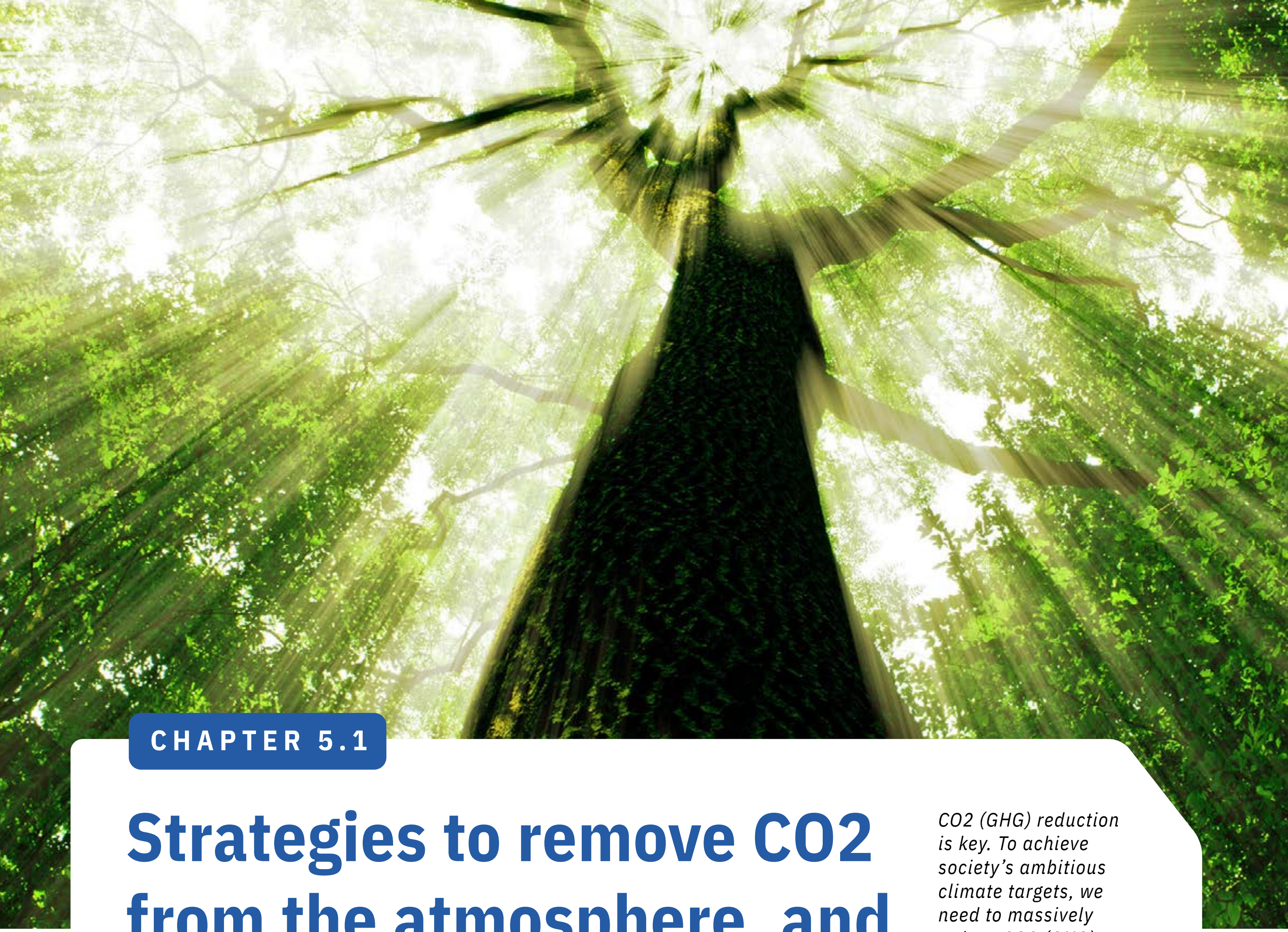
05

Reaping the multiple benefits of bioenergy



CHAPTER 5.1

Strategies to remove CO2 from the atmosphere, and their potentials

Sustainable Bioenergy and Bioenergy with Carbon Capture and Storage (BECCS) will likely be part of the technology portfolio used to reach net zero and net negative emissions

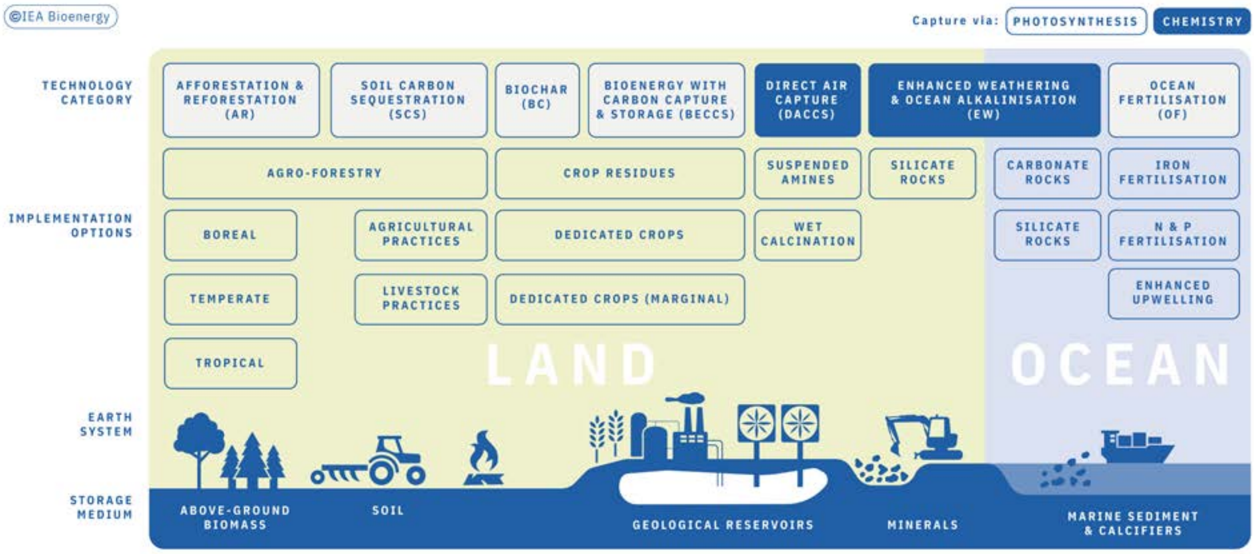
CO2 (GHG) reduction is key. To achieve society's ambitious climate targets, we need to massively reduce CO2 (GHG) emissions immediately. Bioenergy, coupled with carbon capture and sequestration (CCS), can actively remove CO2 from the atmosphere. (Photo credit: shutterstock/Vovan)

To reach ambitious climate mitigation targets, net GHG emissions need to fall to zero by the middle of the 21st century. Due to the delay in implementing mitigation measures and the persistence of GHG emissions, scientists are warning that emission reductions alone are likely to fall short of the Paris Agreement goals. Rather, we need to also ramp up CO2 removal technologies to reach net zero emissions by 2050 and from then on to create negative emissions to further reduce the CO2 concentration in the atmosphere. Bioenergy with Carbon Capture and Storage (BECCS) can play an important role in the CO2 removal technologies portfolio. BECCUS—Bioenergy with Carbon Capture, Utilisation, and/or Storage—could become an additional pathway that, although relying on similar technology, will not necessarily end up in negative emissions.

Global emission abatement

In 2015, nations at the Conference of the Parties in Paris agreed that global temperature increase should be limited to well below 2°C with efforts to limit global warming to 1.5°C. The subsequent Intergovernmental Panel on Climate Change's Special Report on 1.5°C Global Warming assessed the knowledge on 1.5°C pathways.

It concluded that the Paris targets would require CO2 emissions to fall to 25–30 GtCO2eq/yr by 2030. What nations have put on the table in terms of emission reduction pledges would still lead to emissions of 52–58 GtCO2eq/yr in 2030, that is, almost twice the amount that would allow reaching the Paris targets, and far too much to achieve any 1.5°C pathway. Subsequent updates of the Nationally Determined Contributions in 2021, however, still appear to fall short of what is needed to get on track for 1.5°C. Not only would emissions need to hit net zero by the middle of the century; they would also have to transition to net negative thereafter, pulling CO2 removals into the spotlight.



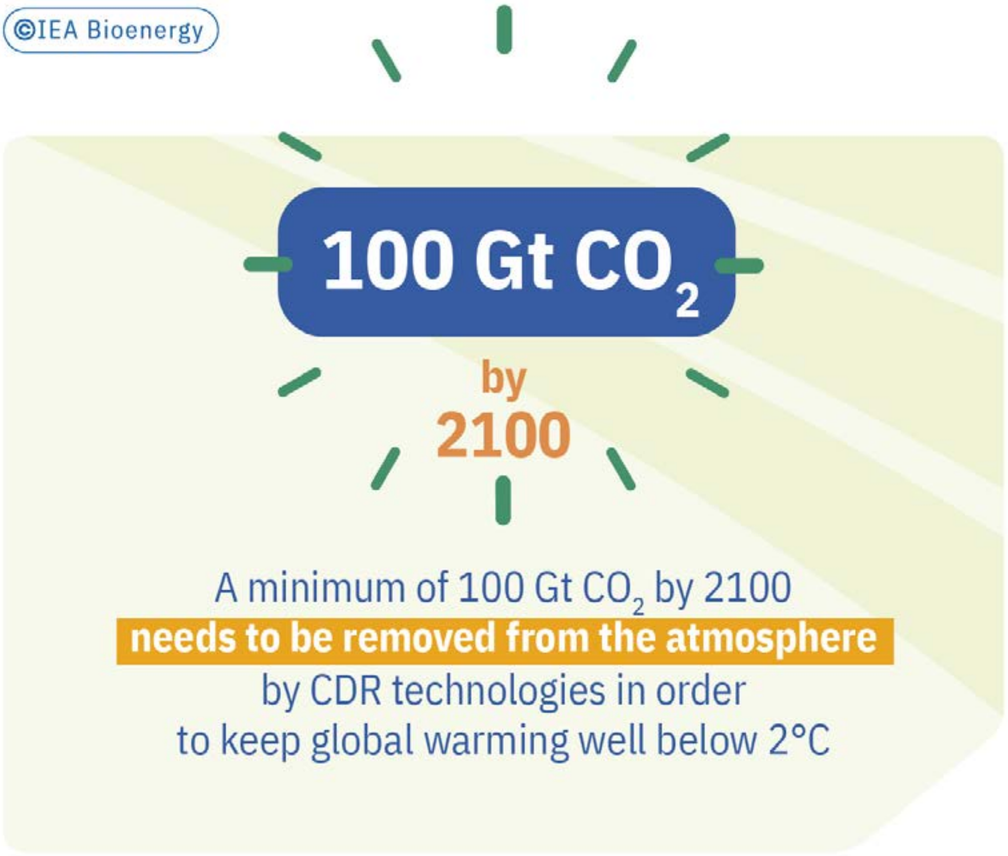
Overview of the existing CO2 removal (CDR) technologies available. These include land-based technologies using photosynthesis (e.g., Bioenergy combined with Carbon Capture and Storage (BECCS), Biochar, or Soil Carbon Sequestration); chemistry-based technologies (e.g., Direct Air Capture, and Enhanced Weathering); and those CDR techniques that can be applied to the oceans (i.e., Ocean Fertilisation)

The role of CO2 removals in emission reduction pathways

The IPCC's Fifth Assessment Report already mentioned the need to remove CO2 from the atmosphere as one of the measures required to limit global warming to 2°C. The situation has since worsened and the contribution of CO2 removals (CDR) is vital if we are to achieve ambitious climate protection targets.

Scenarios are the primary tool used to delineate pathways to reach societally agreed targets at the science–policy interface. One example of climate pathways in line with the Paris Goals is provided by IRENA. In its 1.5°C scenario, the potential for CO2 capture per annum from processes that use biomass—to which CCS could in principle be applied—is around 10 Gt per year by 2050 across multiple sectors. The 1.5°C scenario assumes that BECCS captures and stores around 4.5 Gt per year of CO2 in 2050: less than half its potential. The largest opportunities are in power, heat, chemicals, and biorefineries; but BECCS could also be significant in cement, pulp and paper, and sugar production, and possibly also iron and steel production. BECCS, however, has not been currently validated in these industrial applications, and there are significant complexities to be addressed both regarding its deployment and whether it can be ensured as a sustainable biomass supply.

It has, however, become very clear that continued delays in implementing more stringent climate change mitigation measures and a more ambitious climate target are now making it impossible to achieve the already-ambitious Paris targets without CO2 removals (CDR).



A minimum of 100 Gt CO_2 by 2100 **needs to be removed from the atmosphere** by CDR technologies in order to keep global warming well below 2°C

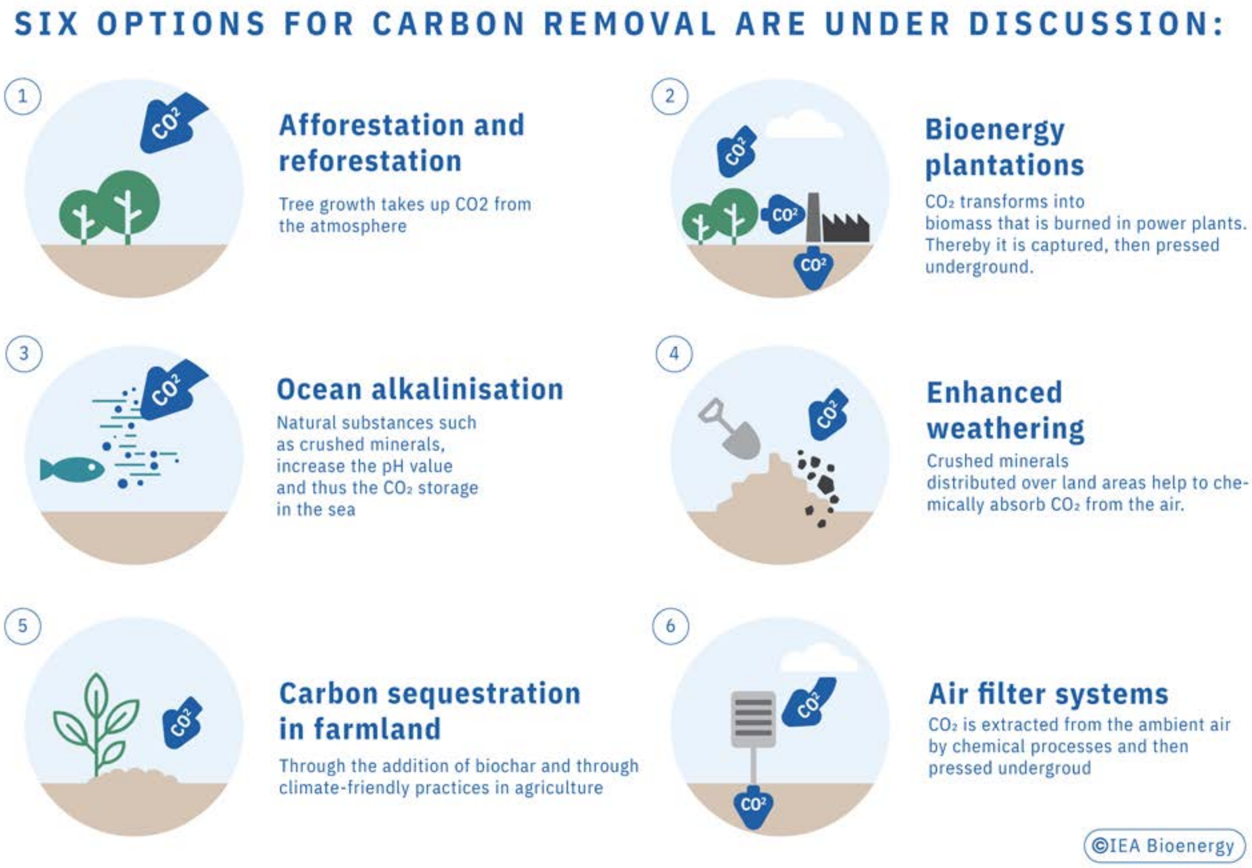
There are some scenarios that explicitly try to exploit hitherto largely untapped mitigation potentials on the demand side. One example foresees a final 2050 energy demand of 245 EJ, which is significantly below current values and also lower than comparable scenarios in the mitigation literature. For example, the scenario with the lowest energy demand in the IPCC's Fifth Assessment Report featured 274 EJ in 2050. Such a low energy demand scenario is thus unprecedented in the scenario literature, but, as the authors point out, it is not inconsistent with historical dynamics. As a result, such low energy demand scenarios manage to stay on a 1.5°C pathways without relying on Carbon Capture and Storage (CCS) and BECCS (bioenergy with CCS) for that matter.

Bioenergy with Carbon Capture and Storage (BECCS) can play an important role in the CO2 removal technologies portfolio

Other studies have introduced a combination of otherwise less considered measures such as lifestyle changes, agricultural intensification, factory-cultivated meat, and lower population. The need for carbon dioxide removal (CDR) thus depends on how fast emissions are reduced in the coming decades; lifting higher mitigation potentials on the demand side can help to reduce that dependence to some extent. However, even those scenarios still need to remove about 100 Gt CO2 by 2100. Further delays in scaling CDR will mean jeopardising our ability to remove sufficient CO2 to maintain 1.5°C global warming.

Strategies to remove CO2 and their potential

There are a number of ways to remove CO2 from the atmosphere. Those most prominently discussed rely on not allowing the emissions previously sequestered in biomass to escape to the atmosphere. In BECCS, systems energy is produced from biomass, and a substantial part of the emitted CO2 is captured and stored underground. The prevalence of BECCS in climate change mitigation pathways has come up against a wide range of sustainability concerns. Most of this criticism is related to the question of the resulting land use change in the face of double-digit Gt removals and, indeed, the bottom-up literature conveys lower removal potentials compared to what some assume them to be. Yet, a number of techniques can be used to remove CO2 (and also other GHGs) from the atmosphere on a net basis. Clearly, all of them come with advantages and trade-offs.



There are six CDR techniques currently in discussion—from afforestation and reforestation to bioenergy with carbon capture and storage, or air filter systems. Source: © Mercator Research Institute on Global Commons and Climate Change (MCC) https://doi.org/10.1016/j.oneear.2020.08.002

BECCUS as an upcoming opportunity

Bioenergy combined with carbon capture and utilisation or storage, also known as bio-CCUS or BECCUS, is a concept that has been discussed in climate change mitigation research for quite some time. Only in the last five years, however, has the implementation of these technologies become the subject of serious consideration within governments and among private actors. The reasons for this are largely related to three factors: i) an emerging awareness of the need for BECCS and other negative emissions technologies if there is to be any chance of reaching for the Paris 1.5°C target; ii) rising CO2 prices; and iii) the rapidly decreasing costs of electricity generation from solar and wind (and expectations of similar developments for electrolysers) that have made BECCUS options based on power-to-X technologies more cost-effective.

In the light of this, identifying and implementing approaches to deploying and integrating BECCUS systems in ways that maximise benefits in terms of climate change mitigation—as well as in terms of energy system integration and sustainability ambitions more broadly—is extremely important.

Hence, several IEA Bioenergy Tasks (40, mainly with 36, 44, and 45) worked jointly from 2019 to 2021 on a project on the deployment of BECCUS value chains. The project focused on understanding the opportunities for, and obstacles to, deployment of BECCUS in different sectors. The aim was to try to cut across the full set of factors that determine successful deployment, from technology readiness, to business model viability, to design of policy and regulatory frameworks. Although some of the work is still in progress, results indicate that much of the technology required can, to a large extent, be considered proven.

More research and development are still required, however, to identify models of on-the-ground deployment that make the most sense from the techno-economic and climate perspectives. This includes aspects such as specific designs, deployment scales, and choice of site locations. There are also many questions remaining regarding process and supply chain integration as well as policy design and implementation. Answers to the above questions can assist in addressing the key and most complex questions, namely: in a given situation should biogenic CO2 be sequestered or utilised? What type of facilities (i.e., bioenergy installations) would best provide BECCS and/or BECCUS under certain criteria (economics, CO2 emissions mitigation potential etc.)? How can the different energy system services be governed when a high level of CO2 emissions mitigation is being targeted? And related to this, what factors and parameters should guide this decision-making process?

A follow-up inter-task project starting in 2022 plans to cover a range of topics to illuminate aspects of these questions and thereby assist policy- and decision makers working within this sector.

The urgency of acting and scaling up CDR technologies to create negative emissions

The utilisation and recycling of biogenic/renewable carbon will not create the negative emissions necessary to substantially reduce the atmospheric carbon concentration, unless the carbon that is utilised is finally captured again and stored. There is thus an urgent need for a societal discourse on the extent to which GHG emissions can be further reduced in the short to medium term, on what that “extent” implies for the amount of removals needed to offset those residual emissions (assuming a priority for removals to address residual emissions and not for large-scale temperature overshoot), and on a portfolio of removal options that not only fulfil certain sustainability criteria but are also socially acceptable.

The need for carbon dioxide removal (CDR) technologies depends on how fast CO2 emissions are reduced in the coming decades; lifting higher mitigation potentials on the demand side can help to reduce that dependence to some extent

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CHAPTER 5.2

Synergies between energy, material, and food and feed services from biomass

Energy, materials and nutrients from biomass are provided within a cooperative set-up (Photo credit: Wesley T Allen)

Sustainable bioenergy facilitates resource efficiency in a circular bioeconomy

Of late, the debate on bioenergy has often focused on the competition between energy and material or energy and food use. Cooperation and the finding of synergies, however, will need to take priority, especially in a world of limited resources. Taking a bird's-eye view of the different biomass utilisation options reveals how sustainable bioenergy—and other bio-based services—intertwine to provide benefits beyond just bioenergy and bio-based production per se.

Limited resources demand energy and material efficiency

Common sense, backed by scientific evidence, makes it obvious that our resources on planet Earth are limited. We will have to make most out of what we have, be able to reorganise not only the energy system but also the broader economy. The biosphere can still provide us with an undetermined diversity of solutions, if biomass is sustainably sourced and deployed according to ever-improving energy- and material-efficiency standards.

For the sake of resource efficiency, using, for example, high quality stem wood from sustainably managed forests for constructing building and furniture with a lifetime of several decades results in higher efficiency than producing consumables, such as recyclable paper or cardboard. The resource efficiency of material products is of higher importance than direct combustion for combined heat and power generation. Food crops from agriculture contribute more to society when consumed by humans than when converted to energy. There is, however, more to resource efficiency, as outlined in the following:

Stop landfilling biodegradable waste

Traditionally, the linear flow style of our current economy reflects a throwaway society and industry. Investments in efficiency have historically focused primarily on improving the input–output ratio of a main product, even though this might involve producing considerable amounts of waste. Reduction, reuse, and recycling of major products have, to date, been less of a priority. Some countries have acted on stemming the immense GHG emissions caused by landfilling biodegradable wastes; the uncontrollable release of methane from landfills (given that methane's GHG warming potential is about 30 times more potent than that of CO2), fuels global warming and directly endangers communities living nearby. This landfilling of biodegradable waste, a highly material- and energy-inefficient practice, is often banned, particularly in Europe.

Meanwhile, anaerobic digestion of the more moist bio-waste and incineration of the drier fractions are widespread waste-treatment solutions, contributing simultaneously to the reduction of fossil fuels and power and/or heat provision, for example, in district heating, and also increasingly in the gas-grid. Even more important, industries have begun recognising the energy content of their residues as an economic added value: in Europe, for example, 83% of wood pellets used mainly for residential heating and combined heat and power are produced from sawdust, a saw-mill residue, while the rest comes mainly from wood reclaimed after material use.

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83% of wood pellets produced in the EU **come from sawmill residues,** generating profits that are additional to those from the material utilisation of wood as a main product

Future products should be bio-based instead of fossil-based

In the next decades, more and more products will be bio-based. On the one hand, the broad product portfolio of fossil-based refineries including not only plastics, but also lubricants, solvents, fine chemicals and bitumen, will need to be replaced by bio-based counterparts. On the other, engineered wood products, carbon fibres, bio-based composites, and bioactive materials will extend our possibilities. The success of these emerging bio-based sectors will largely depend on how well biorefineries can handle different biomass resources and their residual fractions throughout the different process steps. Moreover, binding global treaties against plastic pollution (see UNEA 5.2) and other measures aiming to close circularity gaps will boost the significance of bio-based materials.

We define a “sustainable biorefinery” as the processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat), using a wide variety of conversion technologies in an integrated manner. Today, we are already able to convert a high variety of feedstocks from forestry, agriculture, and landscape management through a portfolio of technologies to platform feedstocks such as starch/sugar, vegetable oil, pyrolysis oil, lignin, and syngas and finally into all the types of chemicals and products currently needed. There is still, however, a wide range of biomass residues that cannot be collected and processed or recycled cost-economically today; this includes harvested algae from eutrophicated water bodies, post-consumer wood contaminated with paints or nails, and novel bio-based composite plastic products.

Look for the economic and environmental benefits of synergies

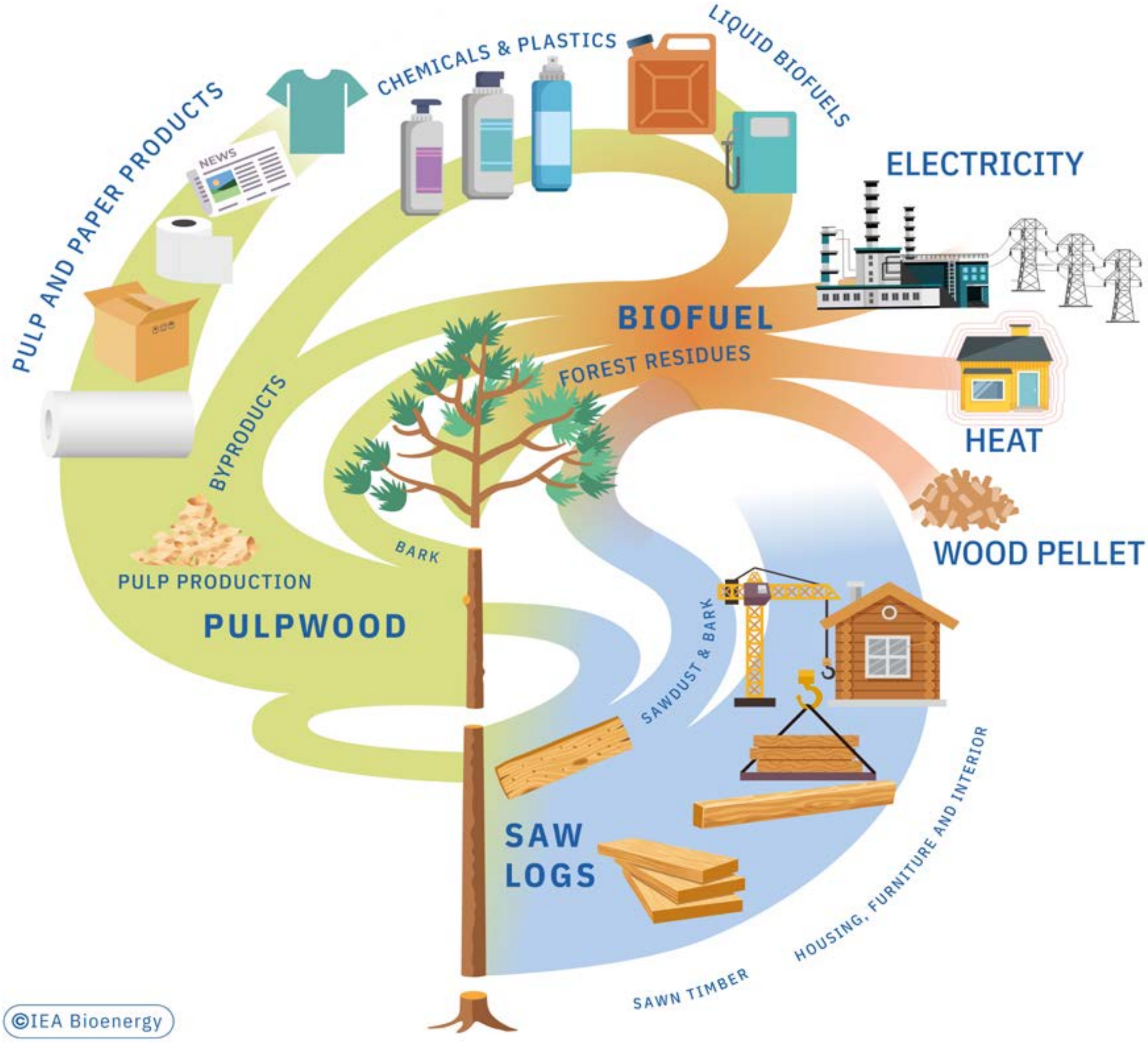
Synergies between bioenergy and other bio-based products include improved economic and environmental performances either via on-site co-production in biorefineries or in different sites and/or firms via entangled biomass supply networks. For example, sawmills processing stemwood to provide construction would create residues such as bark, wood chips, and sawdust. Using these residues for energy improves the economic and environmental performance of the sawmill. Similarly, food processing industries, including olive oil production, dairy, meat, and many others, produce considerable streams of biomass residues. Food processing residues can be converted to energy and in some cases biochemicals, improving the overall efficiency of the industry.

> **Having readily deployable energy valorisation options at hand for the end use of material products will most likely increase in importance when we expand existing and upcoming bio-based sectors.**

Our capability of converting biomass residues into non-energy products increases every day. Novel bioeconomy sectors, however, do not result in feedstock competition for bioenergy. Rather, and by way of example, the expected expansion in the production of bio-based insulation materials for building renovation will create considerable streams of new processing residues and post-consumer biomass. Cascadic use (cascadic principles) of biomass in a bioeconomy, together with landfilling restrictions, will create a broad feedstock base for bioenergy.

Other interesting challenges still remain; most technologies today rely on high quantities of biomass input of homogenous quality to leverage scaling effects. Pre-treating biomass to increase its homogeneity and commoditisation will improve its tradability. On the other hand, biorefineries may become more flexible, and allow for seasonal- and weather-dependent variations. Smaller-scale biorefineries are also being discussed as a means of producing required energy and materials at a community level (biorefinery communities).

When designing business models, the challenges involved in choosing the correct functional units and system boundaries in these non-linear business cases must be embraced so that the economic and environmental benefits are allocated correctly. Entrepreneurs should thus acknowledge the importance of tactical and strategic planning based on Life Cycle Analysis (LCA) and other science-based tools, such as Geographic Information System– (GIS-) based supply chain models.



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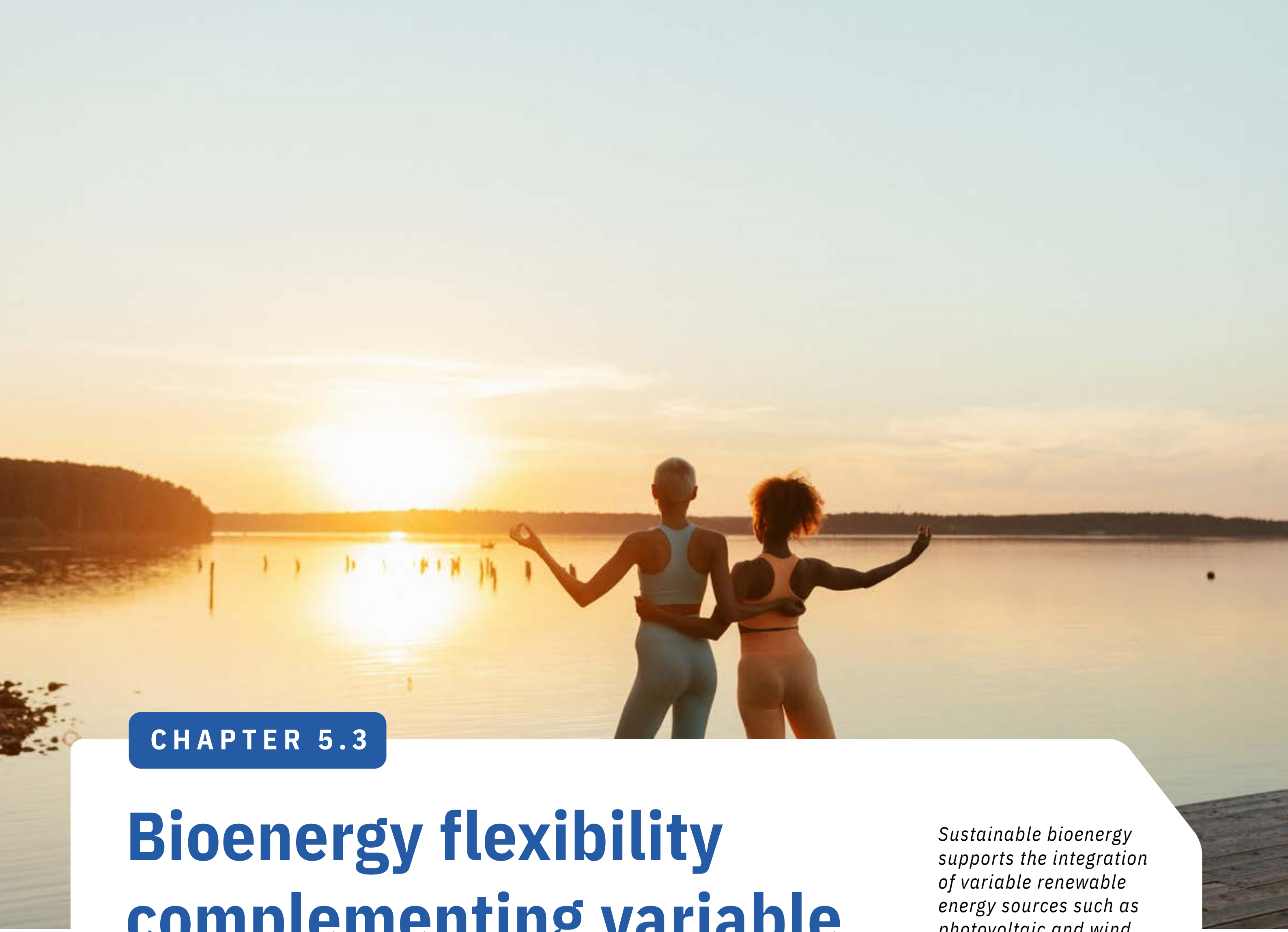

CHAPTER 5.3

Bioenergy flexibility complementing variable renewable energies (VREs)

Sustainable bioenergy supports the integration of variable renewable energy sources such as photovoltaic and wind energy (Photo credit: pexels/Yaroslav Shurae)

The current and coming decades will be characterised by an impressive expansion of PV and wind power. Flexible bioenergy will be one of the decisive options for solving the dynamic puzzle of energy supply and demand

Renewable electricity production based on PV and wind has become significantly cheaper and more efficient over the last decades. We cannot, however, always rely on the sun to shine or the wind to blow when we turn on the washing machine. Fluctuations occur not only on a day-to-day basis, but are also seasonal, for example, there is low solar energy in winter periods. Flexibility services from bioenergy offer a diverse set of solutions for the dynamic puzzle of energy supply and demand. The higher the shares of PV and wind become, the greater the need for flexibility services, for example, from bioenergy.

We need to phase out fossil fuels

The current decades will be characterised by an impressive expansion of photovoltaic (PV) and wind energy. This development will be decisive for phasing out production of electricity from fossil fuels. It will also help provide power for a growing Internet and Communications Technology (ICT) sector and for coupling the power sector with the heating (heat pumps) and transport (electric vehicles) sectors.

The power output of PV and wind installations is generated through input from solar radiation and wind. This is why it varies not only between summer and winter but also between day and night and strongly depends on the weather conditions. Moreover, power consumption patterns for heating, cooking, washing machines, electric vehicle (EV) charging, servers, and industry do not necessarily match these production patterns and often differ significantly.

Flexibility is needed to enable higher PV and wind shares

While the shares of these Variable Renewable Energy sources (VREs) are rather small today, a successful power system diffusion will rely heavily on how well we manage to match and balance the energy supply and demand at all times and for each application. Flexibility has traditionally been provided by large-scale and centralised coal plants and combined cycle gas turbine (CCGT) plants or hydro-power in some countries. Large shares of baseload power supply from nuclear and fossil fuels to date have required only very few flexibility interventions, mainly to cover some peak demand times each year or to ensure power quality.

Increasing periods of power over-supply and difficult-to-meet demand can be expected over the coming decades. Electricity prices will spread, which in turn will create market opportunities for novel and sustainable flexibility services, including battery storage, electric vehicle demand response, and also bioenergy.

The coupling of the power sector to heat and transport might cover short- to medium-term flexibility needs, if implementation of demand-side management is well adjusted to PV and wind expansion. Synthetic fuels from excess renewable electricity in combination with CO2 from biogas, as well as biomass gasification and combustion, can bring some relief in times of seasonal fluctuations. However, high synthetic fuel reliance comes with crucial risks regarding actual emission reductions, costs, supply security, and lock-in of fossil-fuel dependency.

> **Flexibility services are crucial for achieving high shares of PV- and wind-power integration into the energy system, with an important role for bioenergy.**

In comparison to synthetic fuels, demand-side management, and sector coupling, bioenergy can provide long-term flexibility—and not only to the power grid. Intermediary bioenergy carriers such as wood pellets, chips, or bioliquids can be stored and flexibly converted into heat and power. In this way, bioenergy can complement, for example, heat from heat pumps or solar heat, especially in the winter months. Carbon dioxide from combustion or product gases from gasification or anaerobic digestion can be upgraded with hydrogen from variable renewable energy over-supply to biomethane, which can be transported and stored in the gas-grid.

Flexible bioenergy, in theory and in practice

The variety of bioenergy options supporting VRE integration extends over the entire biomass supply chain: “Feedstock flexibility” allows feedstocks to be switched depending on seasonal availability and quality, “Bioenergy carrier flexibility” addresses the possibility of storing energy in the form of biomass over longer periods to induce seasonal flexibility, and of trading it between regions, hence providing spatial flexibility; “Operational flexibility”, is achieved when varying loads of power or heat are provided on purpose to match demand patterns. “Product flexibility” addresses flexible switching between power-, heat-, and chemical-based production.

If one looks at the full catalogue, it is obvious that many technologies and their respective infrastructures are already in place or exhibit high readiness. Moreover, and in relation to other flexibility services, their importance for providing longer-term, seasonal flexibility is a unique feature. Finally, the possibilities for providing flexibility beyond energy, for negative emissions, and for the utilisation of carbon and materials are exceptional. Those flexible bioenergy services also include synergies with hydrogen production based on VREs. Anaerobic digestion and biogas upgrading to biomethane co-produce particularly clean bio-based CO2 streams, which can and should be used to convert hydrogen into an easily tradable and storable energy carrier.

Flexible bioenergy options can significantly reduce GHG emissions from the energy system. In practice, however, sustainable flexibility services and remuneration for them are not yet widespread. Even more so, the implementation of flexible bioenergy is in its infancy, even in pioneer economies—for example, Germany with a flexibility premium for additional biogas storage capacities and Italy with a pilot program for Mixed Qualified Virtual Units programme for virtual agglomeration of bio- (and other) power production. Further market instruments and, in general, a better understanding of how to account for the added value of flexibility must still be developed.

A joint energy system, common challenges

Bioenergy flexibility can complement the system integration of high Variable Renewable Energy sources (VREs). However, dedicated frameworks are required, including market mechanisms and a deeper understanding of the benefits of flexibility. Respective technical, organisational, and social innovations have to be developed to allow for businesses to make economic profits from overall systemic benefits. Meanwhile, first projects will demonstrate the added value of flexible bioenergy on a business level, and their success stories need to be monitored, disseminated, and multiplied. On a systemic level, energy and economic modelling must outline its societal welfare potential.

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CHAPTER 5.4

High-temperature industrial heat

Bioenergy can provide high-temperature heat for industry (Photo credit: istockphoto/Nostal6ie)

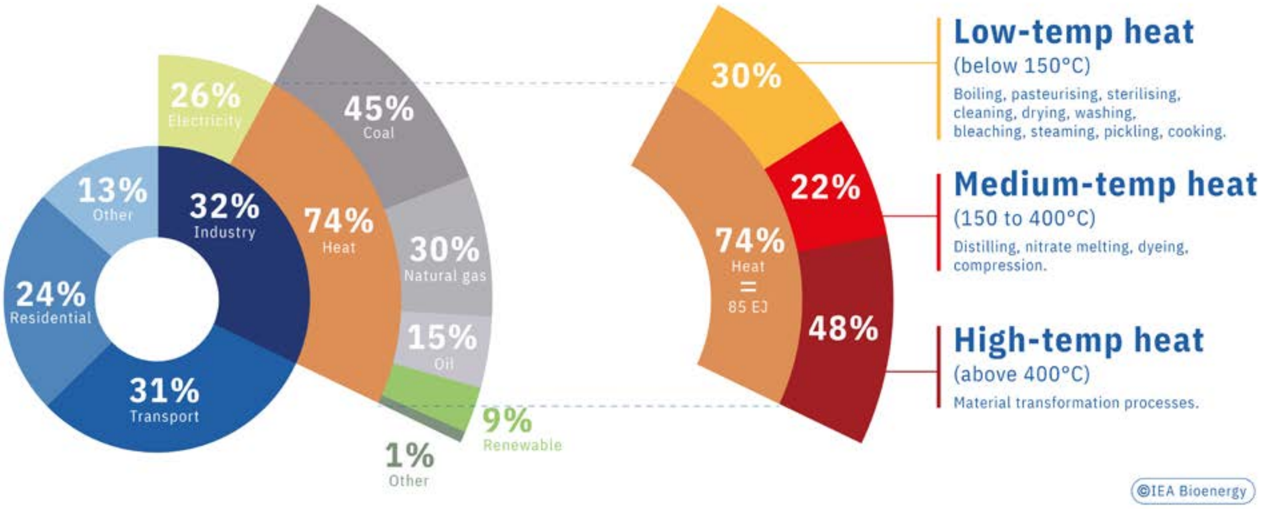
Sustainable heat sources, particularly when high temperatures are required, are dwindling. Bioenergy technologies cover the full temperature range required in industry

Heat is by far the most important form of energy used in industry. The temperatures required by industrial processes are often far beyond 100°C which is the common upper temperature/heating range/limit in residential and commercial applications. Bioenergy technologies are capable of providing heat at a wide range of temperatures via different heat-transfer fluids, which makes bioenergy stand out among other sources of renewable heat. In 2020, the majority (86%) of renewable heat consumed in industry came from bioenergy, equalling 9.4% of the industrial heat demand.

The replacement of fossil fuels from the industry sector is one of the major challenges the world is facing on its energy transformation path. The energy demand in industrial processes is dominated by high temperature heat applications where fossil fuels have particular advantages and electrification is often difficult. Bioenergy solutions are available to take over a relevant share of this demand. According to the IEA Net Zero by 2050 scenario, the use of biomass to produce heat in industry needs to double from 10EJ in 2020 to 20EJ in 2050.

Traditionally, the application of bioenergy in industry is performed in biomass processing industries that use their own residues to cover their own energy demand, for example, in food processing, wood processing, pulp and paper production, etc. With the increasing motivation in industry to reduce net GHG emissions, several other industry sectors are also shifting towards biomass-based heat generation in cases where suitable biomass resources and technologies are available.

While it is evident that the huge demand to replace fossil fuels in large and energy-intensive industries (steel, cement, etc.) cannot be fully covered by biomass fuels, there is a high potential for full-conversion applications in small- and medium-sized industries such as food, wood, or paper industries. In contrast to the larger energy-intensive industries where these cases typically require large volumes of biomass to be shipped to an individual site, the heat demand in these smaller industries can often be better matched with the biomass resources that may be locally available, resulting in smaller transportation distances. At the same time, the often-continuous operation of these industries and the scale of operation effectively match those of several bioenergy technologies available today.



Almost three-quarters of the energy demand of industry is used for heat. Of this, 70% is in the medium- or high-temperature range above 150°C in which many proven bioenergy solutions are available.

Five case studies on the use of bioenergy to supply process heat in industry were recently prepared by the IEA Bioenergy TCP. These cases were selected to illustrate the wide application range of bioenergy conversion technologies and the optimum configuration, depending on local availability of biomass resources, characteristics of the heat demand, availability of space, capital, etc.

Combustion of wood chips and composting residues for process steam generation in a potato processing industry

The first case study deals with process steam generation. Since 2015, the waste-processing company Attero has been operating a biomass-fired boiler that generates process steam for PEKA KROEF BV, a potato processing company near the village of Odiliapeel in the southern Netherlands.

The 10 MW biomass boiler uses very low-grade wood chips and composting residues to produce

10 tonnes per hour of saturated process steam (18 bar) for PEKA Kroef. The steam is used to convert fresh potatoes to various peeled, cut, and precooked potato products, which are then delivered to supermarkets around Europe. The biomass fuel displaces over 8 million m3 of natural gas annually.

Gasification of paper rejects to displace natural gas usage in a pulp and paper process

The case study on replacing natural gas with a paper reject gasifier is a good example of how industrial processes can be converted from fossil-based operation to partly bio-based operating processes. The Eska gasifier successfully managed to reduce natural gas usage and associated GHG emissions. The total waste produced for the site was also reduced, with waste being successfully turned into value.

For businesses using a large amount of natural gas to produce high temperature heat, this example shows how operations can be successfully managed when a switch to bio-based operations is made. It also shows that, overall, their emission profile has improved, which improves the marketability of their products.

Process steam in a dairy factory via fast pyrolysis bio-oil

This case study concerns the use of fast pyrolysis oil produced by Empyro in the industrial size steam boiler of FrieslandCampina (FC). A new natural gas fired boiler was designed and constructed to co-fire pyrolysis oil. In the boiler, process steam is produced (40 t/hr at 20 bar) for the milk powder drying process. The boiler normally operates with 70% of pyrolysis oil and 30% natural gas (heating value basis), but 100% back-up of natural gas is always available to guarantee a continuous steam supply to the core processes of FrieslandCampina. The Fast Pyrolysis Bio Oil (FPBO) is transported from Empyro (Hengelo) to FrieslandCampina (Borculo) by tank truck, a distance of about 30 km. A small on-site storage facility of about 100 m3 is available. The boiler was commissioned in late 2015 and until summer 2020 the use of FPBO has saved the company about 30 million m3 of natural gas and reduced their CO2 emissions by 60,000 metric tonnes.

Waste-to-energy for production of steam for paper production

To reduce its dependence on oil and fossil-based electric power, Nordic Paper decided to start their own energy production using municipal waste as fuel. The reason was mainly economic at a time of volatility in energy prices around 2005–2008. For this reason, Åmotfors Energi was founded with the main purpose of providing the paper mill, owned by Nordic Paper, with steam. The steam is used in the drying of the wet paper as the last step in the process. After a thorough investigation and feasibility study, the best alternative identified was to build a custom-made combined heat and power waste-to-energy plant.

Combustion of wood chips and grain residues for process heat supply in the largest bakery in Switzerland

The fifth case study deals with process heat supply in a bakery. The Coop Group is Switzerland's largest retail company and Europe's second largest wholesaler. Its production and distribution centre in Schafisheim incorporates a high-bay freezer warehouse and Switzerland's largest bakery and confectioner with an annual production of 60,000 tonnes of baked goods. As a substitute for fossil fuels, a biomass combustion plant was built to produce energy process heat for the bakery using thermal oil. As the production of the raw materials for the bakery causes residues in the upstream milling process, the idea of using milling residues as energy for the bakery came up. To ensure the bakery operated flexibly, a concept was used which enables a variable energy production using 50% wood chips and 50% grain residues with the option of switching to 100% wood chips. Consequently, a combustion system was designed that enables the use of forestry wood chips from one silo to be mixed with pellets made from grain residues from a separate storage. The thermal oil boiler and the flue gas cleaning were adapted to comply with the challenges of the biomass fuel mix. To cover the rapid load changes of the bakery process, a gas-fired peak boiler complements the heat supply.

Policy synthesis report

A recently published policy synthesis report provides strategic information on market opportunities/potential and effective ways of addressing technical and non-technical barriers to implementing bioenergy-based process heat. The report builds on the lessons learned in the above cases, while providing a more generic analysis of the market potential and how its implementation can be supported, so as to unlock the enormous potential already mentioned above:

Understanding of the opportunities inherent in biomass-based approaches to providing industrial process requires a thorough analysis not only of the technological demands of the process itself, but also of local feedstock availability and how appropriate fuel logistics systems can be set up. Close collaboration between different supply chain actors and the establishment of long fuel supply contracts can often be key to providing the certainty needed to reduce investor risk. However, there are also key roles for policymakers in helping to fund not only R&D but also close-to-commercial demonstration facilities, as well as in creating demand, for example, through public procurement guidelines that incentivise low emission supply chains.

This policy report highlights the opportunities for bioenergy technologies to deliver heat in industry and compares it with alternatives for decarbonisation such as CCS, electrification, and hydrogen. Specific policy recommendations are provided to accelerate their adoption.

All reports produced during the Inter-Task-Project on bioenergy for high temperature heat in industry are available on the project website: itp-hightemperatureheat.ieabioenergy.com.

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International shipping is responsible for transporting more than 80% of goods worldwide (Photo credit: Unsplash/ Ian Taylor)

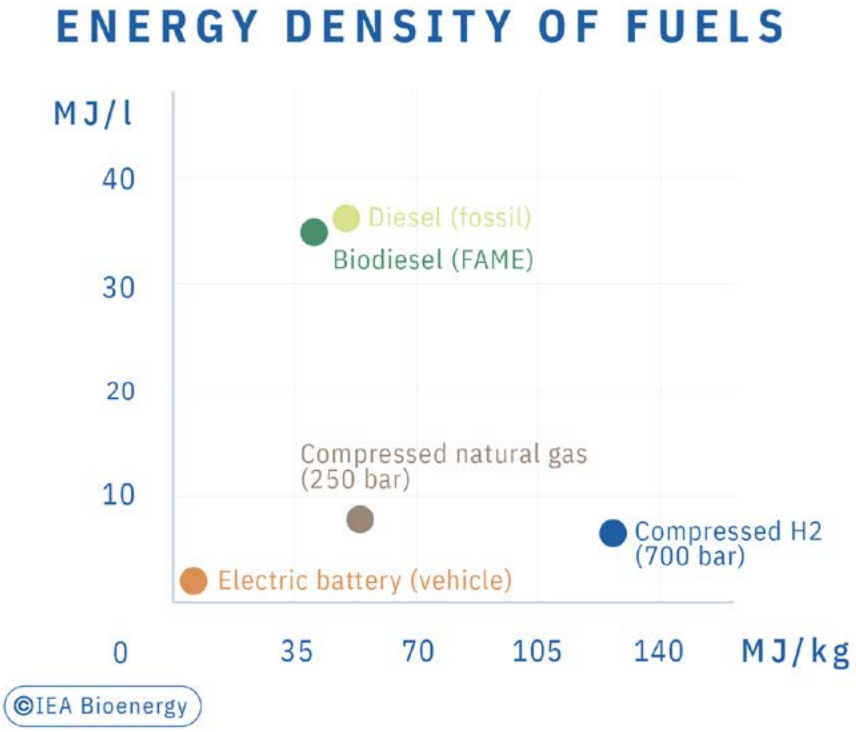
CHAPTER 5.5

Biofuels and long-distance transport—a perfect match

Not all transport services can easily be electrified

As long-distance transport in large vehicles, airplanes, or ships with high power requirements needs to be fuelled by energy carriers with high energy density, it will continue to rely on liquid and gaseous hydrocarbons. Liquid and gaseous biofuels, produced from biomass, can provide low carbon intensity energy in the form required. In the long run, markets for biofuels will shift from road transport to maritime transport and aviation

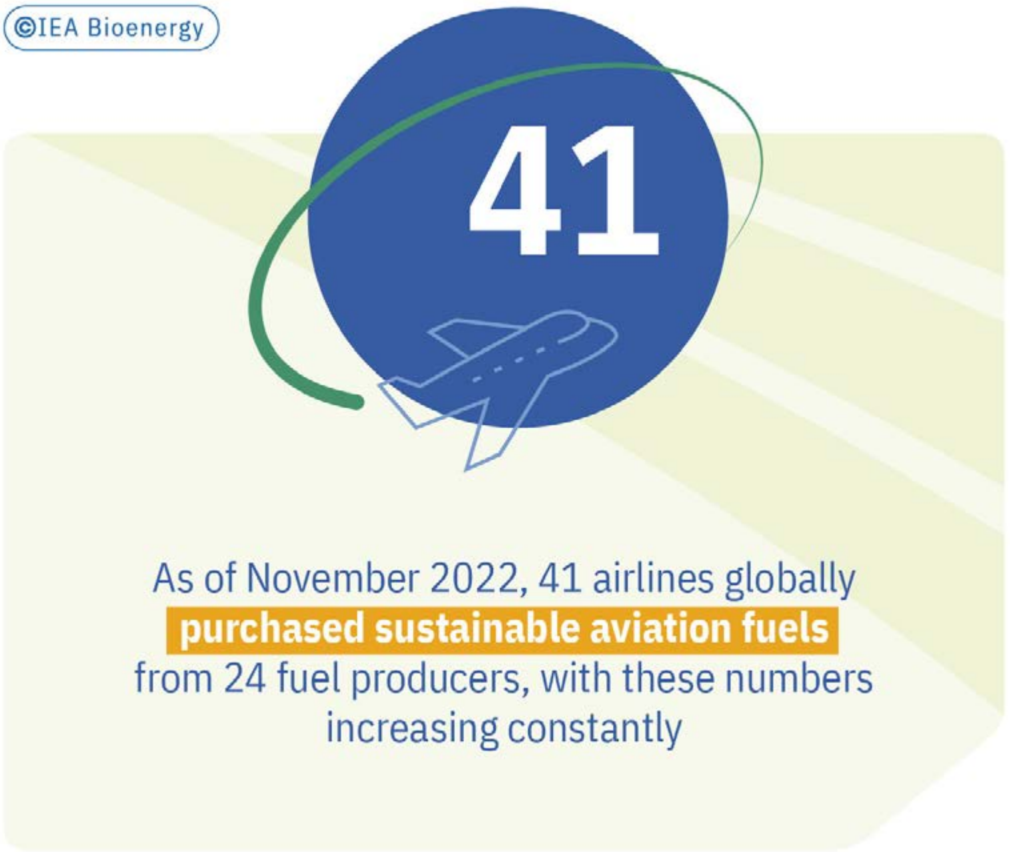
Biofuels have a specific role to play in long distance, heavy-duty transport. Carrying a battery of sufficient size to power ocean-going vessels, or storing hydrogen in sufficient amounts to provide the energy required for intercontinental flights is not imaginable today. Instead, the maritime, aviation, and long-haul trucking sectors are investigating the application of biofuels and other low carbon intensity fuels to fuel their large vehicles and vessels. Liquid biofuels have a volumetric and gravimetric energy density comparable to current liquid fossil fuels and can easily be stored on board; gaseous biofuels (biomethane) are either compressed or liquified to achieve higher energy density. When battery electric cars overtake combustion engines in the next decades, the focus area for biofuel applications will shift from road transport to aviation and shipping.



In its “Net Zero by 2050” Roadmap, the IEA outlines a future energy provision scenario that reaches net zero CO2 emissions in 2050 while ensuring affordable energy access to all. In this scenario, biofuels provide 16% of transport energy demand. The role of biofuels as an energy carrier in shipping and aviation is expected to increase from just over 0% share in 2020 to 21% and 45% in 2050, respectively. In both sectors, biofuels are expected to contribute as much as hydrogen or hydrogen-based fuels, underlining the importance of biofuels in helping to decarbonise transport. It should be noted, though, that the underlying assumptions on the speed of deployment of alternative fuel and powertrain options are challenging and that actual deployment will critically depend on policy measures to support R&D and create markets.

Aviation

The most popular long-distance people transport sector is the aviation sector. While only a small percentage of the world’s population has already been on an airplane, those that do fly tend to fly frequently, both for business and for leisure. The sector is predicted to steadily increase in terms of annual passenger-kilometres, yet has committed itself to carbon-neutral growth from 2019 onwards and to achieving net zero emissions by 2050.



As of November 2022, 41 airlines globally **purchased sustainable aviation fuels** from 24 fuel producers, with these numbers increasing constantly

Check here for most recent information.

The report "Decarbonising Air Transport" by the International Transport Forum (ITF) finds that alternative aircraft propulsion systems such as hybrid-electric aircrafts, all-electric aircrafts, and hydrogen-powered aircrafts are at low-to-medium technology readiness levels. Near-term GHG emission reductions will thus have to come from improved aircraft technology and operations and from the use of so-called lower carbon intensity sustainable aviation fuels (SAF).

These sustainable aviation fuels can be based on biomass or on e-fuels synthesised from hydrogen and carbon dioxide. A number of production pathways have already passed the very stringent and time- and resource-demanding process of the American Society for Testing and Materials (ASTM) certification; however HEFA-SPK (hydroprocessed esters and fatty acids–Synthetic Paraffinic Kerosene), based on fats and oils, currently provides the vast majority of biojet fuel. Hundreds of commercial flights are already operating on up to 50% blends of biojet fuels, demonstrating the technological maturity of flying on biofuels. The Global Framework for Aviation Alternative Fuels (GFAAF) of the International Civil Aviation Organisation (ICAO) visualises airports that receive regular or batch deliveries of SAF.

Shipping

Most of the world's freight is transported by ship in huge ocean-going vessels. Until recently, they have mainly been operating on heavy fuel oil, which is a heavy fraction from oil processing that used to contain up to 3.5% sulphur and was very polluting. In 2020, a new limit on sulphur content came into force, limiting sulphur to 0.50% outside and to 0.10% inside designated emission control areas. Ships can comply either by using fuels that meet these sulphur limits or by installing exhaust gas cleaning systems (so-called scrubbers). Biofuels, electricity, hydrogen, synthetic hydrocarbons (including methanol), and ammonia appear to be the most promising options from the fuel side.

Large, ocean-going vessels use huge combustion engines operating at low-to-medium speed. They can operate on biofuels without any modifications being needed, and that would solve both the problem of local emissions such as sulphur and black carbon (soot) and the need to reduce well-to-wake GHG emissions. Barriers to the wider use of biofuels though are, among others, the lack of economic incentives and a high level of uncertainty related to future marine biofuel supply and regulatory policies.

Clean, low-carbon fuel solutions for shipping include methanol, liquified biogas, hydrogen, and ammonia

Other alternative shipping fuels that have been demonstrated include methane (preferably renewable), methanol, and LNG or LBG (liquified natural gas or liquified biogas); the use of electricity or hydrogen to date has been limited to smaller ships and ferries operating closer to the coastline. Ship owners are eager to purchase fuel- and powertrain-flexible ships, as the average lifetime of such vessels is 20 to 30 years, which is longer than the timeframe we can afford for burning fossil fuels. Maersk, the world´s largest shipping firm, has, for example, announced that in the first quarter of 2024 they will introduce the first of eight new large ocean-going container vessels capable of being operated on carbon-neutral methanol. This is in response to ambitious targets for zero-carbon supply chains of over 100 large customers, with many more expected to follow.

Trucks

The road freight sector carries about two-thirds of on-land freight activity, measured in tonne-kilometres, and is the largest source of global diesel demand. It is important to reduce the sector's dependence on fossil fuel, yet there are limited options available. "The Future of Trucks" report by the International Energy Agency (IEA) investigates four alternative fuels and powertrains: natural gas, biofuels, electric trucks, and hydrogen.

Natural gas can be used in so-called dual-fuel vehicles that use small volumes of diesel to ignite the natural gas. The (fossil) natural gas can also be replaced by biomethane to significantly reduce net well-to-wheel GHG emissions. The methane is stored on board the trucks either as compressed natural gas (CNG) or liquified natural gas (LNG). The deployment of natural gas trucks varies significantly across regions, depending on the availability of fuelling infrastructure and the price differential between natural gas and diesel. The provision of biomethane to refuelling stations is still rare.

Biofuel options for trucks include the well-established fuels biodiesel (FAME), renewable diesel (RD or HVO), and biomethane (from anaerobic digestion), as well as still to be fully developed options such as ED95 ethanol, BioSNG, bioDME, bio-Fischer-Tropsch diesel, and e-fuels. Biofuels can be used in the current truck fleet either neat or in blends with fossil diesel. Biodiesel is typically used as low-level blends with fossil diesel, for example, B7 with up to 7% biodiesel content in fleets; RD or HVO, although also suitable as neat fuel, are also often used as 30% blend to meet the diesel standard density requirements. Especially in Sweden, biomethane is used in municipal bus fleets and in trucks.

The need to carry a large and heavy battery to store the energy required for long-haul freight is a major barrier to the use of electric trucks. Development work is focusing on reducing the need to store electricity by supplying electricity while the truck is in motion. This can be done through electric road systems, such as overhead catenary lines and inductive power transfer. Such trucks and systems are currently in the pilot or early-deployment stage.

Fuel cell electric vehicles (FCEV) in general are still very rare (around 16,000 in total globally as of 2020), and FCEV truck pilots and demonstrations are even rarer. The storage of hydrogen to power a fuel cell for on-board power generation for the electric engine is 300 times more energy-dense (on a weight basis) than the storage of electricity in a lithium-ion battery. Yet, for the same driving range, hydrogen storage still requires four times more space than conventional diesel technology.

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06

Enabling policies and research needs

CHAPTER 6.1

Towards a circular bioeconomy and other sustainability avenues

The biobased supply network connects a multitude of economic activities (Photo credit: Shutterstock/New Africa)

With the bio-based economic sectors being circular by nature, the circular bioeconomy holds unique opportunities and challenges for other economic sectors

While countries, citizens, and scientists have committed to the Paris Agreement, sustainable bioenergy is frequently dismissed as being too complex or even unachievable; arguments often emphasise the perceived competition between energy, material, and nutrient services. It is true that bioenergy systems are highly interconnected, develop dynamically, and have different impacts at different scales. It is exactly this complexity, however, that holds significant opportunities for entering different sustainability avenues and making the successful transition to a carbon-neutral economy.

Strategies for a transition towards a sustainable circular bioeconomy

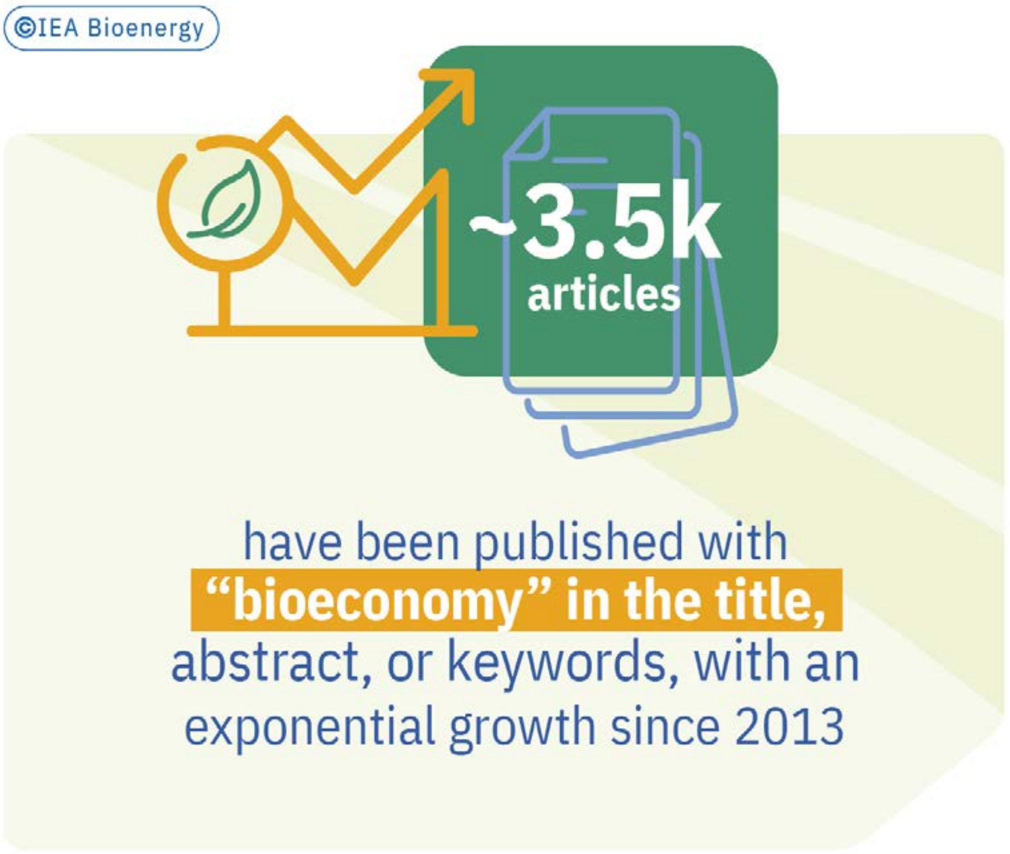
Today, many countries of the Organisation for Economic Co-operation and Development (OECD) have dedicated bioeconomy strategies in place. Although respective strategy documents vary strongly with regard to the type of bioeconomy policy development, and the extent of information on it, we can highlight a common denominator: the sustainable integration of agriculture, forestry, aquaculture, and their primary, secondary, and tertiary residues into an economy in transition.

> **Bioeconomy strategies aim for the sustainable integration of agriculture, forestry, and aquaculture, and their primary, secondary, and tertiary residues into our economy**

At the same time, circularity is high on the agenda for some OECD world regions. Circularity is tantamount to resource efficiency through, for example, reduction, repair, remanufacturing, recycling, and repurposing of products. With modern bioenergy strategies focusing on residues, and the interweaving of material, nutrient, and energy services, bioeconomy concepts and bio-based economic activities have to be understood not only as part of the circular economy, but also as its pioneer sectors (IEA Bioenergy Task 42 perspectives document and the CBE JU proposal annex).

For emerging economies and developing countries, the circular bioeconomy can create business opportunities for a wide range of stakeholders, while reducing import dependencies. For example, the Eastern African Bioeconomy Strategy stresses the chance to connect scientists with rural development to [ensure the supply of] “healthy food, reduce air pollution by travelling in vehicles powered by clean fuel and producing safer and more efficient medication”.

To build upon these circular economy and bioeconomy efforts and to harness the opportunities of the circular bioeconomy, the prevailing circular policy centre of attention on the end-of-life (EoL) of selected product types (see Milios, 2018) has to be extended to a more holistic supply chain view, including sourcing (including waste/secondary feedstock markets), manufacturing, and especially bio-based products and processes. By shifting the current emphasis from competition between bioenergy and other bio-based sectors to their manifold synergy opportunities, significant contributions can be expected for both the circular and the bioeconomy strategies.



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~3.5k articles have been published with **“bioeconomy” in the title,** abstract, or keywords, with an exponential growth since 2013

Sustainability governance bridging all sectors

The joint consideration of the different circular bioeconomy sectors in particular, holds the potential to transfer sustainability governance for bioenergy to other bioeconomy sectors. Processes and supply chains providing bio-based products, food, and feed services could be improved if environmental standards from bioenergy supply chains were to be transferred. Innovative concepts and policy measures such as monitoring indirect land-use change or the large-scale implementation of sustainable forest and landscape management could have an impact on sustainable agriculture and forestry for all bio-based services.

> **Further SDG-related opportunities and challenges of sustainable bioenergy lie in addressing energy poverty, creating jobs in the regions, boosting development in the rural areas, decentralisation, and energy- and resource democratisation**

High shares of variable renewable energy will also require biogenic carbon and energy, for example for synthetic fuels and system flexibilisation/stabilisation. Furthermore, the integration of biogenic carbon supply chains into the renewables-based economy sectors provides the opportunity to significantly diversify the stakeholders and shareholders participating in the overall value creation and thus contribute to resource democratisation. Frameworks and market instruments to valorise social sustainability, for example by rewarding smaller producers and stakeholder diversity, have to be developed and implemented.

The way forward: policy, legislative, and technological frameworks needed

Knowledge and know-how on the bioenergy and biomass markets will be decisive for future biogenic carbon carrier markets for a circular bioeconomy. The sustainable and decentralised character of the integration of the primary economic sectors can provide societal benefits. Environmental and economic sustainability can be improved through resource efficiency and synergies between various energy, material, and food and feed services. The further interweaving of separated supply chains into biogenic carbon supply networks, however, especially regarding a circular bioeconomy, comes with some challenges:

- Biomass provides more than energy and carbon. A departure from the currently prevailing reductionist approach is necessary to valorise the different, more complex bio-based components of biomass—without breaking down macromolecules into smaller building blocks; such useful macromolecules include proteins, sugars, oils and fats, fibres, cellulose, and hemicellulose.
- The technical, economic and environmental evaluation of more than one main product, for example a product portfolio in a biorefinery, is not straightforward. A thorough and standardised characterisation of the bio-based processes can help and should be extended to entire supply networks.
- Standardisation, certification, and labelling of bio-based products and of biogenic carbon carriers must consider an impressively broad range of product performance indicators (see StarProBio project) while tackling a highly diverse and varying feedstock base.
- Economies of scale render the current economy cost-effective but also rather centralised. Small-scale biorefineries, regional supply chains, and biorefinery or circular bioeconomy communities provide significantly more societal and SDG-related benefits. Thus, downscaling will have to be supported by research and development and market instruments for the deployment of the smallest functional units.

To be able to reveal the added value of the bio-based sectors, including bioenergy for the economy and our society, we need to acknowledge their opportunities and challenges. The circular bioeconomy will be based on the potentially last remaining primary economic sectors, forestry, agriculture, aquaculture, and secondary feedstocks via cascading use. By aiming for environmental, economic, and social sustainability in these primary economic sectors we could significantly contribute to a transformation towards a fair and just society under stable environmental conditions.

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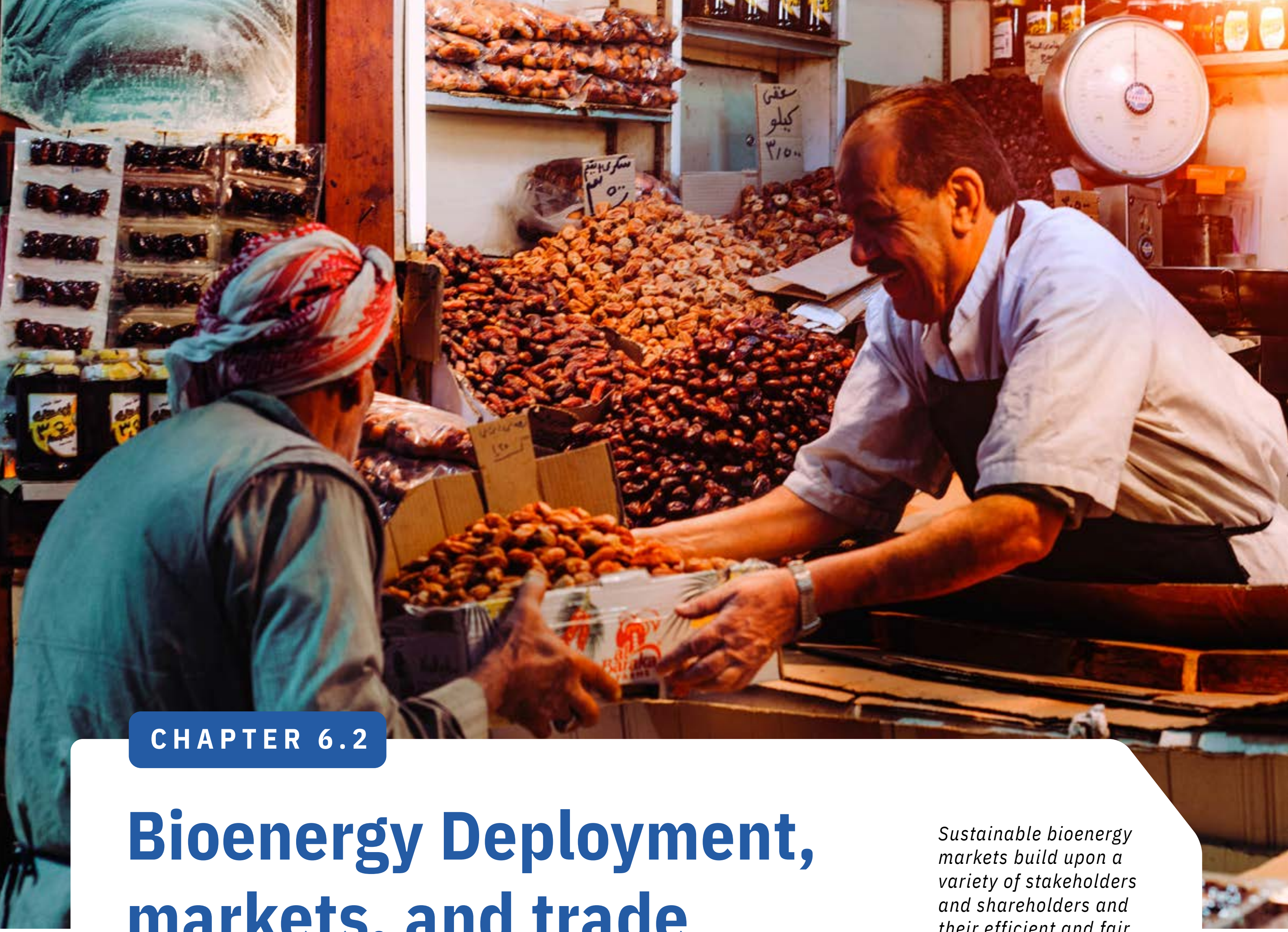


CHAPTER 6.2

Bioenergy Deployment, markets, and trade

Sustainable bioenergy markets build upon a variety of stakeholders and shareholders and their efficient and fair cooperation (Photo credit:Pexels/Quintin Gellar)

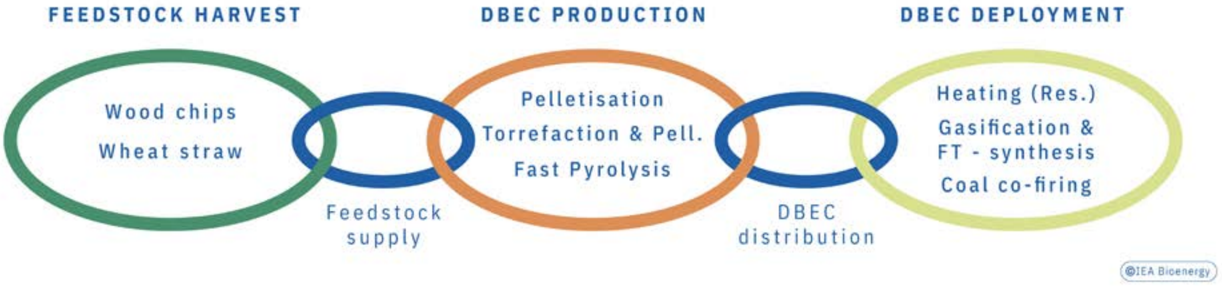
Sustainable bioenergy depends on the continuous supply of biomass, including residues from agriculture, forestry, or industry processing, post-consumer waste, perennial crops, cover crops, and other plantings. Designing markets and supply chains for these highly heterogenous and dispersed goods is particularly challenging but holds great opportunities for the primary, upstream, and circular economic sectors

Be it for heating the home or lighting the office, bioenergy services rely on a continuous supply of biomass feedstock. Bioenergy carrier and biomass markets need to be created with the support of appropriate policies, providing benefits to the multiple stakeholders and shareholders along the supply chain. On the one hand, this renders bioenergy deployment a rather complex endeavour. On the other, it provides a unique richness of opportunities in the primary, upstream, and circular economic sectors.

On the inherent challenges of creating markets for freshly sourced biomass

Supply of biomass for bioenergy applications is naturally organised in a much more decentralised manner than, for example, crude oil sourcing. Unlike oilfields or coalmines, forests and farms are geographically highly dispersed and supply chains involve a variety of stakeholders and shareholders and several supply chain steps.

Within the IEA Bioenergy TCP, the experts of IEA Bioenergy Task 40 are devoted to overcoming the barriers and revealing the opportunities of biomass supply chains with a market perspective, while the IEA Bioenergy Task 43 community focuses on sustainable production and supply and IEA Bioenergy Task 45 on sustainability governance. As biomass supply for energy, material, and food and feed services are inherently linked, recommendations for policy, stakeholders, and shareholders often have a multi-sectoral character. This section thus focuses on providing guidelines for market creation. Residues from forestry, agriculture, or bio-based industries such as sawmills, paper production, food processing, or waste water treatment have some particularly unsatisfactory properties in terms of longer-distance transportation and storage. How can these types of resource be mobilised to meet demand for energy services when those services are located somewhere else or are required days or even months later?



Exemplary representation of supply chains for bioenergy service, including feedstock or residues harvest from forestry or agriculture, supply to pre-treatment plants, and further distribution of densified bioenergy carriers (dBECs) to selected final bioenergy conversion plants. Source: Schipfer F. (2017)

Improving biomass properties for transportation and trade

Biomass pre-treatment can be used to improve properties such as the carbon and energy content and stability of freshly sourced biomass. Through pre-treatment such as chipping, pelletisation, torrefaction, or pyrolysis, longer-distance transportation becomes economically feasible, while homogenisation enables trade because traders and final consumers can better rely on the quality of their purchase. Tradability, also for longer distances over country borders, as well as for inter-modal handling and storing over seasons, is thus understood as a prerequisite for creating markets for bioenergy carriers.

With mobile or small-scale pre-treatment still being rather a niche application today (T40 RT report), most pre-treatment businesses want to harness economies of scale by maximising their capacities. Scaling has to be economically traded-off against feedstock or residues yield, cost, availability, and accessibility which may considerably vary over time and also depend on competing demand developments. Thorough evaluations of these factors are recommended before setting up pre-treatment plants. GIS-based approaches, seasonal scheduling, and feedstock flexibilisation will help this sector progress in the near-term future.

Commoditisation, international trade, and deployment

While pre-treatment of biomass residues is a prerequisite for bioenergy carrier markets, it is often not enough: commoditisation and international trade have thus been on the main agenda, especially of IEA Bioenergy Task 40. Commoditisation means the creation of an interchangeable and standardised or certified good which is traded on a transparent and efficient physical market allowing for equilibrating price dynamics. The challenge now lies in defending and supporting stakeholder and shareholder diversity, an overlooked unique selling proposition of bioenergy supply chains (T40 RT project); this will occur through local mobilisation while interweaving local supply chains into efficient international markets.

> **Several bioenergy carriers have been discussed as commodities: wood chips, biomethane, liquid biofuels, and wood pellets.**

Several bioenergy carriers have been discussed as possibly established commodities: markets for wood chips, biomethane, liquid biofuels, and wood pellets have been closely examined in recent years. Wood pellet markets have received special attention, mainly because of their importance in European renewable heat and power supply, their significant trade flows, and their basis of relatively good data. High search costs for comparable price information, the lack of sustainability labelling and of acceptance for internationally traded pellets do, however, limit the commoditisation and market creation process of this major bioenergy carrier.

Creating biogenic carbon markets of tomorrow

We nevertheless consider wood pellets as a promising future and leading bioenergy carrier commodity, not only for extending the application of bioenergy for power and high-temperature industrial heat but also for providing carbon for steel production or for negative emissions in BECCS facilities. Further technical advances with regard to densification but also progress in terms of sustainable governance and harnessing the socio-economic benefits of pellet supply chains will thus play an important future role.

Finally, the feedstock basis upon which the portfolio of intermediary biogenic carbon carriers is currently built has to be extended, as today only small shares of biomass feedstocks are being utilised. Short-rotation coppice such as eucalyptus, switchgrass or willow, different types of agricultural residues and also grasslands or and aquaculture, (e.g., harvested algae from high-eutrophication water bodies) exhibit untapped sustainable potentials.

A combination of mobilisation strategies will help to improve not only the environmental but also socio-economic performance of sustainable bioenergy markets. GIS-based and data-intensive harvesting and mobile densification services can mobilise distributed resources that are of fluctuating or sudden occurrence. Physical Bio-Hubs act as collection centres, and distribution platforms to provide the biomass for bioenergy and other bio-based applications of tomorrow.

Environmental and social sustainability standardisation and commoditisation ensure the highest societal benefits in the primary economic sectors, while facilitating market uptake of biomass commodities. Multi-level governance ensures cohesion among policy goals at the international, national, and regional level and involves bioeconomy communities so that markets can evolve to benefit all participants.

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CHAPTER 6.3

Governance that safeguards environmentally and socially sustainable biomass sourcing and bioenergy production

Sound forest management as the basis for sustainable biomass production (Photo credit:Unsplash/ Joe Dudek)

Securing a sustainable supply of biomass is at the heart of the deployment of bio-based value chains, including bioenergy and biomass-based products

Environmentally and socially sound production of biomass is a key strategy to ensure sustainable cross-sectoral bio-based supply chains, while being pivotal for any bioeconomy system. A number of steps need to be taken to establish good governance systems, and it is also important to raise awareness among citizens and build trust.

A crucial factor here is to build up and create trust among the public and consumers that biomass can be sustainable at all; and, furthermore, that it can be produced sustainably everywhere in the world and not only in some temperate forests in the northern hemisphere. This requires credible and transparent governance systems based on monitoring and traceability.

Credible and transparent governance systems are required to build trust among the public and consumers that biomass can be sustainable at all.

Sustainable wood production and its benefits need higher visibility

Little attention is given to sustainable production and consumption of wood products on the international development agenda. This is despite sustainable use of natural resources, including forests, being a key principle of the 2030 Agenda for Sustainable Development and the 2015 Paris Agreement and the important contribution of forests to climate change mitigation and adaptation being highlighted.

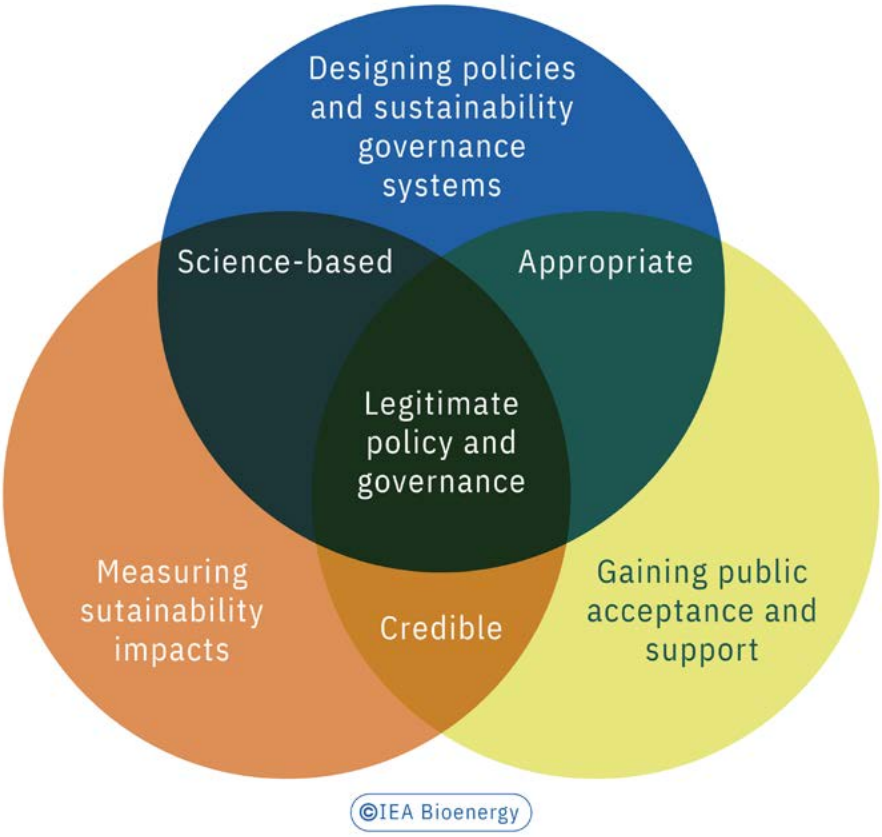
A major reason is persistent reporting on instances of unsustainable practices (e.g., in forestry, and also in oil palm plantations, etc.) by media from practically all over the world. Such reporting has contributed to a lack of finance for building sustainable wood value chains and has hampered marketing efforts. The FAO and Collaborative Partnership on Forests (CPF)-led "Sustainable Wood for a Sustainable World (SW4SW)" initiative has also identified these obstacles; it has been concluded that it is vital to increase the visibility of the benefits of sustainable wood (biomass/bio-based feedstocks) production and consumption: mindsets must be shifted to encourage a more positive and responsive attitude so that sustainable wood value chains can be developed and strengthened. SW4SW highlights the fact that joint efforts are essential to improve understanding of i) what sustainable wood value chains entail; ii) where they can be found, created, or strengthened; iii) what business models are associated with them; and iv) how they can better contribute to achieving development goals at different levels.

Increasing the legitimacy of sustainability governance for bioenergy and the bioeconomy

Increasing international trade of bioenergy products has stimulated interest in the need for broader bioenergy sustainability criteria. Moreover, IEA Bioenergy in a collaborative activity with its global research networks, including the Nordic Council of Ministers, has addressed this pivotal sustainability governance question through a series of studies, publications, and workshops.

A study found that a high level of legitimacy is a precondition for building trust that the system will lead to acceptable and beneficial outcomes (based also on strict validation and monitoring of e.g., achievement of sustainability criteria). Central to this discussion is the nexus of science, policy, and governance, and public acceptance:

There is evidence that people are more likely to perceive a governance system as being legitimate when its design is underpinned by rigorous science, when the science is seen as credible, and when the exertion of power of the governance system is seen to be fair and appropriate. A critical element is always effective monitoring and validation as well as transparent communication of results to ensure that the desired outcomes are being achieved and that the public is aware of this.



The nexus of science, policy, and governance, and public acceptance is central to achieving a high level of legitimacy and trust with regard to sustainability governance for bioenergy and the bioeconomy

Another study discusses the controversy surrounding bioenergy, namely that bioenergy is assumed to be playing a key role in the transition to a sustainable economy in Europe, but that its own sustainability is being questioned in some cases and application types, particularly the use of biomass in large-scale power plants.

Examples from the Nordic countries (Denmark, Finland, Norway, and Sweden) show that many common sustainability risks (including e.g., deforestation, degradation, resource competition, and lack of acceptance) can be managed in the region based purely on voluntary measures. Obviously, risks to economic sustainability may be more challenging than ecological risks, given that, for instance, the competitiveness order of renewable energy technologies (i.e., the relative ranking of photovoltaic, wind and bioenergy) has been reversed in the last decade.

The risk of resource competition harming other sectors in the economy was found to be small and manageable but needing continuous monitoring. Local bioenergy communities turned out to be strong agents of change behind the most expansive bioenergy chains. For these local communities, the fear of non-local actors reaping the economic gains involved in bioenergy chains was found to be one of the larger risks to the trust and acceptance necessary to act as bioenergy communities. From the Nordic experience, it has been concluded that further to the institutional framework involving laws, regulations, and standards, community commitments are essential, and a strong stakeholder involvement is key in sustainable bioenergy development and use—both to safeguard the legitimacy of bioenergy development and to reconcile tensions between the global quest for a climate neutral economy and the local quest for an economically viable community.

> **Further to laws, regulations, and standards, community commitments are essential, and a strong stakeholder involvement is key in sustainable bioenergy development.**

Further to this discourse, scientists state that public acceptance is crucial for promoting sustainable bioenergy and that, consequently, increased acceptance would lead to a greater potential for growth in market share. Public acceptance, in turn, is mainly based on gaining public trust and attracting public support, which requires an efficient policy framework and interactive communication among bioenergy stakeholders.

In parallel to increasing demand for wood pellets in EU member states, the demand for establishing sustainability risk control for the transatlantic trade in wood pellets between the USA and Europe has grown. In addition to EU-wide sustainability requirements for renewable energy, various national regulations need to be met by the importing countries.

With the USA supplying 27% of the EU's pellet demand, sustainability certifications used by the forest bioenergy industry are identified as a key compliance tool regarding EU and member state sustainability criteria, with special emphasis needing to be placed on the feedstock-sourcing procedures and strategies in actual supply chains. This study finds that larger pellet mills usually use less feedstock sourced from certified forest management operations, while medium-sized mills source more certified feedstock. For larger mills, therefore, the greatest challenge seems to be the time-consuming and often technically complex tracing of feedstock origin back to the forest.

A joint report by IEA Bioenergy Task 45 and GBEP concludes that although the importance of bioenergy and bioeconomy governance is increasingly recognised and implemented at different levels, a comprehensive and cross-sectoral and transboundary coordination is still lacking. The nature of connections between primary production (agriculture, forestry, etc.) and conversion (chemicals, construction, energy, fibre, food etc.) requires their interactions to be considered across sectors and beyond national boundaries.

As national SDG frameworks are in the process of being adapted and implemented, there is an opportunity to create synergies between bioenergy and the SDGs. As of now, however, the governance of national SDG implementation is weak, and it may well be necessary to develop a specific bioeconomy governance or "umbrella" framework such as the European Green Deal to integrate sector policies vis-à-vis the bioeconomy.

Sustainability certification and monitoring

Apart from the controversial discussions with respect to sustainable biomass production and whether certification schemes will be able to sufficiently address sustainability risks, it is difficult to obtain recent and global background data on the production quantity of sustainably produced biomass for the different value chains— including bioenergy—from literature. One of the few publications including statistics on certified wood production is the series of Forest Products Annual Market Review by FAO and the United Nations Economic Commission for Europe (UNECE), In their 2016 edition, the global production of industrial round wood with a certified origin is estimated at some 511 million m3—equivalent to some 29% of global production.

These figures come with a significant uncertainty, given the shaky background statistics on global wood production, qualities (e.g., for bioenergy uses), and the unclear situation with respect to overlapping certified forest area under different labels and schemes. They do, however, give an indication of the present order of magnitude of global sustainable biomass production from the forest sector. Nevertheless, while about 10% of the global forest area is already under some kind of sustainable management certification scheme, it has to be said that this area is predominantly located in the northern hemisphere.

For the year 2021, the Sustainable Biomass Program (SBP), an organisation that aims to promote economically, environmentally, and socially sustainable biomass supply through certification, lists 339 SBP certificate holders across 33 countries (including e.g., Australia, Brazil, Canada, China, France, Germany, Japan, Malaysia, Norway, Russia, Spain, Sweden, the UK, and the USA). Together, under their respective schemes, these SBP certificate holders produced and sold on the market more than 13.4 million tons of wood pellets and 1.6 million tons of chips in 2020. These figures indicate that there is already a solid basis for bioenergy feedstock from sustainability-certified origin. However, the aim is to have no unlabelled or unsustainable biomass on the market.

Stakeholder opinion

An assessment of the global view of stakeholders in 2018 (including e.g., biomass producers/users, the general public, academia, NGOs, and policymakers) found that the stakeholders are largely aware of bioenergy development and have a positive view of the sector; the general public is less aware of bioenergy development, however, and not sufficiently committed to it.

Internet and social media were found to be the most consulted sources of information but were also the least trusted, whereas scientific information was the most trusted, but least used. Agricultural residues, energy crops from marginal or degraded land, and forestry residues are widely accepted as feedstocks for bioenergy production. The use of primary feedstock (crop) produced on agricultural land or entire stemwood harvested from the forest, however, attracts criticism. Bioenergy development is generally supported when jointly agreed sustainability requirements are met.

Overall, stakeholders consider that sustainability requirements, including social, economic, and environmental aspects, should be mandatory if they are to fully support the bioenergy sector. They also attach an important role to scientific information. Other expected preconditions for enhanced bioenergy support and gaining greater social acceptance are transparency in demonstrating compliance with sustainability criteria and establishment of a level playing field for equitable market conditions.

A recent IEA Bioenergy workshop on “Governing sustainability in biomass supply chains for the bioeconomy” concluded that as well as creating trust through credible governance systems, monitoring, traceability, and transparency, an important further step will be to agree on and implement a minimum set of key sustainability criteria and related indicators (e.g., based on the GBEP sustainability indicators) in relation to the most important risks and opportunities needing to be addressed by sustainability governance.

Sustainability governance of bioenergy should not be separated from other uses of biomass and the broader bioeconomy. In future dialogues all bio-based value chains need to be represented, as do policymakers, the private and finance sectors, and sectors beyond the bioenergy and bioeconomy community—all with a special emphasis on the younger generations.

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CHAPTER 6.4

Technology research, development, and deployment needs for a low-fossil-carbon energy system

Basic research is a cornerstone to successful technology development for a low-fossil-carbon energy system (Photo credit: Pexels | Edward Jenner)

As half of the technologies needed to fully decarbonise by 2050 are not yet commercially available, further research and development of bioenergy technologies is crucial

The analysis done by IEA for the Net Zero by 2050 roadmap found that about half the technologies that will be applied in our future low-fossil-carbon energy system have not yet been fully developed to commercial scale. Thus, research, development, and deployment activities (RD&D) constitute essential parts of climate change mitigation. While different biomass conversion technologies face quite specific challenges, overall RD&D needs can be identified along the value chain from biomass cultivation to end-use.

To fully deploy bioenergy technologies in our future low-fossil-carbon energy system, RD&D is needed along the value chain from biomass cultivation to end-use. In the IEA Bioenergy Roadmap, IEA energy analysts and IEA bioenergy experts list the numerous topics in several fields, as described below.

Biomass cultivation and supply should be improved through optimisation of crop yields and introduction of new varieties, through minimising inputs such as nutrients and water, and through sustainable biomass sourcing and the establishment of sustainable supply chains. Further R&D needs of biomass cultivation include development of low ground pressure harvesting machinery to extend the amounts of land suitable for bioenergy and to widen the harvesting window, and investment in robotic technologies to aid planting, maintenance, and harvesting in fields. Further work is also needed to understand biomass degradation in storage. Finally, beneficial ways of integrating biomass with conventional agriculture need to be further investigated, so as to take full advantage of possible soil quality improvements, to limit eutrophication, and also limit flooding risks.

For **all technologies**, the following requirements are essential: i) feedstock range of bioenergy conversion technologies needs to be broadened to include a wider variety of crops, residues, and wastes; ii) collection and transport of biomass, in particular residues, should be optimised; iii) catalysts in various processing steps need to be improved for higher robustness and longevity; iv) emerging technologies for producing intermediate bioenergy carriers and biofuels need to be further developed, and several other conversion technologies need to be demonstrated at scale; v) value chains need to be further optimised, and new value chains need to be developed to provide biomass-based energy to important future markets such as shipping, aviation, and high-temperature heat for industry.

Successful technologies have to be developed through basic research, lab-scale experiments, pilot-scale trials, and demonstration operations. It is also important, however, to develop the right technologies that will use sustainable feedstocks, provide high greenhouse gas emission reductions, and can be operated economically. These technologies should support our future energy system and the transition to it, while maintaining sustainability safeguards and reaching high public acceptance.

Technologies should support our future energy system and the transition to it while maintaining sustainability safeguards and reaching high public acceptance

The specific RD&D needs for **thermochemical conversion** (combustion, liquefaction, gasification) include: i) adaptation of small-scale combustion appliances such as stoves, boilers, and district heating systems to reduce harmful emissions of particulate matter and organic compounds and NOx; ii) downsizing of power plants to small- and micro-scale combined heat and power (CHP) solutions; iii) improvement of gasification and hydrothermal/pyrolysis reactor designs to deal with higher ash content feedstocks; iv) increased amounts of volatiles and a higher degree of heterogeneity of the feedstock when using wastes and residues as feedstocks; and v) development of small-scale, modular gasification units for decentralised application.

Specific RD&D needs of **biochemical conversion** (anaerobic digestion and various fermentation processes) include: i) improvement of feedstock pre-treatment methods, in particular for fermentation processes; ii) optimisation of the microbial community to the fermentation; iii) improvement of digestate treatment to produce fertiliser; iv) development of novel strains to economically produce hydrocarbon or long-chain fatty alcohols from sugars; and v) development of technologies to valorise the lignin content in lignocellulosic feedstocks.

Aspects of the energy system that should be addressed through R&D are: i) integration of bioenergy and biofuels with existing industries such as pulp and paper and refineries; ii) development of concepts to fully exploit the potential of bioenergy to stabilise the electricity grid and couple the electricity, heat, and transport sectors; and iii) development of carbon capture and storage technologies adapted to the scale of bioenergy installations.

R&D needs in the **socio-economic aspects and governance** of bioenergy most importantly include: improvement of the understanding of public acceptance of bioenergy installations and technological pushback; and ii) provision of policy blueprints, in particular for sustainability certification governance.

Policy support for technology should be accelerated at all stages of the innovation cycle

In the IEA Special Report on Clean Energy Innovation, IEA analysts advise accelerating policy support for technology at all stages of the innovation cycle. Public support should be measurable and target all phases of innovation (including research, development, demonstration, and deployment) to facilitate both incremental and radical innovation, and also deployment measures for specific technologies. Initiatives such as the IEA Technology Collaboration Programmes, the Clean Energy Ministerial and Mission Innovation are key platforms for coordinating and accelerating global efforts.

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CHAPTER 6.5

How to implement sustainable bioenergy

Global leaders must take joint action to implement sustainable bioenergy and a broader bioeconomy to combat climate change, maintain biodiversity and species abundance, and improve the living conditions of the poor (Photo credit: UNclimatechange)

If everything is "left to the market", the cheapest solution will win instead of the best. Global leaders need to take joint action and support required changes through policies to combat climate change, maintain biodiversity and a viable biosphere, while at the same time enabling sustainable energy access for all

Today, we are facing some of the biggest challenges to humanity. The most pressing needs are to combat climate change, maintain biodiversity and species abundance, and improve the living conditions of the poor. Sustainable bioenergy offers many benefits—reducing GHG emissions, supporting sustainable land use, and providing clean cooking solutions. It has an important role to play now and in the future. The implementation of bioenergy, however, does not happen in a vacuum. It needs to be supported by a well-balanced set of policy measures that make bioenergy solutions competitive with fossil solutions and encourage and ensure sustainable practices.

Most global leaders are well aware of the challenges being faced around the world and are willing to address them. 192 countries have signed the Paris Agreement to combat climate change, and 193 countries have adopted the Sustainable Development Goals aiming to ensure “peace and prosperity for people and the planet, now and into the future”. Virtually all countries have set some sort of target for renewable energy or have introduced renewable energy policies. Yet, political leaders are looking for advice on which policies would be most effective in their specific situation.

In 2011, the Global Bioenergy Partnership (GBEP) developed 24 sustainability indicators for bioenergy. These include environmental indicators such as lifecycle GHG emissions, soil quality, water use and efficiency, biological diversity in the landscape, and land use and land-use change related to bioenergy feedstock production, together with indicators of social and economic well-being. The indicators are starting points from which policymakers and other stakeholders can identify and develop measurements and domestic data sources that are relevant to their nationally defined needs and circumstances.

The International Energy Agency (IEA) is one of the think tanks providing advice to policymakers on how to transform their energy systems. In the 2020 edition of IEA’s Energy Technology Perspectives, IEA analysts advise governments to develop a vision for a sustainable energy future, define pathways towards this vision, track progress towards the stated objectives, enhance international collaboration, support technologies at all stages of the innovation cycle (including research, development, demonstration, and deployment), and adapt policy, finance, and market mechanisms to support new business models.

Effective policy toolkits must be built around five core areas (Energy Technology Perspectives 2020):

- Tackling emissions from existing assets;
- Strengthening markets for technologies at an early stage of adoption;
- Developing and upgrading infrastructure that enables technology deployment
- Boosting support for research, development, and demonstration;
- Expanding international technology collaboration.

For bioenergy specifically, energy analysts of IEA and experts from IEA Bioenergy have published the IEA Bioenergy Roadmap (2017) which identifies several key policy actions. First of all, measures are needed that “level the playing field” such as getting rid of fossil fuel subsidies, pricing in externalities caused by fossil fuel use, and removing barriers in the taxation system. Then a favourable enabling policy environment for bioenergy and renewable energy technologies should be created, such as a long-term stable policy framework confirming markets and targets for the use of renewable energy, ensuring producers have access to markets, and providing compensating mechanisms to reward low-fossil-carbon energy production.

Additional measures should specifically support bioenergy technologies, such as stringent sustainability governance regimes, emissions standards, and measures to monetise the enhanced flexibility that bioenergy can offer. Finally, specific support should be given to new technologies, such as mandatory obligations for deployment of sustainable biofuels at a lower technology readiness level, dedicated financial mechanisms to facilitate demonstration of these technologies, and support for related RD&D.

A list of renewable energy targets and policies in countries worldwide can be found in the "Renewables 2020 Global Status Report" of REN21. As of 2019, 23 countries have introduced heating and cooling regulatory policies, 70 countries have introduced transport regulatory policies, and 143 have brought in power regulatory policies. Policies include feed-in tariffs and feed-in premiums, tendering, net metering, renewable portfolio standards for the power sector; solar heat obligations, technology-neutral renewable heat obligations and renewable heat feed-in tariffs for the heating and cooling sector; and biodiesel or ethanol obligations and mandates for the transport sector.

The transport sector has proven to be particularly difficult to decarbonise. It is thus justified to introduce policy measures that specifically support the deployment of low carbon intensity transport fuel production technologies. In its report "Implementation Agendas: 2020-2021 Update - Compare and Contrast Transport Biofuels Policies", IEA Bioenergy Task 39 summarises the market deployment of transport biofuels and analyses which policy measures supported this deployment. Successful policies include biofuel blending mandates, fuel excise tax reductions, import/export tariffs, renewable or low carbon fuel standards, fiscal incentives, and public financing of technology research, development, and demonstration. Those countries that have achieved the most success in growing their production and use of transport biofuels have used a mix of policies.

> **Those countries that have achieved the most success in growing production and use of transport biofuels have used a mix of policies.**

Throughout all mentioned publications, emphasis is on the following points:

- Policy measures should be part of a long-term strategy and offer stable future markets to attract investors.
- Policy should be technology-neutral and not pick winners; however, policies should reward different options according to the most relevant driver (e.g., GHG emissions reduction or increases in rural income).
- A well-balanced basket of measures is needed that takes into account all affected stakeholders and consumers.

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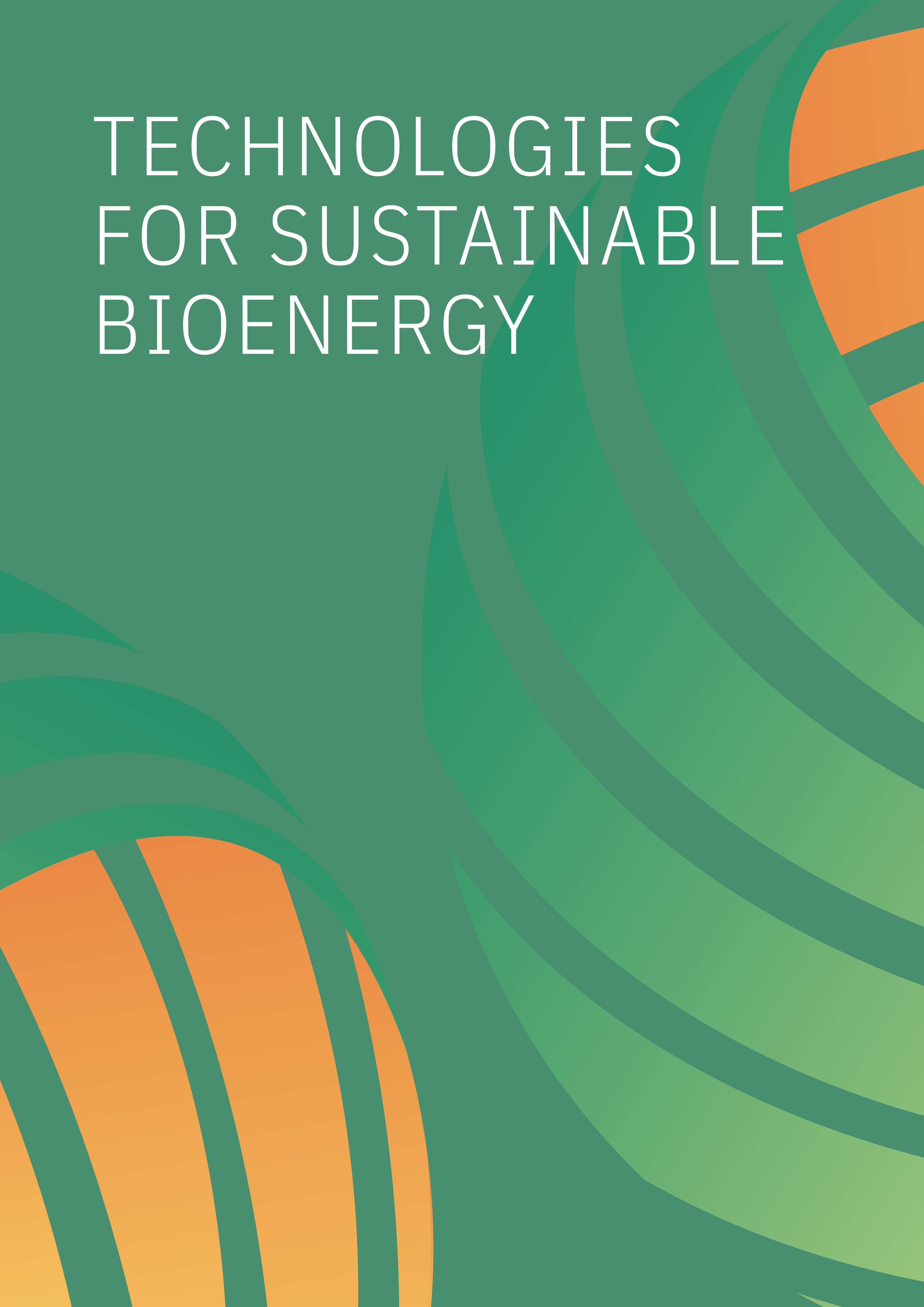
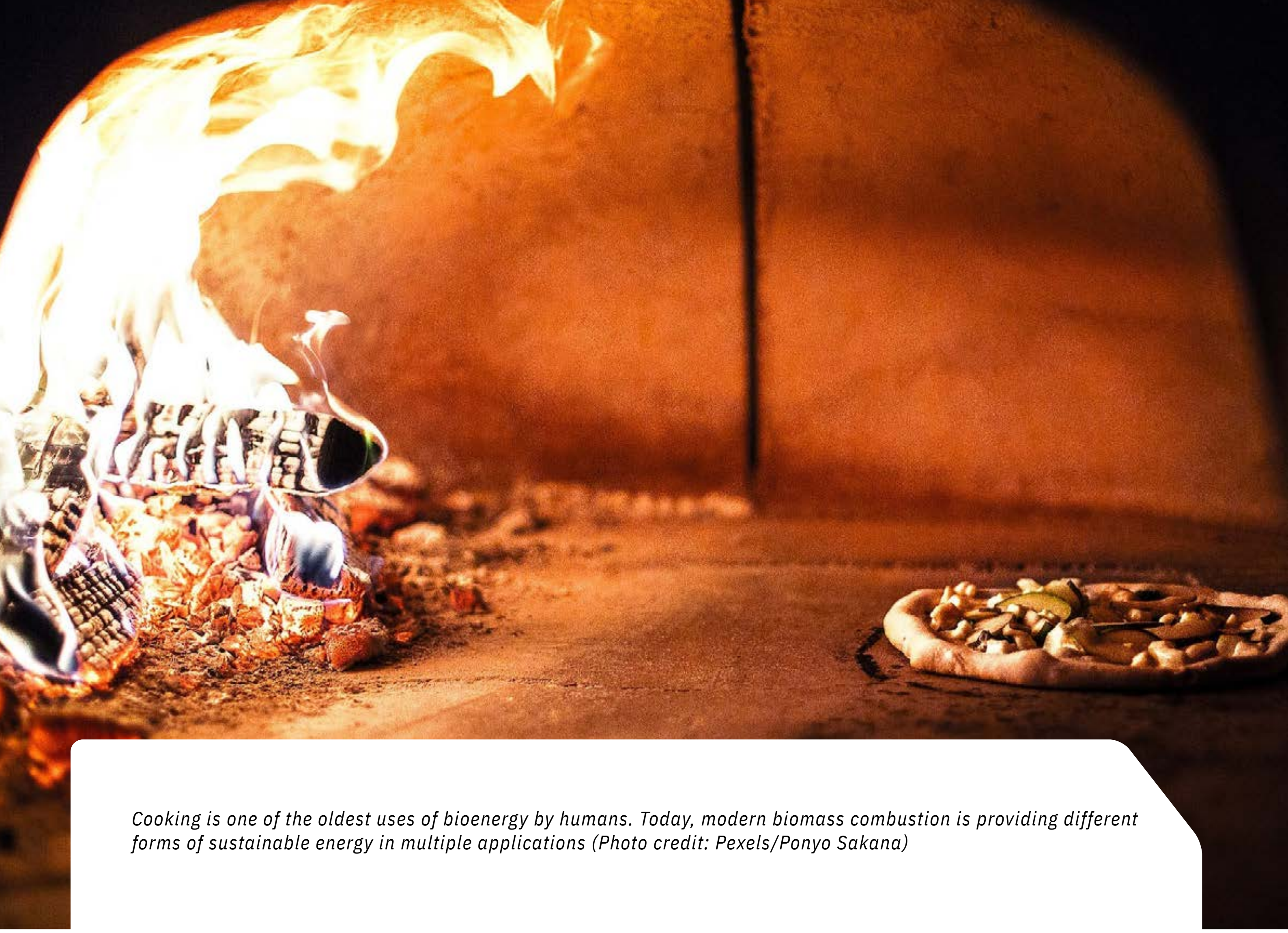
TECHNOLOGIES FOR SUSTAINABLE BIOENERGY



07

Biomass combustion



Cooking is one of the oldest uses of bioenergy by humans. Today, modern biomass combustion is providing different forms of sustainable energy in multiple applications (Photo credit: Pexels/Ponyo Sakana)

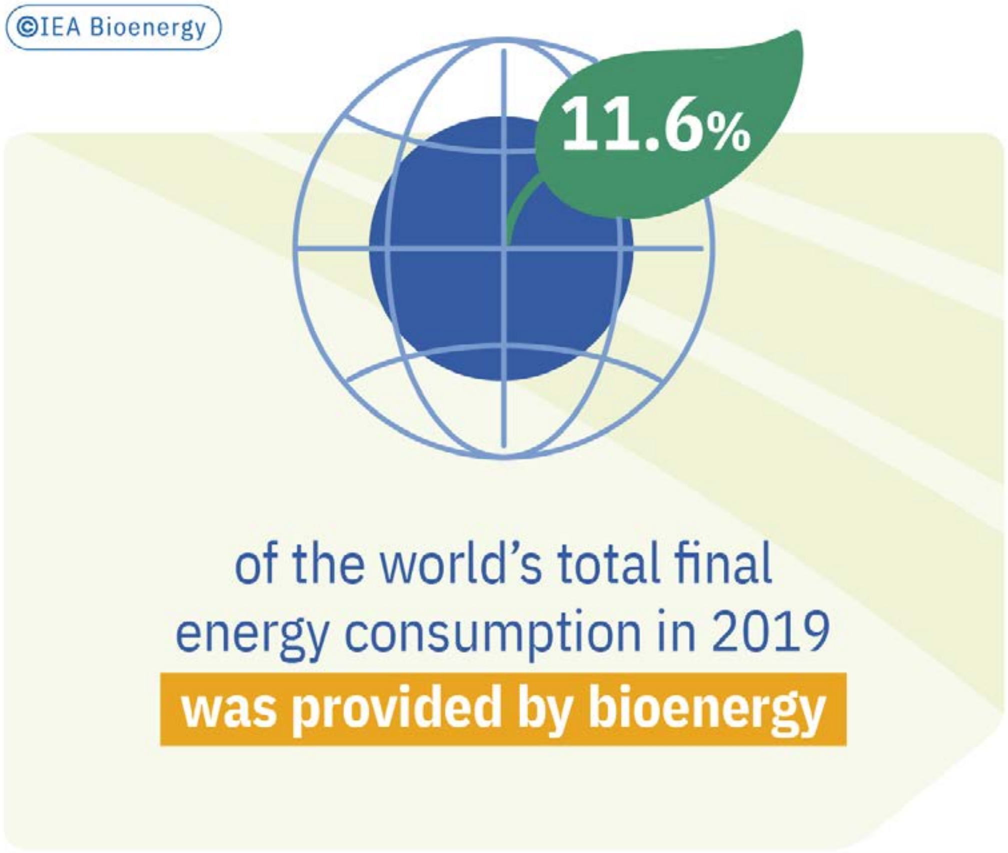
Biomass combustion

The control of fire is considered to be a landmark and a turning point in human history. Biomass burning, initially to provide heat for cooking and protection from predators, is the most important form of renewable energy ever used.

The development of what we call modern biomass combustion technologies—aiming for higher efficiencies and pollution control—dates back to the 1970s when the oil crises revealed the world’s dependence on fossil fuels. The long tradition of biomass use throughout history and its abundance around the globe were the key factors in the quick deployment of modern biomass combustion.

Modern biomass combustion, which has gone through almost 50 years of development, today offers technologically mature solutions across the whole capacity range, from small-scale residential applications with several kilowatts of electricity output to large power plants and combined heat and power (CHP) plants outputting hundreds of megawatts.

Similar to the capacity, the range of fuels is also broad. While woody biomass is still by far the most important biomass fuel, biogenic residues from agriculture, industry, or municipalities are also used in combustion technologies.



Residential applications

Biomass combustion systems are providing low temperature heat up to 100°C for heating and hot water supply in buildings. Such applications can be used either in individual residence/building heating solutions or in central systems distributing heat to buildings via a heating grid (also referred to as district heating).

Small-scale heating systems

Wood-based fuels dominate the market for small-scale biomass combustion systems. In terms of applications, direct heating systems provide thermal energy to the installation space, while central or hydronic heating systems transfer the energy to a heat transfer fluid, usually water.

Traditionally, firewood is still the most common fuel in this sector, but automated systems based on wood pellets or wood chips are steadily increasing their market shares. This trend results mainly from the significant comfort gain that comes with automated fuel supply, but in some countries, the shift from manual to automated systems is also being supported by policies.

While modern units such as pellet stoves and boilers reach high efficiencies of more than 90%, many systems in service are operated with limited efficiencies and high emissions. Due to products having long lifetimes of 20 years or more, many appliances now in use are no longer state-of-the-art. It is thus necessary to replace old and inefficient units with modern appliances to ensure that more efficient and less polluting bioenergy is produced.

District heating

In areas with high heat-demand densities, the installation of heating networks with central units instead of distributed individual heating systems is often advantageous. District heating systems are very common in several countries such as Austria, Denmark, and Sweden. Larger combustion systems benefit from the economy of scale and the availability of efficient flue gas treatment systems. This usually allows lower quality fuels to be used, such as wood chips from forest residues, with concomitant economic benefits.

A major drawback of district heating systems is the relatively high investment costs for the district heating lines and resulting long payback periods. For existing heating networks fed with fossil heat, the conversion to biomass-based heating is usually an economically attractive option.

The economic case for biomass-based district heating is quite complex, as several parameters influence both the costs and the turnover. High overall system efficiency is one of the main keys to successful district heating projects. Quality management programmes have been developed to support effective planning and operation of district heating networks (e.g., Quality Management system for Biomass District Heating Plants).

The biomass combustion experts from Bioenergy Task 32 of the International Energy Agency (IEA) have recently compiled case studies of innovative biomass-based heating applications in various sectors: Bioenergy for heat – the Hot Cases.

Tubing at a district heating plant in Sorø (Denmark). The plant, operated by Sorø Fjernvarme, provides 12 MW of bioenergy to 1,600 customers based on the company's retrieval of garden and park waste (Source: Sorø Fjernvarme/Photo by AffaldPlus)

Industrial applications

Process heat

The decarbonisation of industrial heat demand is particularly challenging due to the varying technical requirements of the applications used. Process heat is often required at high temperatures, which reduces the options for renewable heat technologies. Biomass combustion systems can provide high temperature heat up to 500°C via different heat transfer fluids—the most common being steam, thermal oil, and hot gas/air. For even higher temperatures, biomass combustion is applicable if direct heating via the flue gases is an option. This is why decarbonisation of industrial heat demand is seen as a future key market for biomass combustion systems.

> **It is very common for the pulp and paper industry to cover some of their operational energy demand from production residues**

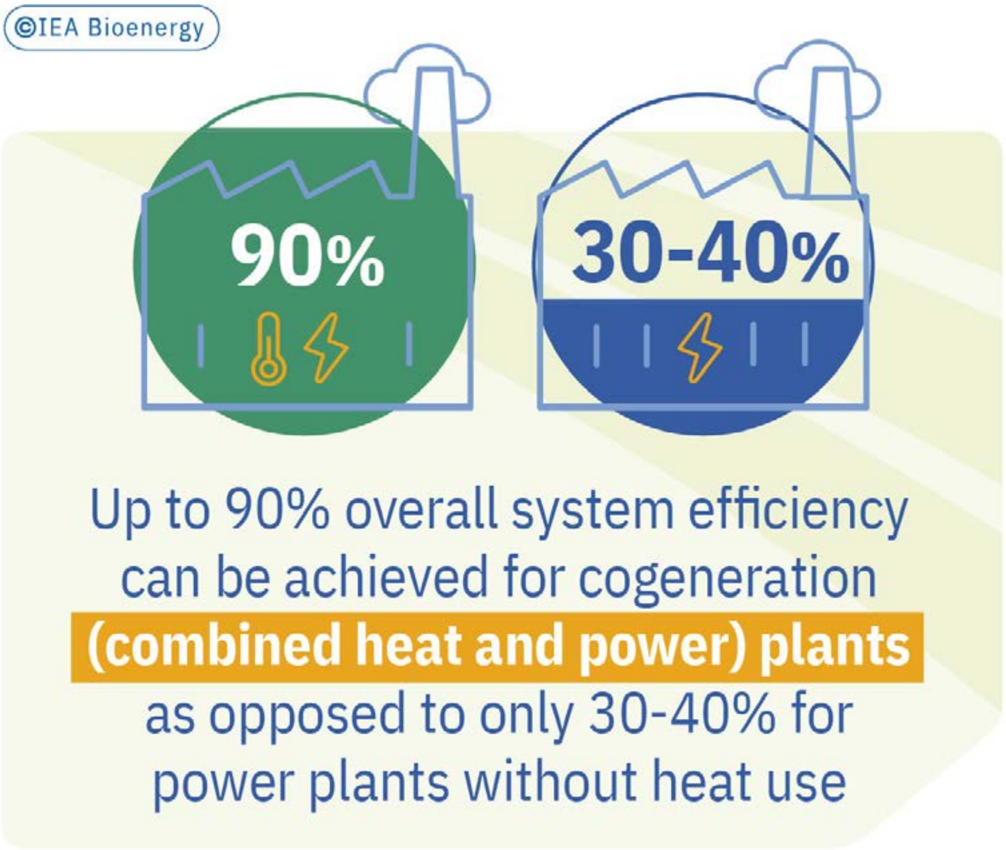
The market penetration of biomass-based process heat applications, however, is often limited to industry sectors with direct links to biogenic material. For instance, it is very common for the pulp and paper industry to cover some of their operational energy demand from production residues (e.g., black liquor). Similar concepts of on-site energetic use of by-products are also frequently applied in the food and feed industry. Good examples were recently published by experts of IEA Bioenergy Task 32:

- Wood chip combustion for process steam in a potato processing industry
- Combustion of wood chips and grain residues for process heat supply in the largest bakery in Switzerland

In contrast, industrial sectors with no relation to biomass have frequently shown limited interest in renewable heat concepts. The main reason is costs. Due to fossil-based energy prices in industry being historically quite low, it is often difficult to find economically competitive biomass-based solutions, unless policy-based market corrections such as carbon pricing or subsidy schemes are in place. Consequently, industry energy prices and regulatory framework conditions can be identified as keys to success for biomass-based process heat applications.

Combined heat and power

The heat derived during the combustion of biogenic material can be used to operate a thermodynamic cycle, usually a steam cycle, to generate electricity. In CHP plants, which are also called cogeneration plants, both forms of energy are provided. This can increase the overall system efficiency compared to power plants without heat use from 30–40% to 80–90%, if heat demand is stable throughout the year.



Up to 90% overall system efficiency can be achieved for cogeneration **(combined heat and power) plants** as opposed to only 30-40% for power plants without heat use

Active flue gas condensation, for example with a heat pump, can increase system efficiency even further. In cases where the heat is mainly used for residential heating, the heat demand in summer will be significantly lower than in winter. In such cases thermal cooling concepts can be considered which use the excess heat during summertime to generate cooling energy via absorption or adsorption heat pumps. Alternatively, biomass CHPs could be operated only in the cold season when there is sufficient heat demand; this practice is already being applied in some regions.

In the low-capacity range, alternative power technologies like Organic Rankine Cycles (ORC), Stirling engines, or thermoelectric generators are applied in addition to steam-based processes. While a few products are already being successfully marketed, several are still in the demonstration phase. A good overview of best practice solutions for decentralised CHP systems and the state of technology of small-and micro-scale CHP technologies has recently been published by IEA Bioenergy Task 32.

Bio4 at Amagerværket, run by the Greater Copenhagen Utility (HOFOR) is one of the largest biomass CHP (cogeneration) plants worldwide with a wood chip fuel capacity of 500 MW, providing heat and power to the city of Copenhagen (Denmark). (Photo credit: Morten Tony Hansen)

Power plant applications

Rankine steam cycles are still the most common thermal power applications in the world energy system. The heat used to produce the steam can be generated through biomass combustion. Biomass power plants apply different combustion technologies depending mainly on the type and quality of fuel they are using. Grate- and fluidised bed–fired systems are very common, having proven their reliability in many applications.

Erecting dedicated biomass power plants usually requires long-term fuel delivery concepts and contracts. Economies of scale help in reducing the specific costs; nevertheless, biomass power plants require significant investments and relatively long payback times, depending on the regulatory framework conditions in place.

In contrast, the full conversion of existing coal power plants to use biomass feedstocks appears to be promising in terms of reducing high investment costs. However, experience—not least with dust explosions—shows that many modifications, predominantly in the fuel and ash handling and preparation phases, are necessary to ensure the safe and reliable operation of such plants. Pre-treatment options such as steam explosion or torrefaction of the fuel can significantly reduce these efforts and the corresponding costs, as they can modify relevant fuel characteristics like milling properties, water resistance, and dust formation tendencies. Task 32 has studied steam explosion process technology as a part of a project on fuel pre-treatment.

Co-firing biomass in coal power plants

In terms of its potential for cutting greenhouse gas (GHG) emissions, the cofiring of biomass in coal power plants is very attractive. Only minor modifications to the plant are necessary to replace up to 50% of the coal with biomass, if the biomass is pre-milled to the required size range for the pulverised fuel boilers. Consequently, the immediate GHG savings in operational coal plants are highly cost-effective. The major drawback of this option, however, is that the share of cofiring fuel is limited and thus does not offer full decarbonisation. Unless it is equipped with carbon capture and storage (CCS) technology, this option can be seen only as a bridging technology towards fully renewable net zero emissions solutions.

More information is offered in this publication: The status of large scale biomass firing – the milling and combustion of biomass materials in large pulverised coal boilers

Waste-to-energy plants

Waste used as a feedstock for waste-to-energy plants is highly heterogenous and often contaminated. The feedstock can consist of residual waste streams from municipal solid waste (MSW), commercial and industrial (C&I) waste, and construction and demolition (C&D) waste. This calls for the use of robust technologies and extensive emission mitigation measures, leading to waste-to-energy facilities being associated with relatively high costs.

The municipal solid waste- (MSW)-to-energy plant in Vienna operated by Wien Energie converts 260,000 tonnes of MSW per year to heat and electricity for the capital of Austria (exterior design by Friedensreich Hundertwasser) (Photo credit: Wien Energie/Ludwig Schedl)

Different technologies are available, but the market to date has been dominated by incineration-based solutions that primarily apply grate-fired and fluidised bed boilers. There is currently a growing interest in alternative waste-to-energy technologies like gasification.

Waste-to-energy plants should not be seen as universal solutions for a malfunctioning waste-management system, but as part of an integrated approach to creating sustainable waste-management and energy systems.

Environmental effects

Greenhouse gas emissions

Biomass combustion applications can reduce life cycle GHG emissions by up to 90% compared to the respective fossil alternatives (Solid and gaseous bioenergy pathways). The main factors influencing GHG balance are the fuel supply chain emissions and the overall system efficiency—GHG emissions during the operation phase are mostly balanced out, with CO2 being absorbed from the atmosphere during biomass growth.

The combination of large-scale biomass power, CHP, or industrial applications with carbon capture and storage (CCS) is attractive in terms of achieving net-negative GHG emissions, but the current state of the art still falls well short of such solutions. Newly built plants focus on innovative technologies like chemical looping combustion, which features higher CO2 concentrations in the flue gas and thereby reduces sequestration costs. When it comes to the retrofitting of existing bioelectricity or biomass-based CHP technologies with CCS, the preferred alternative is clearly post-combustion separation of CO2, as this is currently commercially available.

The IEA Bioenergy project “Deployment of Bio-CCS/CCU Value Chains” compiles case studies that provide deeper insights into the key aspects at stake for companies setting up value chains for capture, transportation, and sequestration or utilisation of biogenic CO2.

Among the different negative emissions options, bioenergy with carbon capture and storage (BECCS) is one of the most promising. A full-scale BECCS project was recently selected to be built at the Stockholm biomass CHP (operated by Stockholm Exergi) and will receive financial support from the EU Innovations fund. The project is expected to produce and compile comprehensive information about the whole BECCS value chain, providing an in-depth basis for further roll-out and implementations of BECCS.

Among the different negative emissions options, bioenergy with carbon capture and storage (BECCS) is one of the most promising.

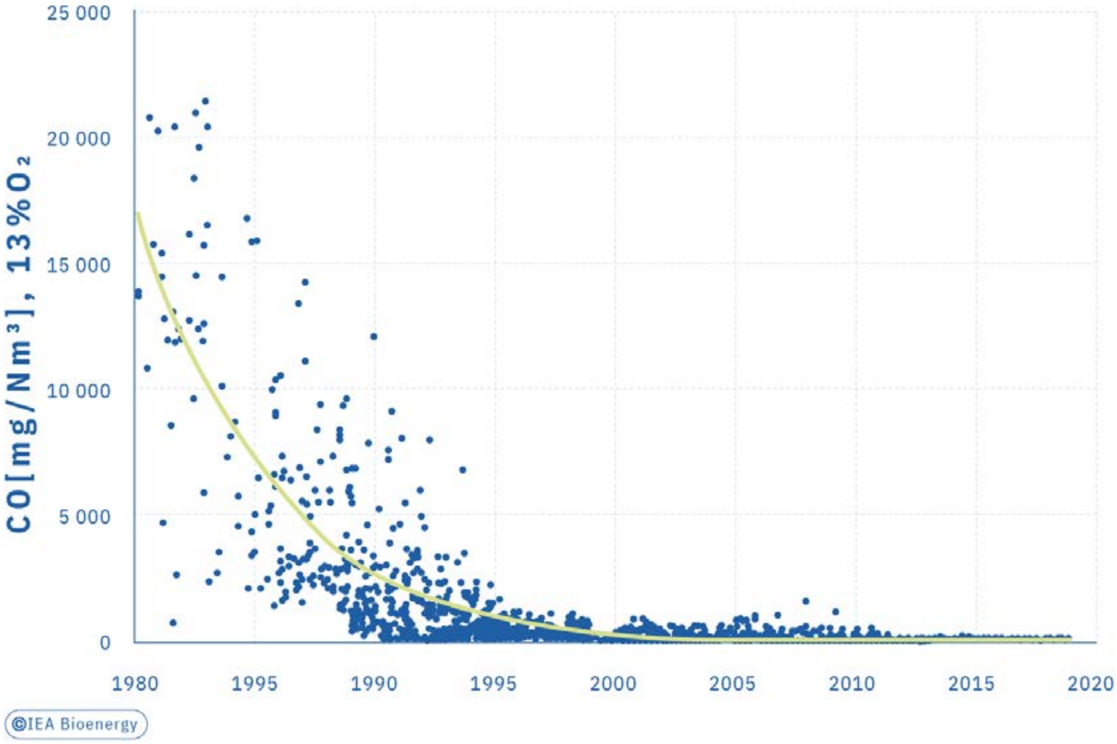
Emission of air pollutants

During biomass combustion, gaseous and particulate pollutants are generated that could lead to adverse health impacts. After decades of research, the formation mechanisms of the major pollutants from biomass combustion are well known. Mitigation strategies have, however, been developed and implemented, leading to significant emission reductions.

When discussing emissions from biomass combustion, it is important to distinguish between organic and inorganic pollutants and also primary and secondary aerosols. Organic pollutants are particularly relevant to small-scale biomass combustion and can be avoided under optimal combustion conditions. Particles formed during incomplete combustion can exhibit a high cytotoxicity, while particles from properly operated appliances are mainly inorganic (derived from ash constituents in the biomass) and exhibit significantly lower or even undetectable cytotoxicity.

Moreover, inorganic particles can be removed effectively by air pollution control equipment such as electrostatic precipitators or fabric filters. While particulate removal of this kind has been state-of-the-art for medium and large-scale combustion facilities for many years, several solutions have also recently been developed and implemented for small-scale applications. Hence, today, such emission abatement technologies are available for the full power range of biomass combustion applications.

Biomass combustion will play an important role in our future sustainable energy system. To ensure low emissions of air pollutants, it is essential to support the implementation of state-of-the-art combustion technology and ensure appropriate operation. A powerful tool in this context is the international standardisation of product- and product- testing requirements accompanied by financial support schemes for high-quality technologies on the one hand and stringent emission legislation on the other. (Reference: Aerosols from Biomass Combustion – Technical report).



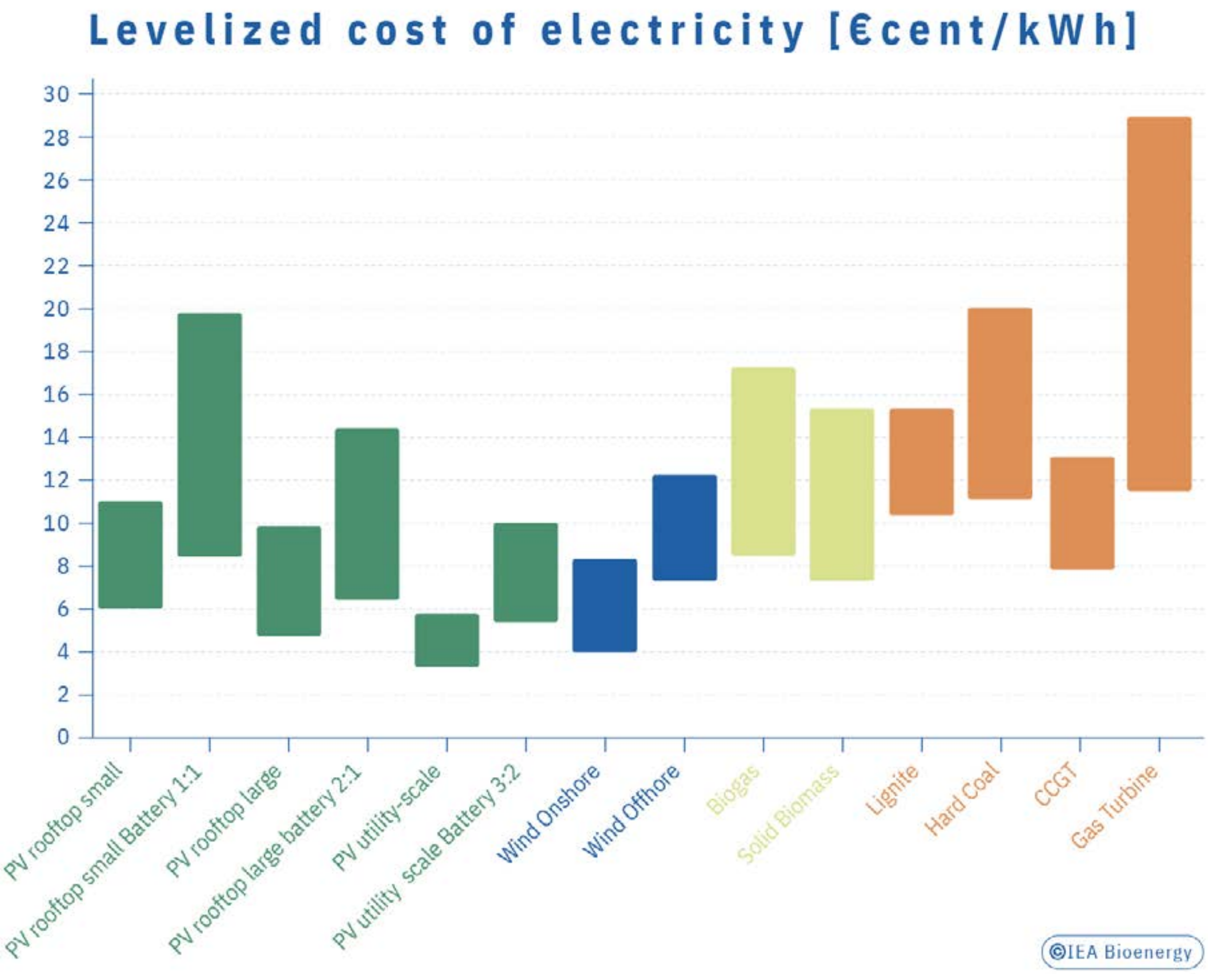
Reducing carbon monoxide emissions from small-scale biomass boilers type-tested at BLT Wieselburg (an accredited testing lab in Austria)

Costs

The profitability of a biomass combustion system is different for heat-only, power-only, and CHP systems. For residential heating applications, biomass combustion systems are often economically competitive under a variety of regulatory framework conditions. Larger-scale heating plants, such as those providing process heat applications in industry, usually require supportive economic environments with, for instance, carbon pricing or taxation systems in place, to make them competitive against fossil alternatives. In general, the economics of biomass combustion systems improve with higher heat demand and higher full-load hours.

For power and CHP applications, supportive regulatory framework conditions are essential. Further major influencing factors are biomass fuel costs and electricity market prices. Depending on electricity prices, biomass combustion-based power is often economically feasible only if financial supporting schemes such as feed-in tariffs or contracts for difference (CFDs) are available.

However, this is also the case for other renewable sources, as a recent study by Fraunhofer ISE concludes for the case of Germany. Levelised costs of electricity (LCOE) from biomass combustion systems were calculated at 7–15 €cent/kWh which, although higher than the average wholesale electricity prices of the past years, falls into a similar range to most of the other technologies investigated. Only utility-scale photovoltaics (PV) and on-shore wind power plants tend to reach lower LCOE, whereas coal and gas power are found at the upper end of the cost range of 20€cent/kWh and above. For fossil fuel systems, moderate emission certificate prices (within an Emission Trading System) of 32–36€/t CO2eq were assumed.



Among the renewable energy technologies and conventional power plants in Germany in 2021, only utility-scale PV and on-shore wind power plants tended to reach lower levelised costs of electricity (LCOE), whereas coal and gas power were found to be at the upper end of the cost range of 20€cent/kWh and above (with CO2eq prices of 32–36€/t assumed).

On a global scale, for most of the projects reviewed by the International Renewable Energy Agency (IRENA), LCOE is in the range of 0.05–0.15 USD /kWh, which is in line with the German case outlined above.

It is important to mention that all conclusions regarding the economy of biomass combustion systems are based on historic data. The extreme volatility of energy prices, particularly the steep increase in electricity and natural gas prices observed in the second half of 2021, is not considered in any of the studies mentioned above. If this turns out to be a long-lasting trend rather than a short-term market distortion, it will affect the (renewable) energy business.

Current research gaps and opportunities

Even if biomass combustion systems in all power ranges can be considered as mature technologies, significant research and development efforts are ongoing and the transformation of the energy system brings new challenges and opportunities that need to be addressed:

- Emission reductions still remain important in the case of small-scale appliances for residential heating, which typically come without secondary pollution abatement equipment, and also for medium- and large-scale combustion plants. Cost-effective solutions for reducing emissions of particulate matter and organic compounds in small-scale heating systems can expect good market opportunities, given that the sales figures for residential stoves and boilers are huge and emission regulation measures have been, and are being, tightened in many countries. For larger applications such as district heating systems, where complete combustion conditions widely avoid organic emissions, the reduction of NOx emissions is one of the major challenges.
- The transition away from fossil fuels in industry, in particular for high-temperature heat applications, is one of the most promising future market segments for biomass combustion technologies. The general trend towards greater electrification will also take place in many industries, but it is not well suited to all applications. Developing tailored sustainable energy solutions for providing heat to industrial processes is thus a promising new market segment for biomass combustion.
- Energy systems worldwide are under rapid development in order to comply with the climate change mitigation targets; they offer several unique opportunities for biomass combustion-based technologies. Increasing shares of wind and solar power are significantly improving the GHG balance of power-generation systems, but at the same time they are increasing the demand for grid balancing. Biomass combustion-based technologies offer the required high level of operational flexibility needed for grid balancing. At the same time, it is clear that additional efforts will be necessary to reduce GHG emissions in order to achieve the climate targets of the Paris Agreement. Biomass-based carbon capture and storage or utilisation concepts, where the carbon is sequestrated or synthesised into new products, can lead to net-negative GHG emission balances.
- Several technology manufacturers, following their vision of downsizing power plants to fit into every building, are developing robust and efficient small- and micro-scale CHP solutions. Most concepts are based on state-of-the-art wood pellets or wood-chip boilers which are equipped with different power units such as Stirling, micro-steam engines, or Organic Rankine Cycles (ORC). Due to the technological and economic challenges faced by such technologies, only a few products have entered the market. The idea of providing cost-effective CHP solutions for residential buildings, however, remains attractive, in particular as they nicely complement solar systems by providing energy during periods of low sunshine.

In research and development projects, computer modelling and simulation tools are often combined with experimental settings

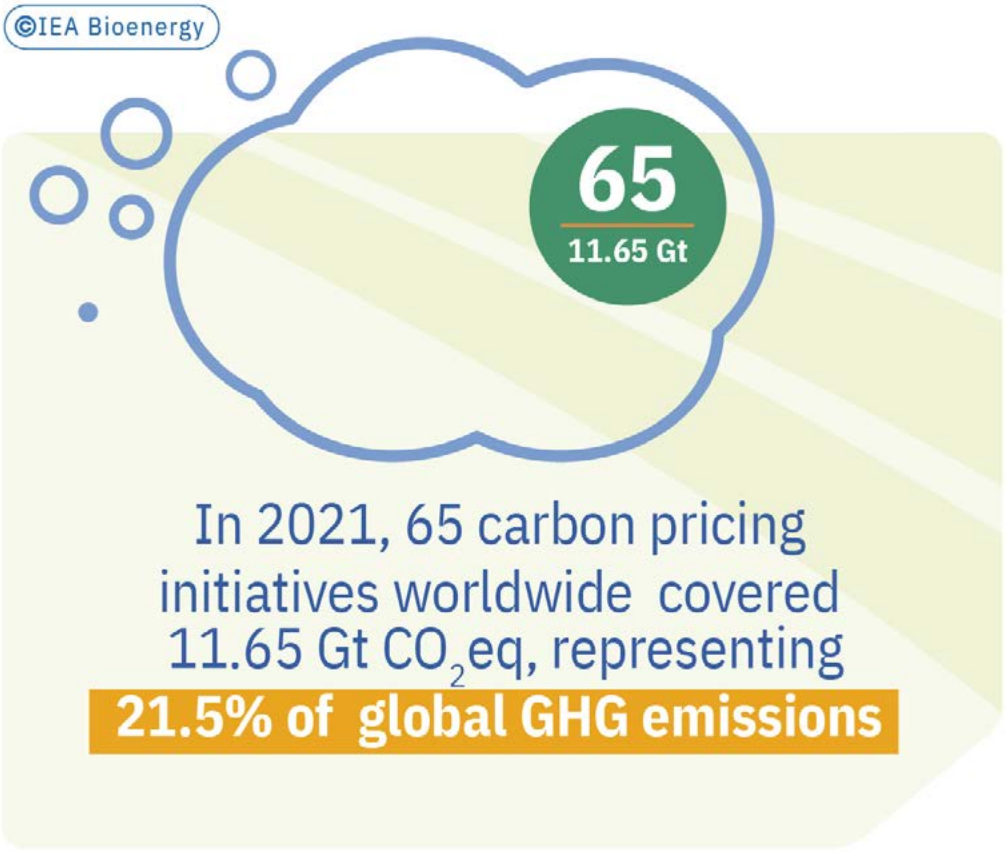
Powerful policy instruments

Many countries have implemented financial support schemes to stimulate the market penetration of more efficient modern biomass combustion systems. High capital expenditure (CAPEX) often poses a significant market barrier, especially for small-scale applications; several governments have thus implemented subsidy schemes that offer funding for the technology investment.

The actual implementation of such programmes differs from country to country, and even regionally or locally. In addition to such general financial incentives for renewable energy installations, specific programmes supporting the replacement of fossil fuel–based appliances have proven their effectiveness. Moreover, recently, such programmes have begun to include scope to replace old biomass-based technologies which can no longer be considered state-of-the-art in terms of efficiency and emissions.

For power applications, technology-specific feed-in tariffs or contracts for difference are the most common type of policy support. The procedures for defining the amount and the allocation of tariffs differ between countries. Today, most feed-in tariffs are constant over a defined period of time; however, new support systems tend towards CFDs that include compensation for the gap between the renewable power production cost and the actual electricity price.

Such dynamic systems are popular, as they reduce support costs when electricity market prices are higher. Once the shares of fluctuating renewable energy in the electricity system increase, the need for flexible and plannable production capacities may rise. In such a scenario, the value of electricity provided to the grid is likely to vary significantly according to the time (day/night, summer/winter), thus calling for dynamic financial support schemes.



Completely different policy approaches aim to discourage people from using fossil fuel–based technologies. Measures such as carbon pricing or taxation systems, which impose taxes on fossil fuels and exempt or incentivise use of biomass fuels have already proven their effectiveness in Denmark. In 2021, 65 carbon pricing initiatives worldwide covered 11.65 Gt CO2eq, representing 21.5% of global GHG emissions. Sweden was the first country to introduce carbon pricing and has the highest carbon price in the world of almost 140 USD/t CO2eq; this has proven effective at driving decarbonisation.

Alternatively, the use of fossil fuels can also be prohibited directly or indirectly, as is currently the case for heating oil in residential applications (e.g., in Austria).

A recent report of Task 32 highlights the opportunities for bioenergy technologies to deliver heat in industry, and compares these with alternatives to decarbonisation such as CCS, electrification, and hydrogen. Specific policy recommendations are provided to accelerate their adoption.

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08

Gasification for multiple purposes

Gasification as a technology allows us to establish biomass- and waste-based biorefinery processes, leading to a more sustainable energy system (Photo credit:Unsplash/Dustan Woodhouse)

Gasification for multiple purposes

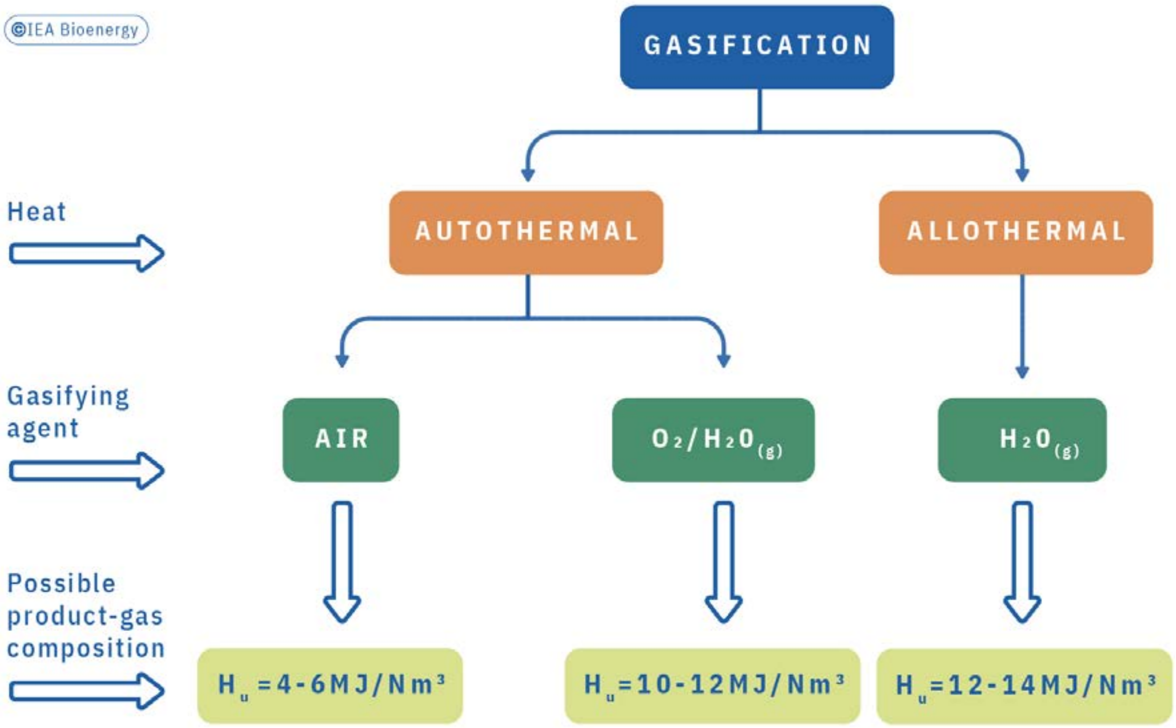
Gasification is the thermo-chemical conversion of solid biomass or residues into product gas. This gaseous secondary energy carrier is the basis for a broad spectrum of valuable products. Product gas can be either used for direct heat and power generation or upgraded into green gases or liquid products. The product spectrum includes hydrogen, synthetic natural gas (SNG), liquid transportation fuels, kerosene, and chemicals. Gasification is thus significantly more versatile than direct combustion. It can be applied in different market segments and react to market changes, offering a powerful pathway towards sustainable energy transition.

> **Gasification is significantly more versatile than direct combustion.**

Gasification occurs when a solid feedstock is heated and brought into contact with a gasifying agent. Typically, either a single agent—air, steam, carbon dioxide, oxygen—or a defined mixture can be used. This results in the conversion of the solid feedstock into a product gas. This gas is mainly composed of hydrogen, carbon monoxide, carbon dioxide, methane, and possibly nitrogen. However, the composition is heavily dependent on the gasifying agent used and influenced by the feedstock and operating conditions.

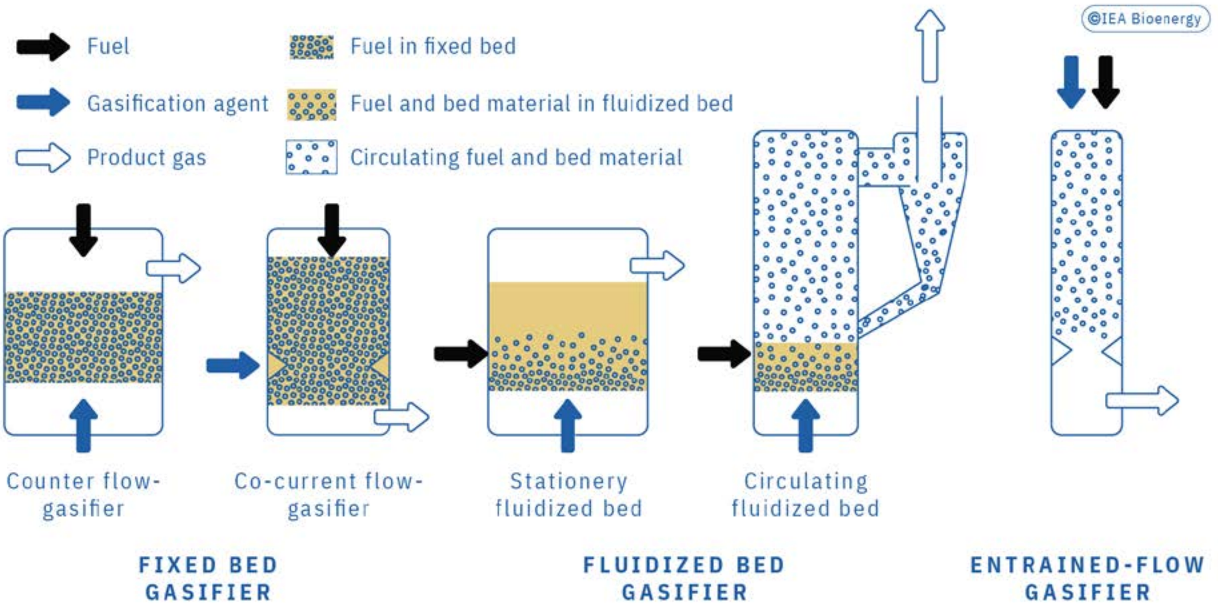
Gasification is a superordinate term and a broad variety of different gasification technologies exist. The selection of the technology depends on a number of different factors. Of these, the most prominent are the selection of feedstock, the end product(s), and the scale of production. The end product(s) gained from a gasification process will determine the gasifying agent and the operating conditions, among other parameters.

The typical product gas is mainly composed of hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen (respectively, H2, CO, CO2, CH4, and N2), if air is used as the oxidant. The composition varies significantly between different gasification concepts. Autothermal gasification, using either air or oxygen/steam mixtures, is characterised by a lower content of H2 in the product gas in comparison to allothermal gasification which uses steam. In recent years, the use of CO2 as a gasification agent has been attracting increased interest. CO2-based gasification would be categorised under the section “allothermal” gasification.



Product-gas compositions from different gasification concepts

The scale of production defines the utilisation of fixed bed, fluidised bed, or entrained flow gasification reactors. The selection is also heavily based on the choice of feedstock, as feedstock characteristics lead to constraints on which reactor type is suitable. This is especially relevant for feedstock with relatively high water content. In specific circumstances, other technologies, which are not further discussed in this report, may also be suitable. Fixed bed gasification is typically used in small-scale applications in the kW-scale range to produce heat and power. Fluidised bed reactors are used in medium- to large-scale applications ranging from around 10 to many hundred MW. Thus, fluidised bed gasification enables more complex biorefinery processes with downstream gas upgrading equipment. The same is true for entrained flow gasification, which is typically applied at even larger scales (above 100 MW).



Gasifiers vary in the way the feedstock is brought into contact with the gasification agent (Source: IEA Bioenergy Task 33 report "Gasification applications in existing infrastructures for production of sustainable value-added products")

Technology readiness level and status of implementation

Originally developed in the early 19th century to produce a burnable gas from coal, gasification of coal and oil residues has been carried out and improved for decades in commercial applications. Development intensified in the 1980s due to the increasing energy needs of emerging markets in developing countries (e.g., China).

Biomass gasification for heat and power generation has already been successfully introduced into the market and is widely deployed. The strongest focus lies on air gasification from wood-based biomass. The aim is to produce a gas of low calorific value (4–5 MJ/Nm^2) for heat and/or power generation. This can be achieved either by operating stand-alone power plants using biomass as the feedstock or by substituting biomass-based product gas for coal in coal-fired plants. The latter method is used to reduce the fossil-fuel input in existing coal-fired plants. Using product gas from biomass gasification in the coal-fired plant has the advantage of not introducing biomass-related impurities into the coal-fired plant. On the downside, such a configuration requires parallel systems, one for coal and another for biomass, thereby increasing costs and complexity.

Biomass gasification for heat and power generation is already widely deployed

(see IEA Bioenergy Task 33 database)

While the above-mentioned applications have reached market maturity, current developments within the field of gasification have shifted the focus of the technologies. On the one hand, cascadic use of biomass shifts the feedstock for gasification more towards biogenic residues and wastes. On the other hand, the upgrading of product gas into more valuable end products transforms gasification from being a purely energetic use of feedstock into more complex multiproduct biorefinery processes. In this regard, process chains combining gasification technologies with advanced gas cleaning, gas upgrading, and potentially synthesis processes are being developed. The most important future applications are the production of Fischer-Tropsch (FT) diesel and kerosene, biomethane, and hydrogen.

For biorefinery processes, gasification technologies using steam, oxygen, or carbon dioxide are becoming more relevant, as nitrogen-free synthesis gas is needed for further upgrading. This development is currently at pilot-to demonstration scale (TRL 5–7) for CO2-based gasification or in the first phase of commercialisation (TRL 8–9) for steam-based gasification.

As well as medium- and large-scale biorefinery applications, small-scale gasification (< 1 MWth) has been successfully developed and introduced to the market. These systems are commonly based on fixed-bed conversion technologies and operated using air as the gasification agent. After a basic cleaning step, the product gas is combusted in modified engines to provide heat and electricity. Most applications are operated with wood chips. The fixed-bed conversion technology usually requires higher fuel quality compared to fluidised-bed systems which are often applied in medium- and large-scale gasification. The most critical fuel parameters that need to be monitored and adjusted for wood chips are water content and share of fine particles.

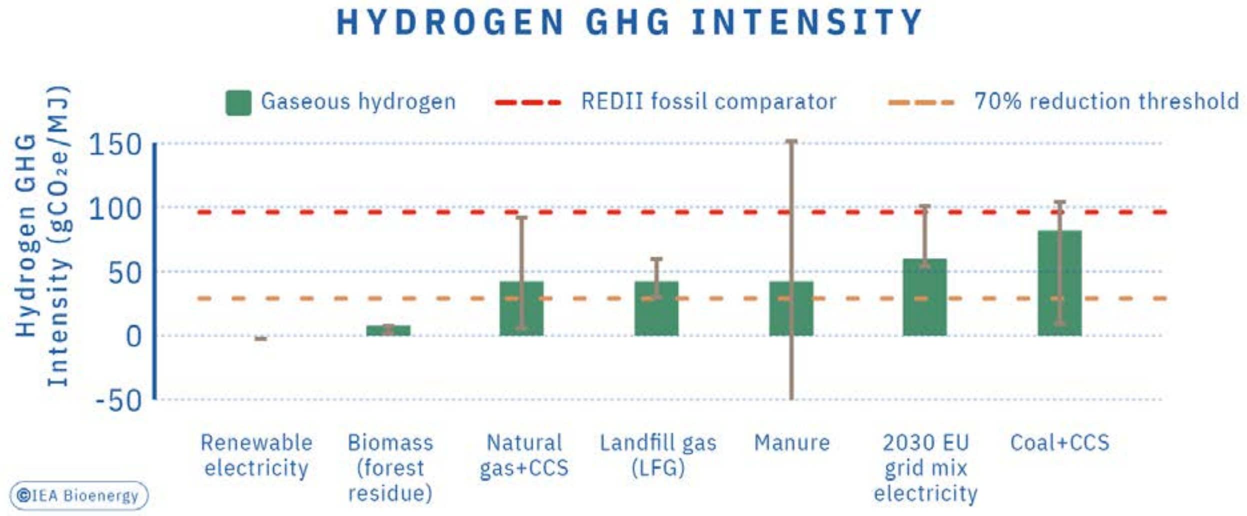
Environmental effects

Greenhouse gas emissions

Gasification of biomass feedstocks or biomass residues can have a major impact on GHG emission reduction. The exact amount of GHG emission reduction depends on the production pathway—from feedstock cultivation through harvesting to processing—and has to be assessed for every feedstock-to-product pathway separately.

One important product of gasification technologies is hydrogen. If hydrogen is produced from renewable electricity via electrolysis, related GHG emissions are close to zero. Gasification of forest residues for producing hydrogen also creates only very low GHG emissions. Hydrogen produced from natural gas—where CCS is not applied—has very high GHG emissions of almost 100 gCO2eq/MJ. Even when CCS is applied to natural gas- or coal-based hydrogen production, GHG emission reductions are, on average, limited and above the 70% reduction threshold for new biofuel installations, as required by the European Union (EU) Renewable Energy Directive.

In the cited study, forest residue was used as biomass feedstock in the gasification pathway. However, different biogenic residues could also be used. Preliminary analysis by the authors of the study showed similar GHG intensities among agricultural residues, forest residues, and energy crops.



GHG emissions and intensities of fuels are calculated on a well-to-wheel basis. Hydrogen produced through the gasification of biomass offers very high GHG emission reductions/very low GHG intensity (Adapted from ICCT White Paper: Life-cycle greenhouse gas emissions of biomethane and hydrogen pathways in the European Union)

Emission of air pollutants

Pilot scale gas cleaning at 1 MW gasification facility in Vienna, where air pollutants or their precursors are separated from the product gas to make it suitable for subsequent catalytic synthesis processes (Photo credits: BEST)

The product gas from gasification of biomass or waste mainly contains pollutant species precursors. These are molecules that become known pollutants once the product gas is combusted. For example, in the case of nitrogen, instead of nitrogen oxides (NOx), mostly ammonia (NH3), and to a minor extent, for example, hydrogen cyanide (HCN) are formed. With regard to sulphur, instead of sulphur oxides (SOx), mostly hydrogen sulphide (H2S), and to a minor extent, for example, carbonyl sulphide (COS), are formed. Pollutants and greenhouse gases can be separated before further use of the product gas.

When nitrogen-free gasifying agents such as steam, oxygen, and/or carbon dioxide are used, the volume of the product gas is significantly lower when compared with flue gas from combustion for the same input of feedstock. Therefore, the concentration of pollutant species or their precursors in the product gas is accordingly higher, easing their removal.

Costs

Biomass gasification is a rather costly technology. The investment costs for biomass gasification systems for the production of heat and power are in the range of 5,000 to 10,000 EUR/kWel. The main advantage of such installations is that they can be used to convert coal-fired plants into biomass-based plants, thereby enabling a switch to renewable fuel and avoiding stranded assets.

Biomass gasification and subsequent synthesis for the production of transport biofuels offers the opportunity to produce high-quality, drop-in biofuels for sectors that are otherwise hard to decarbonise. Investment costs range from 0.55 to 1.1 EUR/litre biofuel. While the resulting fuel production costs of 1.15–1.39 EUR/litre will be higher than for fossil fuels, they are quite comparable to production costs of other advanced biofuels. A similar situation is expected for the synthetic natural gas route from biomass gasification, which has estimated production costs of 65–80 EUR/MWh.

Current research gaps and opportunities

An observable shift from biomass gasification for combined heat and power applications to residue- and waste-based gasification for biorefinery processes leads to several RD&D needs.

Combustion (front) and gasification (back) reactors in Vienna, with adapted reactor design to allow for the use of biogenic wastes (Photo credits: BEST)

The use of biogenic residues and wastes as feedstocks necessitates reactor design adaptations**.** These is due, among other factors, to higher ash content, increased amounts of volatiles, and the feedstock having a higher degree of heterogeneity. Pollutants from the conversion of biogenic residues and waste need to be addressed downstream in the gas cleaning process. Depending on the end product, extensive fine gas cleaning needs to conducted.

To establish **biorefinery concepts** based on gasification, full process chains from feedstock to end products need to be developed. While many process units already have a high degree of maturity, their technology readiness depends on the interfaces and combined operation within the process chain. In this regard, there are currently multiple pilot- to demonstration-scale projects under way to establish complete biorefinery concepts.

As the concepts are manifold—ranging from direct product gas combustion to various complex synthesis applications —RD&D needs to **evaluate and benchmark different process chains**. Economic feasibility will depend on the market needs and regulatory framework. Significant investments are needed to bring gasification-based technologies from pilot- to demonstration- and, finally, to industrial-scale.

> **Significant investments are needed to bring gasification-based technologies from pilot- to demonstration- and, finally, to industrial-scale.**

Hybrid technologies that combine electricity and biomass feedstocks can improve product yields of gasification-based (or other) biorefineries. Combining hydrogen from electrolysis with product gas from gasification leads to higher amounts of end products such as liquid transportation fuels or synthetic natural gas. While thorough investigations have already been performed in this regard at smaller scales, such coupled processes still need to be demonstrated and scaled up.

Small-scale gasification for decentralised heat production or on-site production of materials is moving towards modular set-ups, to increase reliability of operation. Modularity is also advantageous during maintenance and servicing, and this supports faster commercialisation. The IEA Bioenergy Task 33 database lists 10 units in operation today, of which five are at commercial scale.

The **sequestration of CO2** has recently been gaining in importance. Carbon capture and storage technologies will have to contribute if the ambitious targets for decarbonisation of the global economy are to be reached. If applied in sustainable bioenergy processes, it is even possible to achieve negative CO2 emissions. CO2 can be captured from the syngas before conversion to, for example, Fischer-Tropsch fuels, which would roughly double the amount of mitigated CO2 while only slightly increasing overall biofuel production costs.

Another possible pathway is to produce **sustainable hydrogen from gasification** while capturing CO2 to achieve carbon-negative hydrogen production. This can be achieved either by conventional gasification technologies or by novel processes such as Sorption Enhanced Reforming (SER). During SER, limestone is used as bed material in connected fluidised bed reactors. If the limestone is shifted between two temperature levels (approximately 600–700°C and 830–930°C) the bed material allows the selective transport of CO2 from the product gas to the flue gas. The bed material is first calcined to calcium oxide (CaO) at elevated temperatures. The CaO is then carbonised in the gasification reactor with the CO2 captured from the product gas. Afterwards, calcination occurs once again in the combustion reactor resulting in the release of CO2 into the flue gas.

Powerful policy instruments

Gasification can be applied in different market segments, including public transportation, offering a powerful pathway towards sustainable energy transition (Photo credit:Unsplash/Ina Carolino)

Depending on the application, successful policy instruments either include investment subsidy schemes and technology-specific feed-in tariffs for green heat and electricity production or, in the case of transport biofuels, blending mandates and investment support to demonstration facilities.

In a recent study three different scenarios for the implementation of biomass gasification for Fischer-Tropsch (FT) diesel and Synthetic Natural Gas (SNG) production in Austria were evaluated, with each scenario based on one of the following policy instruments:

- Product-based subsidies of 10–40 EUR cent/L diesel and 5–20 EUR/MWh SNG
- Investment support of 24–66% for diesel and 16–72% for SNG from wood
- Implementation of carbon tax of 60–170 €/t CO2eq fossil diesel or 25–120 €/t CO2eq for natural gas

According to the results of the study, either of these policy instruments would be appropriate to make the production of diesel or SNG from wood economically viable in Austria. In all three scenarios, the ranges are mainly related to the expected fuel price ranges.

Carbon tax is not the only promising policy instrument. Product-based subsidies or investment support could also do the job.

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09

Direct thermochemical liquefaction

Bio-oil from fast pyrolysis is a sustainable alternative to fossil oil. It is used as boiler fuel today, but can also be upgraded to transportation fuels or chemical (Photo credits: Bioenergy TCP)

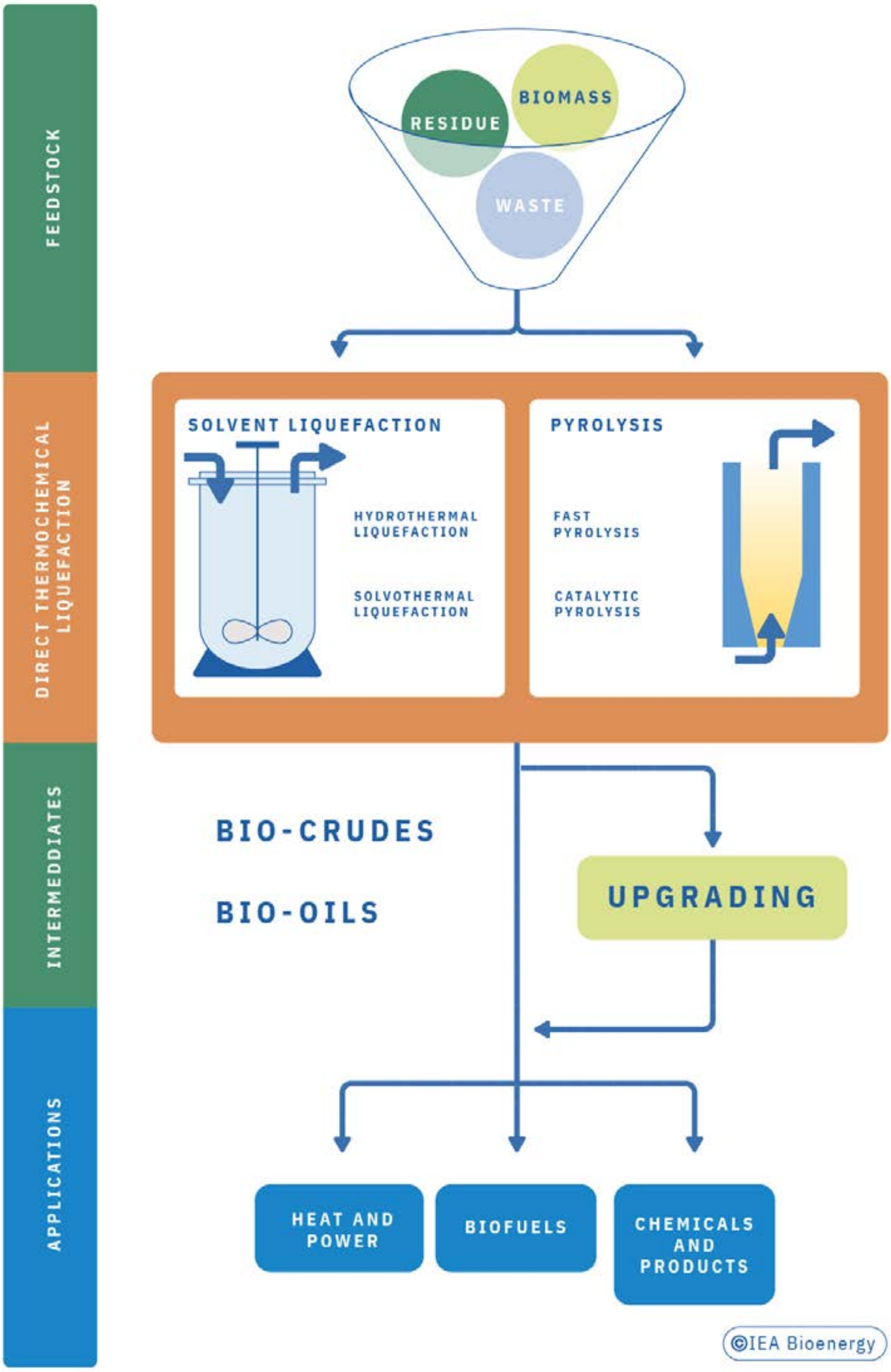
Direct thermochemical liquefaction

The term direct thermochemical liquefaction (DTL) covers two main technologies: solvent liquefaction and pyrolysis. Both can use a range of resources such as biomass feedstocks and biomass-based residues and wastes. The products of these processes are bio-crudes (from solvent liquefaction) or bio-oils (from pyrolysis).

Both bio-oil and bio-crude are energy-dense liquids, obtained from biomass, that are easier to transport and handle. Fast pyrolysis bio-oil is used commercially for heat production in boilers today. Moreover, through further processing steps, bio-oil and bio-crude can be upgraded for use as low carbon intensity biofuels for transportation, and also as chemicals and other valuable products.

Solvent liquefaction is the thermochemical conversion of biomass at an elevated temperature in the presence of a pressurised solvent. The process leads to a biomass slurry which is called bio-crude. The underlying mechanism is the conversion of polymers in the solid biomass into primarily liquid components. This is why solvent liquefaction could essentially be described as the pyrolysis of biomass in a liquid solvent environment.

A distinction is made between hydrothermal liquefaction and solvothermal liquefaction. This difference is based on the solvents used. Hence, hydrothermal liquefaction uses water, and solvothermal liquefaction uses a range of different solvents. Various catalytic methods are used in combination with both liquefaction processes.



Products from direct thermochemical liquefaction can directly contribute to decarbonising heat and power production and transport applications. Source: IEA Bioenergy Task 34 Direct Thermochemical Liquefaction

Hydrothermal liquefaction (HTL) was already attracting attention in the 1970s and 1980s. A wide range of raw materials can be processed using HTL, as no pre-drying of the feedstock is necessary. During the process, the pressure is maintained above water vapour pressure. The water thus remains liquid, acting as both solvent and primary reaction medium. The hydrolytic degradations that occur are much more efficient at lower process temperatures than dry thermochemical conversion technologies. Due to optimised process conditions, solids can be minimised, and the main part of the product is the desired bio-crude.

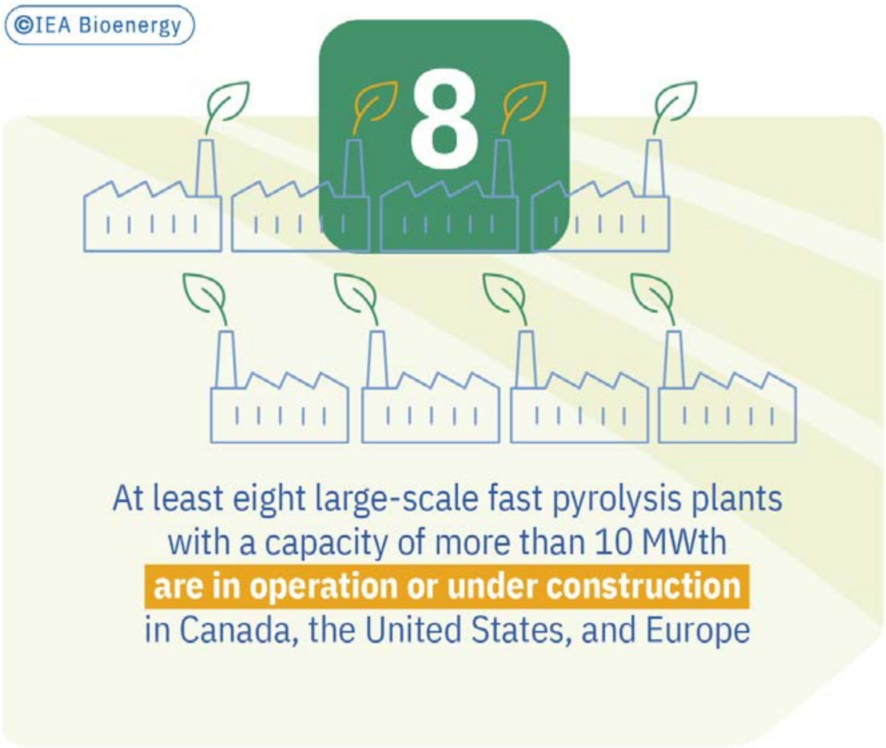
The product of **solvent liquefaction** is commonly known as bio-crude. In contrast to bio-oil, which is produced from fast pyrolysis, bio-crude usually has a lower content of oxygen and water. Bio-crudes are very different from petroleum oil and bio-oils. For example, bio-crudes are thermally more stable, exhibit higher viscosities, and have lower densities than bio-oils. However, bio-crude is not readily miscible with petroleum.

Pyrolysis is the thermochemical decomposition of solid biomass performed at elevated temperatures in the absence of oxygen. Thus, a solid, a liquid, and a gas fraction are achieved. The three product fractions are typically referred to as charcoal (or char or biochar), bio-oil, and product (or synthesis) gas. The distribution between the three products mainly depends on the pyrolysis process parameters, such as operating temperature and residence time in the reactor. Different modes of pyrolysis are also distinguished: fast, intermediate, and slow (depending on the process used—either torrefaction or carbonisation).

Pyrolysis can be viewed as a biomass densification step (e.g., torrefaction) to increase the energy density before long-distance transport. Fast pyrolysis is already established as a suitable technology for the production of marketable fuels. Additional applications with higher added value, such as production of activated carbon, are also state-of-the-art.

In fast pyrolysis, organic substances are heated within a few seconds up to 450–600°C in the absence of oxygen. Thus, the production of organic vapours is optimised at the expense of non-condensable gases (NCG) and char. The fraction of organic vapours is condensed into a liquid, the Fast Pyrolysis Bio-Oil (FPBO). Fast pyrolysis typically converts 50–75% of the weight of dry biomass into FPBO. Both of the other product fractions, char and NCGs, are used to generate heat and power for internal and external use, but the char can also be used to increase the level of carbon in soils and thus create negative greenhouse gas (GHG) emissions. The clean, mostly wood-based FPBO is used commercially to replace fossil heavy oils and natural gas in heat and power generation. FPBO typically contains up to 40% water and up to 5% solids.

Bio-oil or pyrolysis oil is a liquid biofuel produced by biomass pyrolysis. Bio-oil is a liquid emulsion of oxygenated organic compounds, polymers, and water. It contains acidic and reactive compounds which are thermally unstable. Bio-oil has a water content of 20–30% and an oxygen content of up to 40%. Consequently, bio-oil is different from bio-crude produced by solvent liquefaction. It also has properties that are dissimilar to those of petroleum oil and it is not miscible with petroleum. International standards are in place to regulate bio-oil quality for use as boiler fuel.



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At least eight large-scale fast pyrolysis plants with a capacity of more than 10 MWth **are in operation or under construction** in Canada, the United States, and Europe

Technology readiness level and status of implementation

Direct thermochemical liquefaction has the potential to make a major contribution to increasing the circular economy in the field of bioenergy and biochemical production.

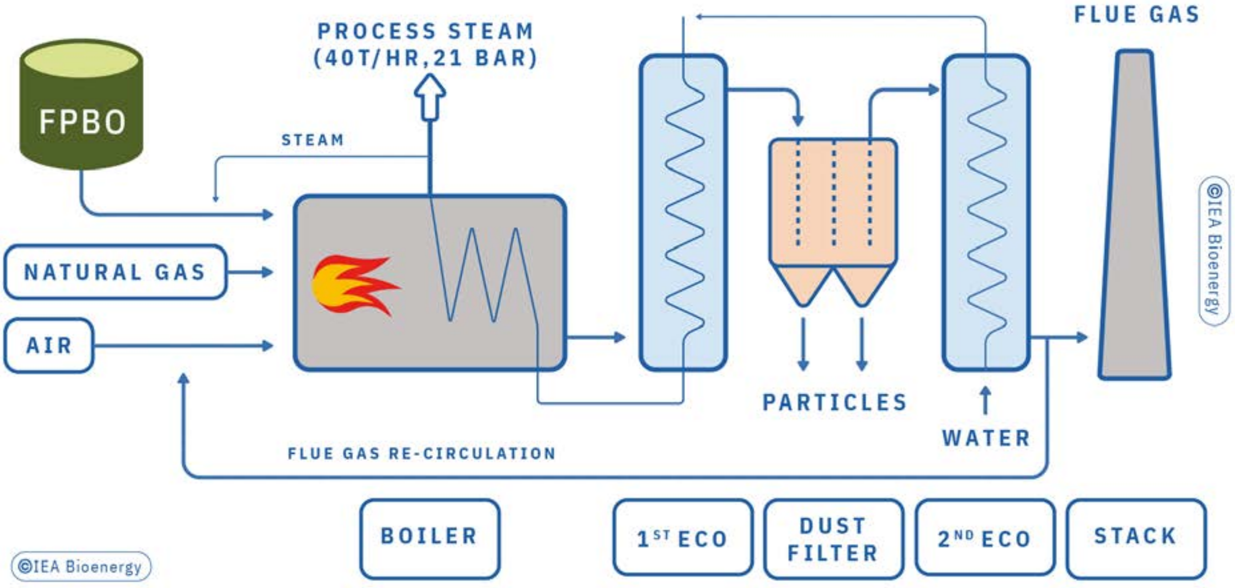
A study of commercial and demonstration scale thermal liquefaction plants in 11 countries that are active in the field, reveals that, to date, only fast pyrolysis plants are at demo- to commercial-scale (i.e., TRL 8–9). In contrast, hydrothermal liquefaction plants are at smaller (demonstration) scale. Wood and forest residues are the most used feedstock in commercial applications. Most of the bio-oils and bio-crudes produced are used as renewable heating oil and renewable fuel oil, respectively.

> **Fast pyrolysis plants are at commercial technology readiness level (TR 8–9), while hydrothermal liquefaction plants are scaling up from pilot- to demonstration-scale.**

Hydrothermal liquefaction (HTL) technologies are now scaling up from pilot- to demonstration-scale. It is worth emphasising that the use of different feedstocks, like agricultural and urban waste and sewage sludge, as well as non-bio feedstocks, like waste plastics and waste tires, is increasingly being investigated or put into practice.

According to experts of IEA Bioenergy Task 34, the direct thermochemical liquefaction technologies are making important advances with respect to bioenergy deployment. An extension of production through additional fast pyrolysis units has recently been observed. With more and more pilot projects reaching a technological readiness level beyond 6 and with reducing cost levels, diverse demonstration plants can be expected in the near future. Future policy support could increasingly drive the number of commercial DTL plants for the bioenergy sector.

One very good example is a demonstration of FPBO co-processing in an existing fossil refinery which is being enabled by increased carbon prices. The Pyrocell fast pyrolysis unit has been in operation since 2021, and its product is currently being co-refined in the fluidised catalytic cracking (FCC) unit of Preem refinery in Sweden. This is allowing FPBO to be upgraded in an economic manner to increase the share of renewable carbon in traditional transportation fuels.

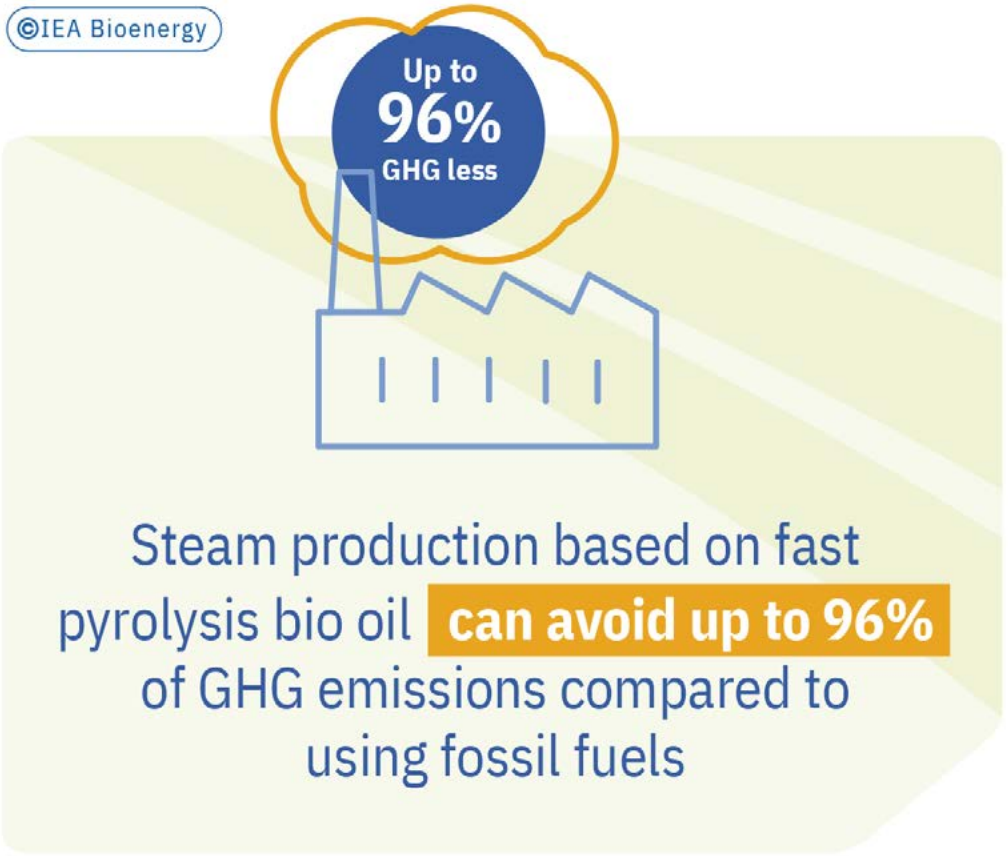


Fast pyrolysis bio-oil produced by Empyro is co-fired with natural gas in FrieslandCampina´s steam boiler (Source: IEA Bioenergy Task 34 report “Industrial heat case study 3: Process steam in a dairy factory via fast pyrolysis bio-oil”)

Environmental effects

Direct thermochemical liquefaction plants based on biomass and biomass-based wastes and residues have great potential in terms of GHG reduction when they are substituted for fossil fuel-based production. A recent study by IEA Bioenergy highlights the application of FPBO as a heating oil for steam production in industry. This evaluation indicated a 96% reduction of GHG emissions compared to using fossil fuels.

Moreover, the reutilisation of waste and residues in direct thermochemical liquefaction applications for the creation of new valuable chemicals, materials, or products enables circular economy-based production, thereby saving on other non-regenerative resources.



Steam production based on fast pyrolysis bio oil **can avoid up to 96%** of GHG emissions compared to using fossil fuels

Costs

The existence of commercial fast pyrolysis units shows that the cost of bio-oil can be competitive under given (local) market conditions. To date, this has only been the case for the use of FPBO as a boiler fuel.

Only few cost estimates are available for the production of a transportation fuel by DTL technologies, for which additional upgrading steps (primarily hydroprocessing) are required. Moreover, different DTL technologies are at different technology readiness levels, which makes comparison difficult. The National Renewable Energy Laboratory of the U.S. Department of Energy assessed the thermochemical research pathways of fast pyrolysis vapours for the production of transportation fuels and evaluated some process economic aspects as follows.

The capital costs for a fast pyrolysis plant with integrated upgrading to produce, for example, transportation fuels, mainly depend on the design and size of the plant. Individual installations include the following:

- Feedstock & Handling;
- Pyrolysis & Vapour Upgrading;
- Pyrolysis Vapour Quench;
- Hydroprocessing & Separation;
- Hydrogen Plant;
- Steam & Power;
- Cooling Water & Utilities;
- Water management.

Costs for each of these items include capital recovery charge, net electricity, and fixed costs, as well as expenses for raw materials, catalysts, and waste treatment. However, these individual costs can vary enormously.

To keep production costs as low as possible, it is essential to take into account the feedstock being used and the targeted applications of the products and by-products when planning the plant design and business case. The cost-intensive pre-drying of raw materials can be cited here as an example. At best, costs can be considerably reduced through a suitable choice of feedstock. By-products such as the resulting process heat should also be used to increase economic efficiency. Consideration should also be given during the planning stage to the location of a direct thermochemical liquefaction plant, as this will influence the downstream transport costs of feedstock and products.

Current research gaps and opportunities

Co-firing of pyrolysis oil with natural gas is already well established, but other technologies such as upgrading to transport fuels still need to be further developed. (Photo credit: ETA-Florence Renewable Energies)

Experts of IEA Bioenergy Task 34 have shown that direct thermochemical liquefaction technologies have matured and that they are driving bioenergy commercialisation forwards. Commercial fast pyrolysis units and additional pilot plants for other DTL technologies have been successfully operated, which has led to a technology readiness level of 6–9. Given the variety of technology readiness levels, different aims can be stated for the immediate future. Regarding fast pyrolysis, overall production capacities need to be extended and value-added uses of the bio-oil commercialised. The main aim for other DTL technologies, such as hydrothermal liquefaction, is their scalability to industrial capacities at reasonable costs.

However, to gain entry to the energy markets, the commercialisation of several technologies still faces economic and other non-technical barriers. There are a growing number of companies and technologies working towards, or that have already realised, commercial applications. Even though an increasing number of plants are under development and in operation, in terms of improving technologies, the following are needed:

- Long-term operation of large-scale reactor systems for emerging processes;
- Operation in real environments for more developed processes;
- Demonstration of actual production costs for transportation fuels;
- Establishment of a minimum product quality for value added bio-oil/bio-crude applications with norms and standards for producers and users;
- Continuation of refining measures for safe handling, transport, and use;
- Supporting pioneer applications and identification of innovative niche markets for biofuels and bio-oils; and
- Dissemination of information

In addition to the technological challenges, there are also open issues regarding the application of products. The use of bio-crudes and bio-oils as a product or intermediate for higher-value products is associated with particular challenges:

- Uncertainty of long-term cost estimates;
- Raw material supply and availability for planning purposes;
- Defining minimum product quality for value added bio-oil/bio-crude applications, and development of norms and standards for producers and users. These standards are needed for DTL products before they can gain a foothold in the market. Thus, various test methods, already developed, have been validated in round robin tests by the IEA Bioenergy Pyrolysis Network.
- Fast pyrolysis bio-oil is registered as a Registration, Evaluation, and Authorization of Chemicals (REACH) product in Europe. Accurate data on the bio-oil composition are needed to comply with this registration. The test methods being developed are thus essential to assess the qualitative and quantitative chemical composition of bio-oils, and also to monitor them during this early stage of market introduction.
- Rational insertion points for bio-oil and bio-crude in the (not fully compatible) hydrocarbon economy;
- Economic challenges to increase product value and flexibility; and
- Material incompatibility with the existing fuel handling system

Direct thermochemical liquefaction technologies provide several opportunities. Through this, a wide variety of residues and waste, in addition to biomass, can be processed, and valuable products developed. Depending on what wastes are used in the direct thermochemical liquefaction process, the bio-oils, bio-crudes, and also the char obtained from processing can be further processed into valuable products. Thus, these technologies can make a considerable contribution to establishing a circular economy and preserving resources.

In addition to large centralised plants, smaller decentralised plants are currently the preferred choice for processing residual and waste materials in order to shorten feedstock transport distances.

Moreover, thermochemical liquefaction technologies offer the economic opportunity to provide system services such as flexible (bio-)energy supply and biomass-based CCS. In addition, biochar offers opportunities for storing carbon in soil, increasing potential revenues (e.g., for carbon farming).

Powerful policy instruments

Stable policy support and long-term commitment are of the utmost importance for the introduction of new value chains. Direct access to R&D facilities is also highly desired. Currently, there are no policy instruments in place that directly and specifically support direct thermal liquefaction technologies. DTL technologies and their products do, however, benefit from general incentives such as a carbon tax/price, due to their high potential for reducing GHG emissions. Moreover, quota or direct support of applications such as regulations including second-generation biofuels in the transport sector lead to a relatively stable environment to further develop DTL technologies and value-added applications of its products.

> **Stable policy support and long-term commitment are of the utmost importance for the introduction of new value chains**

The construction of the Empyro pyrolysis oil production plant in the Netherlands is a successful example of a commercial plant. At the time of Empyro's development, a new incentive system was established through the Dutch SDE+ scheme which aims to encourage sustainable energy production. This incentive system provided financial support to produce renewable heat for 12 years.

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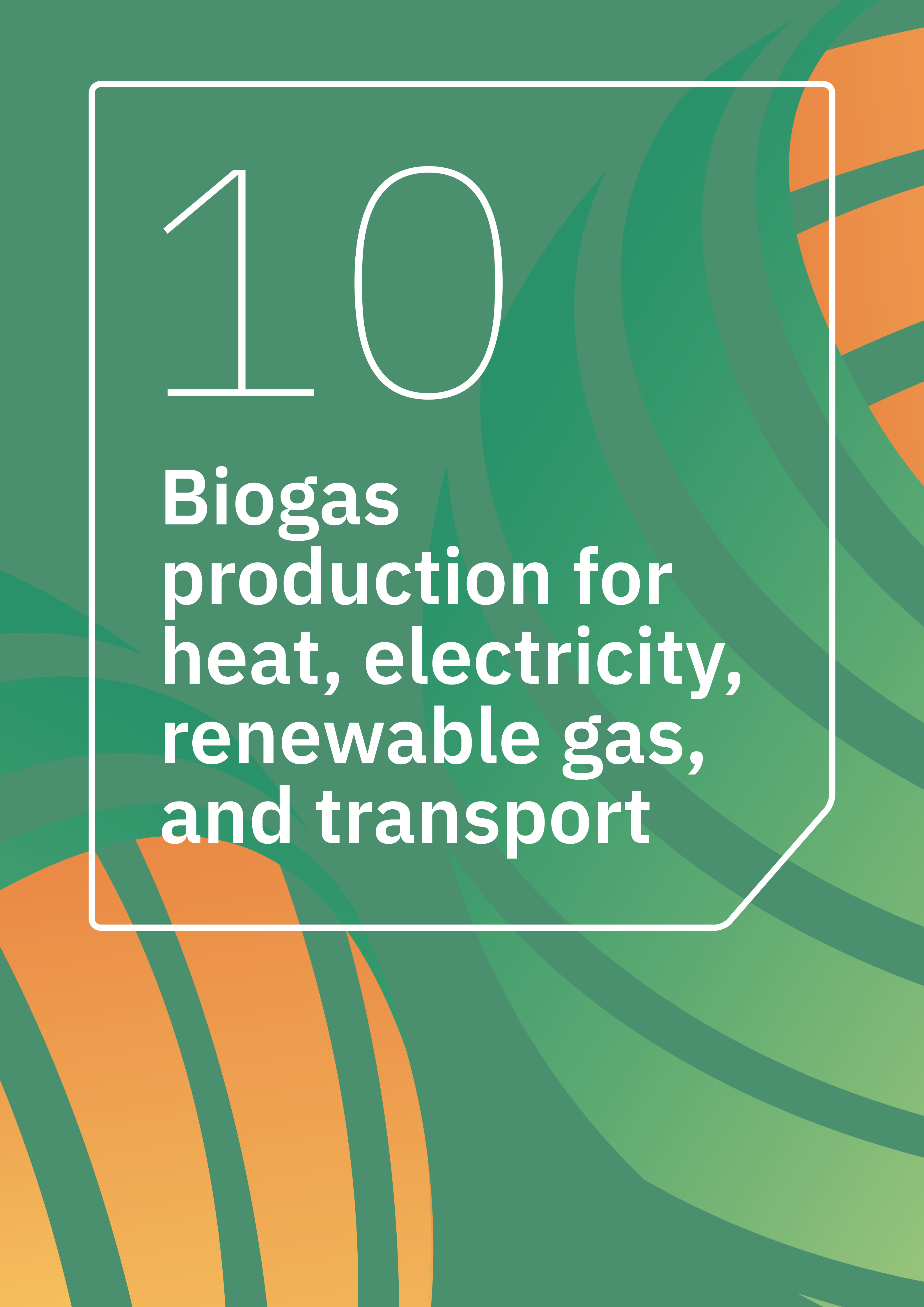

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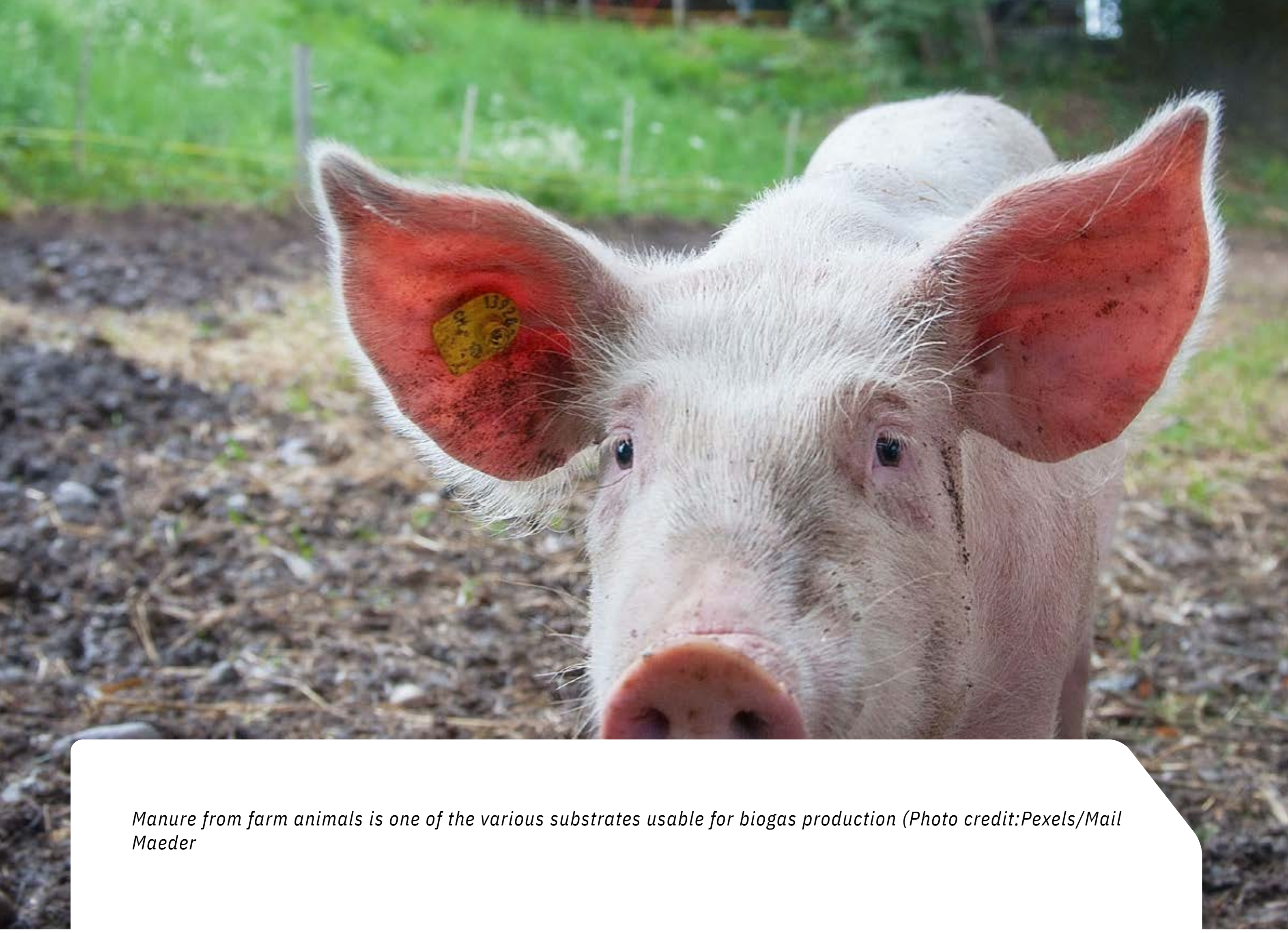
Biogas production for heat, electricity, renewable gas, and transport



Manure from farm animals is one of the various substrates usable for biogas production (Photo credit:Pexels/Mail Maeder

Biogas production

Biogas is largely produced from different types of residues and by-products: biodegradable wastes (e.g., organic fraction from municipal solid waste), industrial by-products/wastes (e.g., food and beverage industry), agricultural by-products (manure, straw), and wastewater (sewage sludge, industrial wastewaters). In some specific countries, biogas is produced from purposely grown biomass feedstock, for example, maize or so-called cover crops, which allow an additional crop to be harvested on an agricultural cultivation area.

Biogas production, also called anaerobic digestion, is a biotechnological process through which a mixed microbial culture is broken down in the absence of oxygen. As the organic matter (proteins, carbohydrates, fats) degrades, it is converted to intermediates (hydrogen, volatile fatty acids, alcohols, etc.) and finally to biogas. The biogas produced consists mainly of methane and carbon dioxide, together with small amounts of hydrogen, hydrogen sulphide, ammonia, and water.

Biogas can be used locally for heating or for combined heat and power production. Alternatively, energy producers can upgrade biogas to biomethane. This upgrading includes removal of impurities and carbon dioxide from the gas. The greatest effort lies in removing the carbon dioxide due to its high concentration (typically 30–40%). The most commonly applied technologies for gas cleaning are membrane separation, water or chemical scrubbers, and pressure swing absorption (PSA). Once the CO2 is removed, the final product is called biomethane which has similar properties to natural gas, allowing it to be directly substituted for natural gas and using the existing infrastructure and utilisation technologies. Biomethane can be injected into gas grids or directly passed on to customers (e.g., local fuel stations); it also increases the share of green gas distributed to customers. Depending on local regulations, biomethane might need the addition of propane to adapt its calorific value and odorification when it is injected into the grid.

After the anaerobic digestion process, undegradable biomass, nutrients, and water remain as the non-gaseous by-products. This fermentation residue is called digestate. In most cases it is liquid; however, after, for example, dry digestion processes or centrifugation, solid digestates are produced. These digestates (either liquid or solid) are ideally utilised as fertilisers and applied on land in a circular economy approach. To enable this, the digestate has to meet certain quality requirements (regarding e.g., heavy metal content), which are mainly influenced by the feedstock quality.

Finally, biogas plants can provide versatility and flexibility to the energy system: versatility because they produce heat, electricity, and biomethane; and system because they can be stored: raw biogas (on-site), upgraded biomethane (gas grid), heat (heat storage). In addition, the CO2 separated during biogas upgrading can be seen as another product and utilised as CO2 fertiliser in horticulture or in future in methanation and power-to-gas concepts.

Biogas plant integrated into an agricultural setting in Austria (Photo credit: ROHKRAFT/Karl Pfiel)

Technology readiness level and status of implementation

Anaerobic digestion for the production of biogas is a very well established, mature technology (TRL 9) and is applied worldwide. It has a long tradition, with simple approaches having been applied for wastewater and sewage treatment for thousands of years ago. More industrialised and sophisticated approaches were developed at the end of the 19th and beginning of the 20th century after the introduction of septic tanks and Imhoff tanks for wastewater treatment.

Biogas production technology is very well established and applied worldwide

Today, biogas technology has various fields of application:

Wastewater treatment: Biogas applications are used for the biological stabilisation of sewage sludge and the treatment/pollution reduction of high strength industrial wastewaters. In both cases, energy recovery by biogas is a welcome side-effect.

Waste treatment: In municipalities the driver for biogas plants is the treatment of food waste and bio-waste (e.g., the organic fraction of municipal solid waste). Wherever such wastes are landfilled, an (uncontrolled) anaerobic degradation process also takes place and the landfill gas can be recovered (if the landfill has been designed to accommodate this); this is comparable to biogas, although it also contains other types of impurities. In different industries (food and beverage, biofuel) residues and by-products accumulate which can also be treated in a biogas plant for energy recovery.

Agricultural applications: Agricultural residues (manure, straw, harvesting residues) can be treated in biogas plants. Energy crops (e.g., maize) are also used as biogas feedstocks in countries such as Germany, although this has recently been on the decrease.

Environmental effects

Using manure as a feedstock in biogas plants can avoid methane emissions from manure storage

Biogas plants have a high potential for reducing emissions:

- Biogas (or biomethane) directly replaces fossil gas in industry or in CHP units. Biomethane also replaces fossil fuels in the transport sector.
- Waste Management: Including biogas plants in the waste management system drives separate collection of organic wastes and reduces direct landfilling.
- Methane emission reduction: The treatment of specific feedstocks can reduce the emissions

of methane which is a very potent GHG. Treating manure in a biogas plant can avoid methane emissions from manure storage. Recovering and using the gas produced in landfills and treating organic wastes in a biogas plant rather than sending these wastes to landfill also have a very positive environmental effect.

- Air pollution: The combustion of biomethane in internal combustion engines releases fewer local air pollutant emissions than fossil fuels.
- Nutrient management is an essential part of biogas concepts. Nitrogen and phosphorous emissions to groundwater or surface water can be reduced by good practice in digestate handling, thereby reducing eutrophication.
- Digestate as biofertiliser replaces fossil-based fertilisers. Stabilised organic matter is also returned to the soil, and this can act as a carbon sink.

To guarantee that biogas plants will have positive environmental effects, it is essential to ensure minimum fugitive emissions from the process. Emissions during the combustion of biogas (e.g., NOx) should be kept to a minimum.

Costs

Biogas plant treating organic waste (Pinto, Spain) (Photo credit: University of Natural Resources and Life Sciences, Vienna/IFA Tulln)

The costs of biogas production can be categorised as follows: investment costs (depreciation costs), feedstock costs, staff costs, maintenance costs, and other running costs.

Feedstock costs: If wastes are used as a feedstock, a charge—a gate fee, for example—is usually levied for treating the wastes, thus producing revenue. While industrial residues and by-products can be very cheap to use as feedstocks, other products, like fermented energy crops, can be very costly. There is thus a wide range of possible feedstock costs, and these are highly dependent on the specific biogas project and the national boundary conditions.

Investment costs: Investment costs (depreciation costs) including peripheral equipment and installations make up a large share of biogas plant costs. The investment costs of a biogas plant naturally depend on its size (capacity and throughput). Biogas installations follow economies of scale, meaning that as the capacity of a plant increases, the specific investment costs decrease. Plant capacities are, however, limited by available substrates and infrastructure; this means that the lower specific costs associated with larger-scale plants are sometimes not achievable.

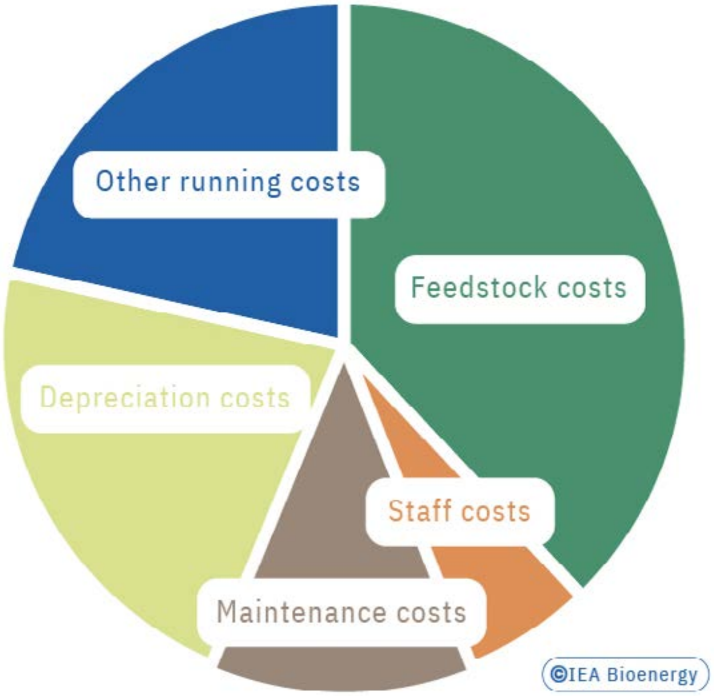
Moreover, some investment costs are feedstock-dependent. Biogas plants for the treatment of municipal wastes are more expensive because they have large closed halls (e.g., with low pressure to reduce smells). These halls are used for the handling and pre-treatment of feedstocks, with impurities (packaging, plastics, metal, etc.) being separated from the organic matter. Investment costs for energy crop digesters or industrial wastewater treatment reactors are often lower, as they need fewer peripheral installations. Another substantial part of the costs can be the biogas utilisation. From an investment perspective, direct heat utilisation is the cheapest solution. In industrial settings the biogas produced can often be co-fired in gas burners, with no or limited adaptation needed. More sophisticated gas utilisation concepts (e.g., combined heat and power production, upgrading to biomethane, fuel cells) result in higher investment costs.

Staff costs: Today, state-of-the-art biogas plants are well automated, resulting in fairly low staff costs; however, extensive feedstock pre-treatment—as occurs with the organic fraction of municipal solid waste or packaged food waste—can increase the demand for human labour. In general, biogas technology, and in particular the microbial degradation process, is rather complex; it is thus clearly advantageous to have well-trained staff to guarantee a stable, reliable operation.

Digestate logistics costs: The digestate produced can generate considerable costs, depending on the size of the installation and how integrated it is into local organic fertiliser utilisation. The most common digestate utilisation is land application as fertiliser, but this is limited because there may not be farmland nearby and/or because of environmental legislation (e.g., the EU Nitrate Directive). This means that in very large-scale biogas installations, the digestate land application can become a bottleneck because the transport distances to agricultural land where the digestate can be applied increases with the size of the installation, and so too do the transportation and application costs. In small-scale biogas plants–especially in an agricultural setting–the digestate application as a fertiliser on the land is often not a problem. Large digestate storage facilities are typically needed, as land application can be prohibited during winter, the agricultural soils cannot effectively take up nutrients and digestate must be stored.

Other costs: These are costs for maintenance of the machinery, property, insurance, administration, etc.

The following figure shows the typical cost distribution of German biogas plants.



Relative cost distribution in German biogas plants based on average values. Considerable numbers of German biogas plants use energy crops, which explains the high feedstock costs. This is very country-specific to Germany and will be different in other countries. Source: BIOGAS-MESSPROGRAMM III, FNR 2021

Current research gaps and opportunities

Biogas production provides a wide range of opportunities. It is a mature technology that can be applied for a large range of feedstocks. It can be very effectively linked to agriculture and food processing or wastewater treatment. It not only contributes to energy provision, but also effectively addresses environmental challenges (waste treatment, nutrient management, and emission reduction). It also supports rural development.

A recent trend has been the push towards greening gas grids and consequently increasing biomethane production in biogas plants. Examples from Sweden show that biomethane can also play an important role in the transport sector, for both light- and heavy-duty vehicles.

Biogas can play an important role in the energy system and support rural development

Biogas technology has the following aspects which still have potential for optimisation:

Systems integration: A promising approach for innovative biogas projects is the system integration of a plant into its surroundings and its specific boundary conditions. As projects differ from case to case, different aspects of biogas technology can be more attractive. An important example is the ability to ramp production up and down in relation to demands from the power grids (where intermittent renewables like solar and wind are playing an increasing role). Biogas technology is also easy to combine with biorefinery concepts for the treatment of intermediates or residues or with power-to-gas concepts in combination with renewable hydrogen.

Feedstock pre-treatment: Different technologies can be applied for the pre-treatment of biogas feedstocks: mechanical, thermal, microbial, enzymatic, and combinations of these. Pre-treatment has two aims: to break down feedstocks/feedstock components that were not previously microbially degradable; and/or to decrease degradation time. As feedstock pre-treatment often increases investment costs and energy input, it has to be verified for every specific case/feedstock that pre-treatment is efficient and advantageous.

Digestate treatment: In large-scale biogas applications the digestates (fermentation residues) can create a bottleneck; as land applications are limited by regulations (e.g., the European Nitrate Directive), large quantities of digestate may need to be transported over long distances for application. A great deal of R&D activity is taking place to investigate and optimise the treatment or processing of digestate. These processes are converting digestate into a nutrient-rich concentrate (that is more economical to transport over large distances) and process water.

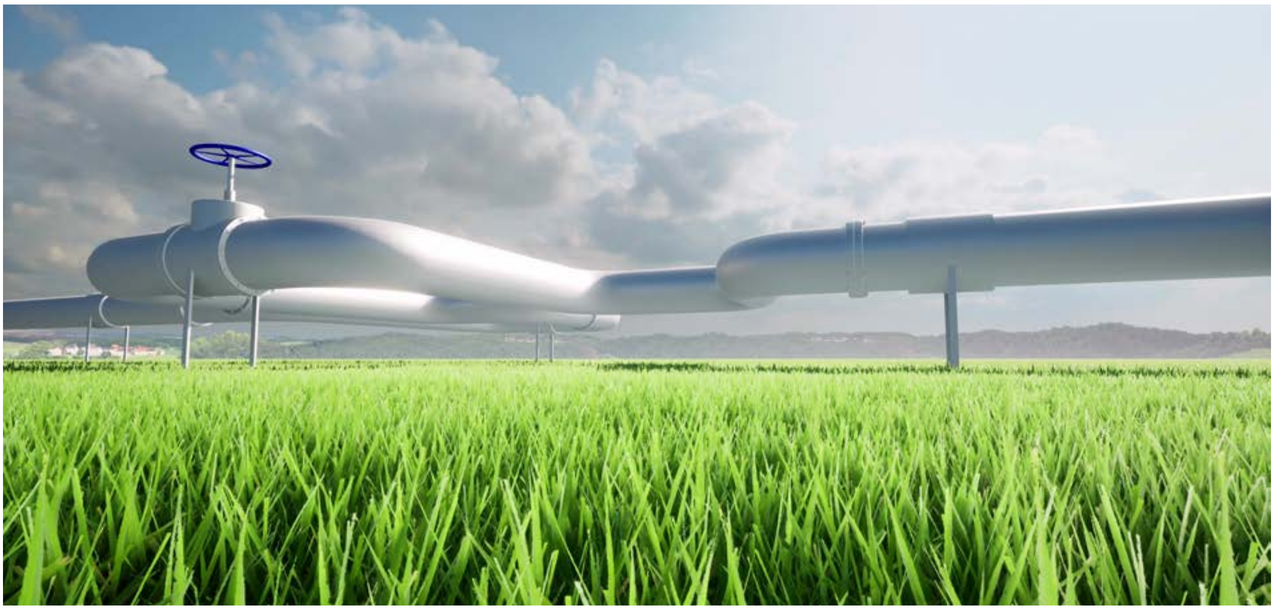
Digestion of industrial wastes: During large-scale industrial processes, specific residues or wastewaters often occur. The anaerobic digestion process has to be tailored to treat the specific substrates and counteract inhibitions or deficiency in trace elements.

Economically viable small-scale biogas plants: As feedstock availability limits the capacity of biogas plants, small-scale plants tend to have high specific costs due to economy of scale. For a sustainable utilisation of substrates and their integration into agricultural infrastructures, economic solutions for small plant capacities (e.g., 50–200 kWel) are needed.

Biogas plants as biorefineries: The biogas process not only has the potential to produce energy: intermediate products such as carboxylic acids can be valorised directly as chemicals.

Experimental laboratory biogas digesters (Photo credit: BEST)

Powerful policy instruments



Biomethane can serve as a substitute for natural gas (Photo credit: Shutterstock / Volodimir Zozulinskyi)

In the vast majority of cases, the implementation of biogas is dependent on government incentives. The reasons for supporting biogas production and use are diverse: production of renewable energy (power, biomethane); reducing negative environmental impacts (e.g., avoiding methane emissions); and achieving a circular economy together with sustainable food production or waste treatment. The general idea is to provide incentives that reflect the actual costs of investment and long-term operation of the renewable gas industry; this can ensure bankability for the developer and a price-effective market environment for the user of renewable gas. Several different approaches can be used to support biogas development:

Clear framework policies: Roadmaps need to be created for renewable gas development, including for substrate availability, development costs, defined time-specific targets as a portion of energy use, and what infrastructure is required and/or already available. Unnecessary barriers and inhibitory regulations need to be eradicated as much as possible at the technical and regulatory level.

Waste regulations: Specific waste regulations can also encourage increased biogas production. Landfill bans support the biological treatment of organic waste in, for example, biogas plants. As a result, gate fees are provided to the waste treatment facility.

For the direct financial support of biogas production (or utilisation) the following examples can be given:

- Feed-in tariffs: In many countries feed-in tariffs guarantee a higher price for the energy provided by biogas plants.
- Specific investment subsidies: A share of the investment costs is covered by the funding institution.

- Quotas: These place an obligation on fuel providers to ensure that renewable fuels supply a minimum proportion of the fuel market; quotas are a very effective policy tool for avoiding price competition between renewable gas and fossil gas.
- Tax exemptions: Support can also be provided by granting tax exemptions to the biogas sector. In Finland, Norway, and Sweden, for example, these tax exemptions are directed to users of biogas.
- Carbon price: Avoided CO2 (GHG) emissions must have a sufficient monetary value associated with them; a realistic carbon price would stimulate development and drive the transformation of green gas while encouraging competition between renewable technologies in specific sectors, which should lead to the phase-out of specific incentives.

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11

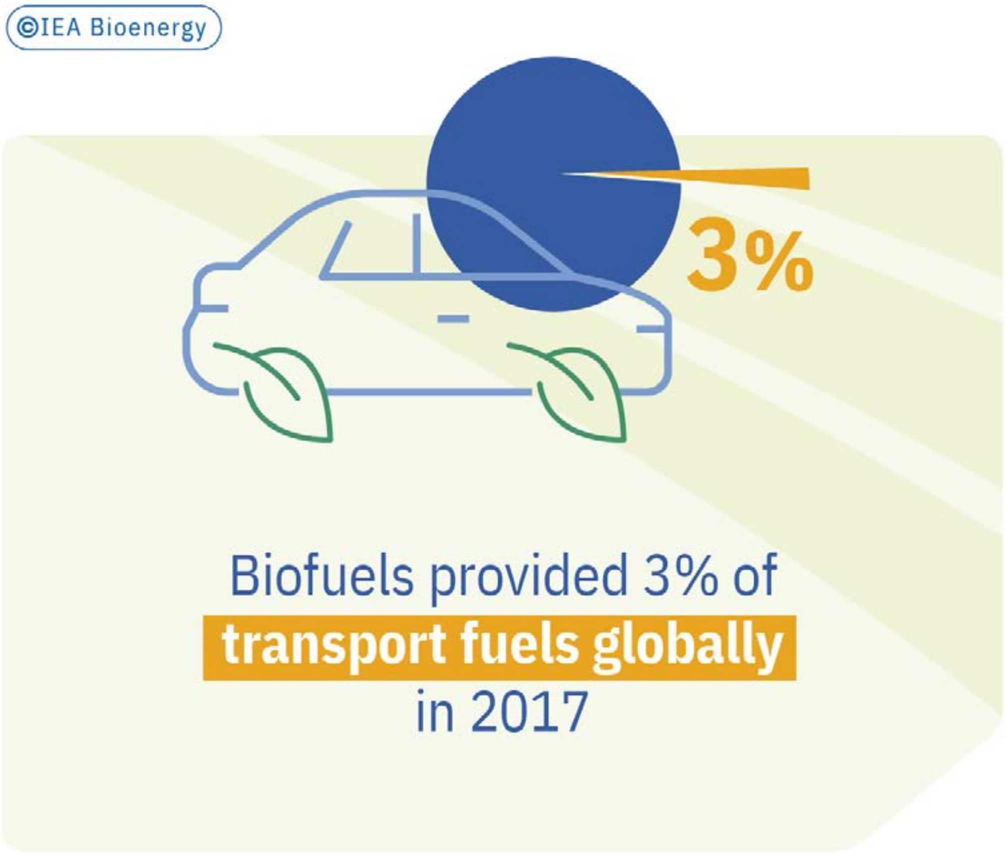
Transport biofuels

Transport biofuels can significantly reduce GHG emissions of the current fleet (Photo credit:Pexels/ Roman Odintsov)

Transport biofuels

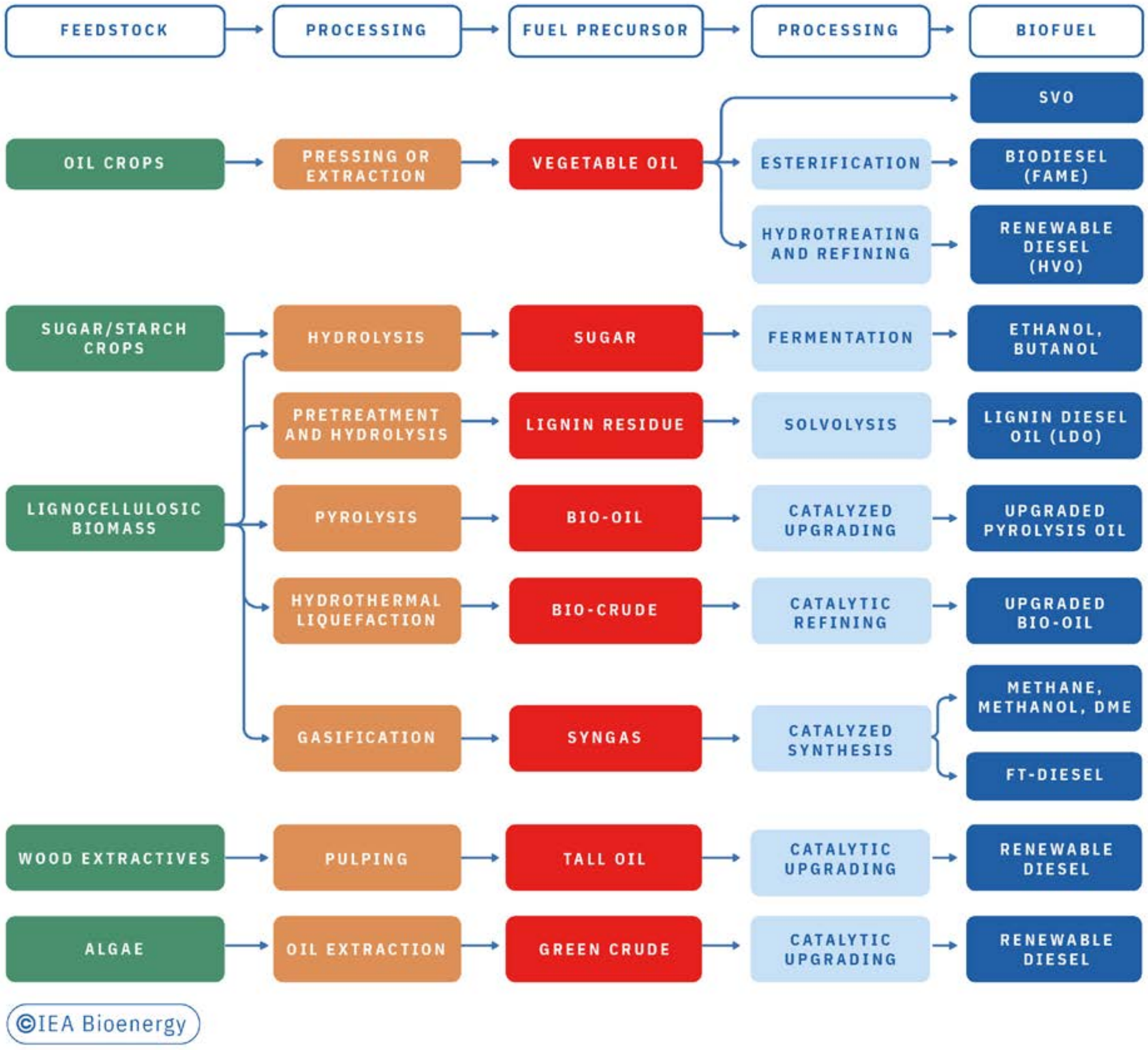
Sustainable transport biofuels are already offering low carbon intensity mobility to the legacy fleet and will become more important in shipping and aviation in the future. Total GHG emissions—from biomass feedstock production, through feedstock conversion to biofuel, and to the latter's use in internal combustion engines (ICE)—are typically between 32% and 98% lower than those resulting from the use of fossil fuels such as gasoline, diesel, and natural gas. Biodiesel, bioethanol, and hydrotreated vegetable oils (HVO) are already widely used and provided some 3% of transport energy globally in 2017 (Renewables 2020 Global Status Report). In comparison, renewable electricity provided only 0.3% of transport energy in 2017.

There are already technologies for producing biofuels based on forestry and agricultural residues and waste materials, and these continue to be improved through research and development. The production costs of transport biofuels are usually higher than those of fossil fuels. Their market introduction and use typically depend on dedicated supportive policy measures. While battery electric vehicles are expected to gradually replace light-duty vehicles powered by an internal combustion engine (ICE), long-distance and heavy-duty transport are harder to electrify. That is why after 2030 biofuels are expected to be primarily used in aviation, shipping, and heavy-duty road transport (trucks) rather than in light-duty vehicles.



Feedstocks for the production of transport biofuels include oil-seed crops, sugar and starch crops, lignocellulosic agricultural and forestry residues, and wastes such as straw, corn cobs, wood chips, wood extractives from pulping processes, and even water-based plants such as micro- and macroalgae. A wide range of mechanical, chemical, thermochemical, and biochemical processing steps are applied to convert these feedstocks into transport biofuels (The Role of Renewable Transport Fuels in Decarbonizing Road Transport – Production Technologies and Costs).

Several synthesis technologies used for the production of transport biofuels can also be applied using renewable, low carbon intensity hydrogen produced through electrolysis and recovered or captured CO2 as feedstock; such fuels are called e-fuels (electrofuels) or power-to-x fuels. Examples of potential e-fuels include methane, methanol, and upgraded Fischer-Tropsch liquids.



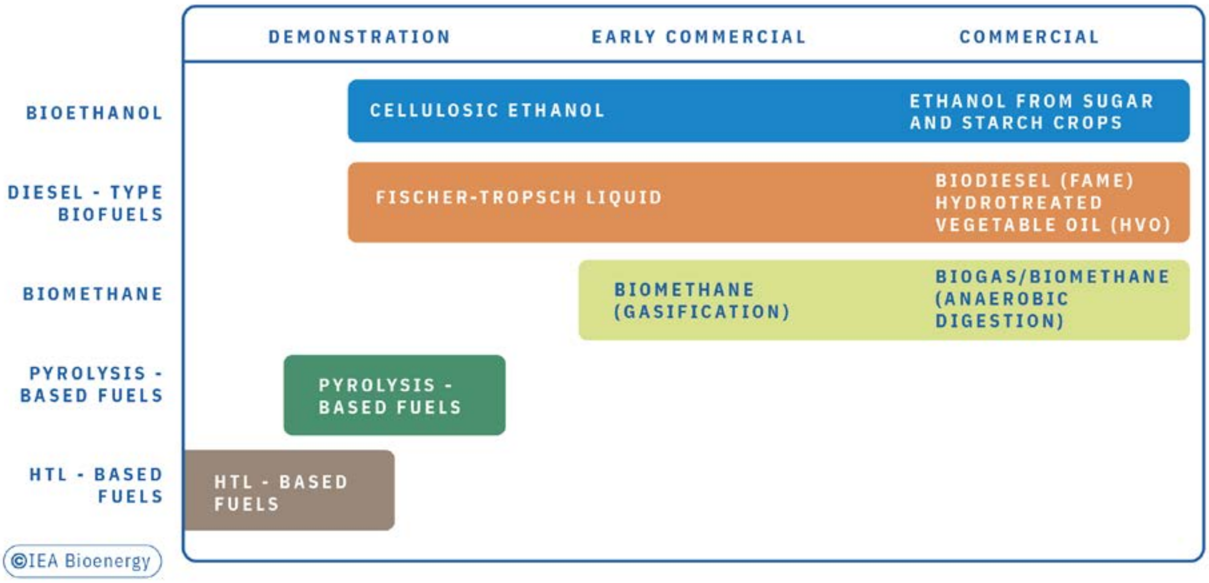
Biofuels can be produced from a large variety of biomass feedstocks

Technology readiness level and status of implementation

In the case of transport biofuels, a number of production technologies have reached maturity, are already at TRL 9, and are widely deployed. These so-called **established biofuels** include ethanol from sugar and starch crops, biodiesel from triglycerides and lipids (FAME), hydrogenated triglycerides and lipids (HVO), and biomethane from upgrading of anaerobic digestion biogas.

About half of the technologies that will decarbonise our energy system in 2050 are not yet fully developed (IEA Net Zero by 2050 Roadmap).

Other production technologies are not yet fully developed, and still need to be demonstrated at full scale. About half of the technologies that will decarbonise our energy system in 2050 are not yet fully developed (IEA Net Zero by 2050 Roadmap). These so-called **emerging biofuel pathways** include ethanol from lignocellulosic feedstocks, gasification-derived biofuels, pyrolysis-derived bio-oils, hydrothermal liquefaction-derived bio-crudes, lignin-derived biofuels, sugars to biofuels, and biofuels derived from non-lignocellulosic biomass such as microalgae. TRLs for these technologies range from 3 to 8. Current demonstration facilities for these advanced biofuels are mapped in the IEA Bioenergy Task 39 interactive map and database. A few e-fuel production facilities which are based on CO2 from biomass are also included in this demonstration facilities map.



Overview of technology pathways and their technology readiness level (TRL); Adapted from: The Role of Renewable Transport Fuels in Decarbonizing Road Transport – Production Technologies and Costs

Energy demand in the transport sector is unevenly split across transport modes. In 2019, global road transport used the major share (42% in trucks and 35% in cars), while maritime transport used 13%, aviation 7%, and other transport, including rail, only 3%.

Currently, transport biofuels are mostly consumed in light duty road transport, supporting the decarbonisation of the sector. In future decades, when electrification is expected to power significant shares of light duty road transport, biofuel use will remain important but is likely to refocus on powering sectors that are harder to electrify. Research has thus started to address the issue of providing biofuels to maritime transport and aviation.

Road transport

Ethanol, biodiesel (FAME), and HVOs are the most common biofuels used in the road transport sector. While, initially, several automakers allowed the use of neat biodiesel (FAME) in their vehicles, they no longer do so due to its poor cold flow properties and problems in modern exhaust gas after-treatment systems. Instead, biodiesel (FAME) is blended with diesel fuel at levels of, for example, 5%, 7%, 10%, 20%, and 30%.

Ethanol is most commonly used as a low-level blending component with gasoline at levels of, for example, 5%, 10%, 15% , and 27%. Ethanol can also be used in adapted drive trains in so-called flex-fuel vehicles at a level of 85%. In Brazil, thanks to favourable climatic conditions and specially developed vehicles, ethanol is also being used in hydrous form (~95% ethanol, ~5% water).

HVO, as well as upgraded paraffinic fuel produced through Fischer-Tropsch synthesis, is a so-called drop-in fuel that can be fully substituted for fossil diesel. To date, due to restrictions in the diesel standard, the most common use of HVO is as a 30% blend with fossil diesel. The use of pure HVO, for example by freight companies wishing to decarbonise is, however, becoming more common.

Biomethane is another example of a drop-in fuel that can be used directly in natural gas vehicles as a substitute for (fossil) natural gas.

A range of other biofuels is under investigation, including methanol, butanol, dimethyl ether (DME), and other ethers. These fuels are likely to require fuel-related adaptions to the drive train, lubricants, and exhaust after-treatment systems.

It should be noted that although low-level blending of biofuels is efficient for quickly reducing GHG emissions and building a market for biofuels, high decarbonisation targets can be achieved only with high-level blends or neat biofuel applications.

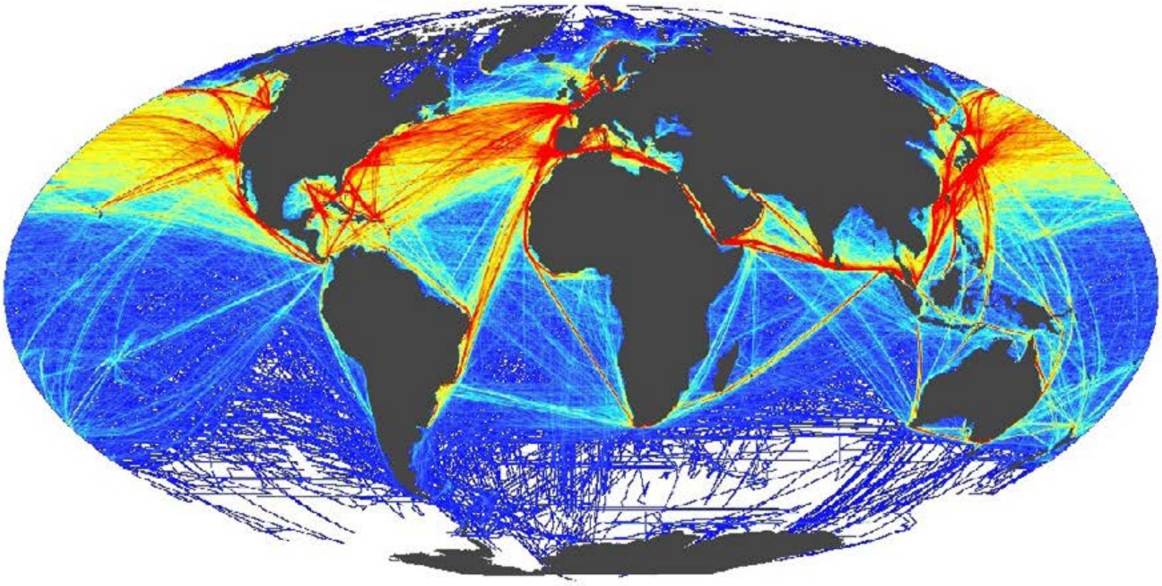
Shipping

International merchant shipping is responsible for transporting more than 80% of goods worldwide. Shipping is the least carbon intensive mode of transport (expressed as per tonne-km) and produces only 2–3% of global GHG emissions. International shipping vessels are, however, traditionally fuelled with heavy fuel oil (350 million tonnes per year). This high energy density but very low-quality fuel has a high sulphur content, making shipping the largest source of anthropogenic sulphur emissions and a significant emitter of nitrogen oxides and airborne particle emissions.

The International Maritime Organization (IMO) has the target of decreasing the carbon intensity of the shipping sector by 50% by 2050 and mandating new ships to increase energy efficiency. The maximum allowed sulphur content of marine fuels was reduced from 3.5 wt.% to 0.5 wt.% in 2020. This significant drop in sulphur content does not, however, allow the continued use of high-sulphur heavy fuel oil unless scrubbers are used to clean the exhaust gas. International shipping companies are thus looking into alternative solutions.

Shipping is moving towards the use of cleaner fuels to reduce GHG and sulphur emissions

Sustainable biofuels are among the most promising short- to medium-term solutions for reducing both GHG and sulphur emissions from shipping transportation. A range of feedstocks and biofuel production technologies could be used to produce marine biofuels, and the best solution for each case depends on local parameters such as distance to major fuel hubs, carbon pricing and other supportive policy measures, and availability of biomass.



Visualisation of merchant shipping routes and the frequency they are used. The majority of shipping fuel is provided through only a few major ports. Provision of alternative shipping fuels could focus on these major ports

The main barriers to the implementation of marine biofuels are the lack of economic incentives and the high level of uncertainty related to price development of biofuel feedstocks, sustainability criteria, and regulatory policies. This underlines the importance of supportive and stable long-term policies for triggering investments in alternative marine fuel development and deployment. Establishing supply chains or adapting engine and fuels systems to biofuels seem to be of relatively little concern, according to interviews with key shipping sector stakeholders

However, the current marine fuel standard or specification includes parameters that cannot be met by many prospective marine biofuels, thus obstructing their use, trade, and production. To accelerate the adoption of sustainable biofuels for marine applications, we would need to revise marine fuel standards, but that will require time and successful demonstrations using large volumes of marine biofuels; this would impose high costs on marine biofuel development and deployment. In the interim, technical reports such as the IMO interim guidelines on using ethanol and methanol as marine fuels, approved in November 2020, can help support this transition.

Aviation

While the aviation sector currently accounts for only 2% of global CO2 emissions, it is predicted to expand further; stakeholders have committed to carbon neutral growth after 2019 and to achieve carbon neutrality by 2050. Measures to achieve future reductions in GHG emissions include more efficient aircraft, improved air traffic management, offsetting of GHG emissions, and the use of low carbon intensity fuels.

Biojet fuels are already available at many airports (Photo credit: istockphoto / Chalabala)

Although biojet fuels produced by a variety of production pathways have been approved for use in aviation, hydrotreated esters and fatty acids (HEFA)–Synthetic Paraffinic Kerosene (SPK) fuels provided the vast majority of biojet fuel used in 2021. HEFA-SPK biojet fuel is anticipated to dominate the aviation biofuels market for at least the next 10–15 years. Approximately 150 million litres of biojet fuels were produced globally in 2021, which represents less than 0.5% of total jet fuel demand. As the volume of suitable feedstock (oils and fats) for the HEFA process is limited, it is important to develop further production pathways that can make use of more abundant renewable feedstocks.

The certification process for new biojet fuel production pathways is lengthy and requires relatively high volumes of fuels for testing. This imposes high costs on biojet fuel development and deployment. These costs, along with a range of technological challenges, constitute a significant barrier to the commercialisation of new production pathways.

Current biojet fuels cost several times more than their fossil counterparts, making their use economically unattractive. Costs may decrease, for example, through improvements to the biojet fuel production process, yet supportive policies will be essential to both create market demand and to further catalyse biojet fuel development.

Environmental effects

Sustainable biofuels based on residues from agricultural production such as, for example, corn stover offer GHG emissions reductions without requiring additional land use for feedstock production (Photo credit: Pixabay/Straw pexels)

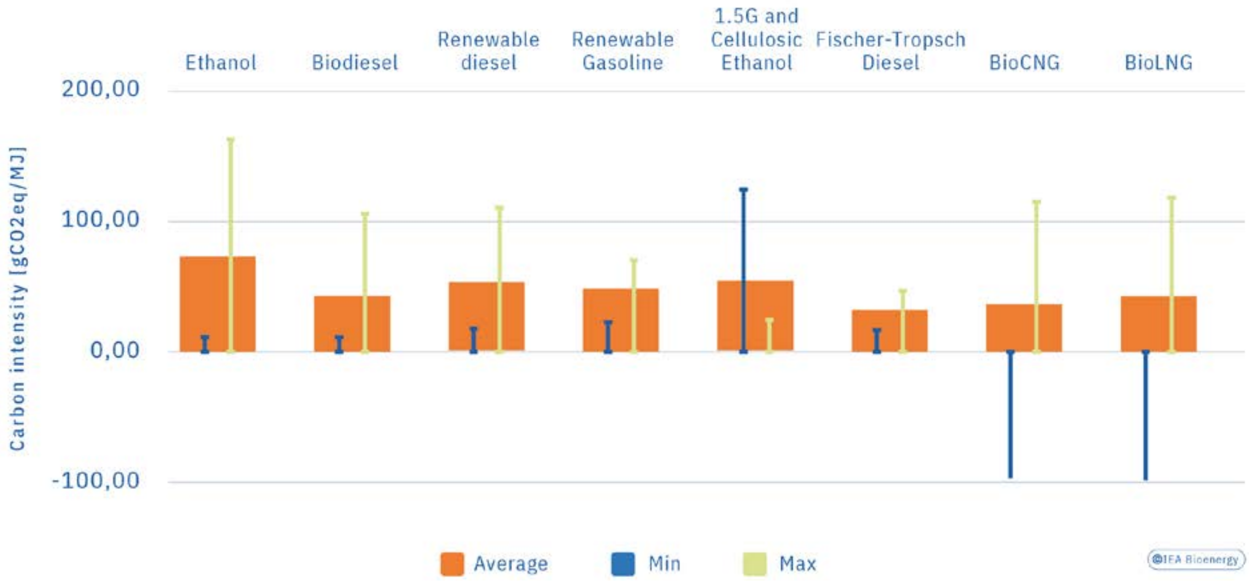
Major drivers for introducing transport biofuels around the globe include their use as a substitute for fossil fuels, improved energy security, reduced GHG emissions, and increased rural incomes. When the environmental effects of biofuels are analysed, the focus is typically on the impacts of GHG emissions and fossil energy use. There are, however, other important negative environmental and health effects to take into account, such as acidification, eutrophication, human toxicity, ecological toxicity, biodiversity, and water and land footprints, which are less well studied and deserve attention.

Life-cycle assessments (LCA) range from the cultivation or collection of biomass feedstock, to harvest, storage, and transportation, then conversion to biofuel and distribution to the end consumer, to the final use of the biofuel in the engine. All resources used and energy inputs required along the value chain are considered, and all resulting GHG emissions counted. CO2 released from the final fuel combustion process is credited as biogenic CO2 rather than fossil-derived CO2; these biogenic CO2 emissions are equivalent to the amount of atmospheric CO2 taken up by the plant biomass during growth. Resulting GHG emissions are allocated to the final product and by-products, with different default allocation methods being used by different LCA tools and studies.

Important GHG emission calculation tools for transport biofuels include GREET (USA); GHGenius (Canada); the methodology prescribed in the EU Renewable Energy Directive; Virtual Sugarcane Biorefinery (VSB, Brazil); and Open LCA. Due to variations in the underlying datasets for feedstock cultivation and processing, regional variations—in, for example, fertiliser type, application amount and timing, and the choice of allocation method—different biofuel LCAs sometimes can, and do, produce different and even widely conflicting results. A number of reports have been produced to explain the variations in results for different biofuel LCA studies and to help policymakers understand the sensitivities and findings of transport biofuel LCAs. It is important to understand that LCAs do not deliver point values but value ranges, and that they should serve to identify levers for improvements along the processing chains.

In the USA and the EU, renewable fuels have to reduce GHG emissions by at least 20% and 65%, respectively, if produced in new installations; in both regions, therefore, biofuels over their life-cycle have to produce fewer GHG emissions than fossil fuels typically do. Biofuels that are based on wastes or residues typically achieve high GHG emission reductions (80% or higher). Some production pathways even offer the potential to achieve negative emissions, for example, when emissions resulting from the decomposition of untreated wastes are avoided through conversion of the wastes into biofuel or when CO2 emissions from the production process are captured and stored (CCS). Typical values for GHG emissions of various pathways can be found, for instance, in Annex V of the EU Renewable Energy Directive recast.

Another way of measuring is to calculate the carbon intensity (CI) of fuels, as this represents the net GHG emissions emitted across the full life cycle of the fuel. For comparison, the carbon intensities of producing and using fossil gasoline or diesel are about 95 gCO2eq/MJ. Real-life values for the carbon intensity of biofuels provided for California in 2019 are well below the carbon intensity of fossil fuels.



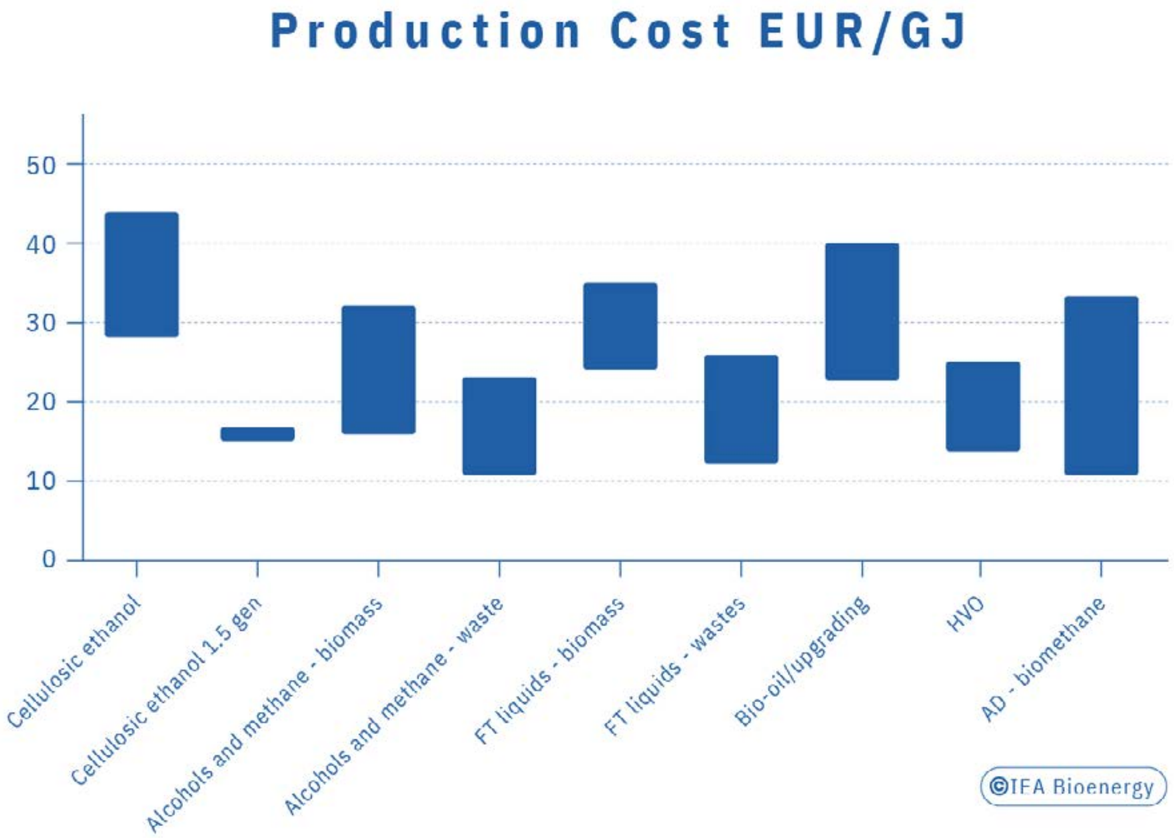
Production costs for advanced biofuels assessed in 2019 are higher than the 8–14 EUR/GJ price range for fossil transport fuels in the years 2017–2019. Source: Advanced Biofuels—Potential for Cost Reduction

As policies based on actual GHG emission reductions of biofuels (like Low Carbon Fuel Standard (LCFS) policies) become more common across the world, the CI of current and emerging biofuels is expected to decrease, for example, through the increased use of wastes and biomass residues as raw materials. This will reduce or avoid the use of fossil fuels to supply energy for production plants and the ongoing technological learning will result in the realisation of larger-scale processing facilities that achieve greater economies of scale. There is also a strong potential in many locations to improve plant efficiencies and reduce costs through more widespread implementation of industrial symbiosis in biofuel production plant design.

Costs

The costs of producing transport biofuels are usually higher than the price of the fossil fuels for which they are being substituted, making their production uneconomic in the absence of policy measures to support production. There is potential to reduce these costs by using lower-cost feedstocks and other input materials such as enzymes, thereby enhancing the conversion efficiency or improving the monetisation of co-products. Technology developers and biofuel producers across the globe are exploring these avenues. For example, the recent capacity increase for the production of hydrotreated vegetable oil- (HVO)-type fuels is being driven by several regions such as Sweden and California which are economising on production costs through a combination of using low-cost feedstocks and production incentives, and also through carbon credits markets created by LCFS policies.

Other production routes, especially those using lignocellulosic materials such as wood or straw as raw material, that require collection and transport, are still uneconomical. To better understand and communicate the scope to reduce the production costs of such biofuels, IEA Bioenergy published a study entitled "Advanced Biofuels – Potential for Cost Reduction". The study illustrates that it is difficult to develop and demonstrate these technology pathways, as the investment required is about 5–10 times higher than for established biofuels like HVO or conventional ethanol, depending on the conversion pathway.



Production costs for advanced biofuels assessed in 2019 are higher than the 8–14 EUR/GJ price range for fossil transport fuels in the years 2017–2019. Source: Advanced Biofuels—Potential for Cost Reduction

The IEA study also demonstrates that feedstock costs and capital costs are the major contributors to overall biofuel production costs. It finds that production costs using biomass feedstocks that must be collected and delivered lie in the range of 17–44 EUR/GJ and are reduced to 13–29 EUR/GJ if wastes are used as feedstocks. This compares with a range of fossil fuel prices of 8–14 EUR/GJ in 2019, when the assessment was carried out. There are early market opportunities for producing lower-cost advanced biofuels from wastes and through integration of advanced biofuel production with existing biofuel processing plants. As a side note, fossil fuel prices have increased significantly since the above assessment was carried out, from around 60 USD/barrel in 2019, through a low in early 2020 at <20 USD/barrel, up to a spike of >120 USD/barrel in early 2022.

Further cost reductions can be achieved through technology learning from demonstrations that reduce investment costs, and also through cheaper access to capital as the perceived investment risk decreases. In addition, carbon pricing can help to bridge the gap between biofuel production costs and the price of fossil fuels.

Current research gaps and opportunities

Biofuel production pathways are at different technology readiness levels, and R&D needs vary according to feedstock, conversion technology, and technological maturity. Many publications provide insights and guidance on where to focus research and development efforts to make further advances in biofuels. Examples of such publications include the following:

- IEA Biofuels Technology Roadmap (2011)
- IRENA Advanced Liquid Biofuels (2016)
- IEA Bioenergy Technology Roadmap (2017)
- ETIP Bioenergy Strategic Research and Innovation Agenda (2018)
- IRENA Advanced Biofuels - What holds them back (2019)

Although these publications were written several years ago, the majority of technology-specific challenges they describe remain valid. A selection of R&D needs for important transport biofuel pathways is presented below.

Biogas

Specific R&D needs include the development and demonstration of feedstock pre-treatment to enhance gas yield and allow processing of recalcitrant materials and the development and demonstration of improved technologies for biogas production and upgrading to biomethane. The use and valorisation of digestate needs to be improved, and conventional biogas facilities should be upgraded to integrated biogas-based biorefineries that efficiently co-produce biofuel precursors (fatty acids, biogas) and bio-based products.

Lignocellulosic ethanol, higher alcohols, hydrocarbons

Specific R&D needs include:

- the development of improved feedstock pre-treatment and conversion processes (less intense use of water, energy, chemicals, and enzymes) to improve process efficiency and product titre;
- the development of novel strains to produce hydrocarbons or long-chain fatty alcohols from sugars;
- the development and demonstration of improved separation technologies (e.g., ethanol recovery from fermentation broth or avoidance of product inhibition through continuous removal of products);
- the development of lignin valorisation towards energy/fuels and bio-based products.

Gasification

Specific R&D needs include: i) feedstock pre-treatment for, and feedstock flexibility in, primary conversion; ii) the development and demonstration of improved gas cleaning (e.g., hot gas cleaning) and upgrading; iii) the demonstration of hybrid renewable energy power processes; iv) the improvement of catalyst longevity and robustness; and v) the efficient use of low-temperature heat.

Direct thermochemical liquefaction (pyrolysis and HTL)

Specific R&D needs include:

- the development of systems with improved intermediate quality (e.g., reduced oxygen content);
- the demonstration of upgrading of intermediate products (including co-processing);
- the improvement of catalysts for all conversion steps.

Opportunities with respect to biofuels include:

- increasing the feedstock flexibility of technologies;
- adapting marine standards to enable wider use of biogenic fuels;
- developing supply chains for providing and bunkering biofuels for ships and planes;
- enabling the co-processing of bio-oils and bio-crudes in petroleum refineries;
- developing carbon capture technologies compatible with the size of typical biofuel production facilities.

Pilot and demonstration facilities enable technological learning to improve efficiencies and reduce costs of biofuel technologies (Photo credit: Krysja)

Earlier hopes that large quantities of biofuels could be produced based on aquaculture of algae, thus not requiring fertile land for cultivation of the raw material, have not materialised; the higher costs of cultivating and harvesting algae compared to other biomass feedstocks require higher-value (i.e., non-fuel or energy) products to be economically viable. Research is still ongoing, focusing on biorefinery approaches with higher value algal biomass-based products providing the critically needed revenue to reduce the net cost of producing algal-based biofuels.

Powerful policy instruments

Supportive policies have been, and will continue to be, essential to foster the growth of the advanced biofuels used to decarbonise transport. To date, most policies have focused on road transport. Other transport sectors, such as rail, aviation, and shipping, have, until recently, received comparably less attention, despite being large energy consumers and GHG emitters. Transport policies and industry efforts are, however, being increasingly extended to focus on decarbonising long-haul transport sectors (i.e., road, rail, aviation, and shipping), where electrification is much more challenging.

The market introduction of biofuels and the development of even more efficient biofuel production technologies should be supported by a well-balanced basket of policy measures and long-term, stable policy commitment. Policy tools that have been successful include blending mandates, excise tax reductions or exemptions, renewable or low carbon fuel standards, and a variety of fiscal incentives and public financing mechanisms. There are two main policy types: technology-push policies, that aim to drive early-stage technology development through RD&D support, and market-pull policies, that help create demand for established or technically more mature transport biofuels.

The market introduction of biofuels and the development of even more efficient biofuel production technologies should be supported by a well-balanced basket of policy measures and long-term, stable policy commitment.

Within the basket of successful policy tools, biofuel blending mandates are the most widely adopted (e.g., in Brazil, Canada, Japan, South Korea, United States, and the EU. In most cases these blending mandates are based on the volume or energy content requirements, and thus effectively support the use of biofuels that can be produced at the lower end of the production cost range: they are, however, less effective in terms of stimulating the development and deployment of higher production cost biofuels that achieve even lower carbon intensities.

The first policy to introduce carbon intensity (CI) as a measure for incentivising biofuels was the 2007 Low Carbon Fuel Standard (LCFS) of the state of California (USA). LCFS-type policies encourage the more efficient production of established biofuels and also stimulate the development and deployment of biofuels that offer higher GHG emission reductions by increasing their market value. These types of carbon intensity–based policies are becoming more common. As of late 2021, the states of California, Oregon, and Washington in the United States, the province of British Columbia in Canada, Brazil, Germany, and Sweden have all implemented such LCFS-type policies, and many other regions (e.g. Canada with its upcoming Clean Fuel Standard) are also considering doing so.

Pan-national regulations are important in terms of driving the introduction of alternative fuels in sectors like aviation and shipping. For the aviation sector, the International Civil Aviation Organisation's Carbon Offsetting and Reduction Scheme for International Aviation (ICAO CORSIA) sets the global aspirational goal of keeping the global net carbon emissions from international aviation at the same level from 2020 onwards. To achieve this goal, an important element is the use of sustainable aviation fuels. In November 2021, ICAO published its Sustainability Criteria for CORSIA Eligible Fuels and Default Life Cycle Emissions Values for CORSIA Eligible Fuels. While ICAO has no right to make regulations, it convenes its 193 members and supports them in setting up regulations to reach this aspirational goal. The proposed ReFuelEU Aviation Directive is an example of a (regional) regulation of this kind.

For the shipping sector, the International Maritime Organization (IMO), which is responsible for measures to prevent pollution from ships, has adopted two distinct regulations that make biofuels advantageous for the shipping sector. The first is the so-called IMO 2020 that sets a new limit on the sulphur content of the fuel oil used on board ships. The second is the Initial IMO Strategy on reduction of GHG emissions from ships. The strategy sets a framework for national and regional regulations, such as the proposed FuelEU Maritime Directive.

Biofuel-specific R&D funding programs and investment support for demonstration facilities are an important element in stimulating the research, development, and demonstration of emerging biofuel technologies.

Countries that use a mixture of market-pull and technology-push policy instruments have been the most successful in terms of increasing biofuel production and use and also at developing and deploying fewer mature emerging biofuel production technologies. To further expand the production and use of transport biofuels, it will be important to establish long-term policy support comprising a well-balanced and adaptable basket of policy measures, including safeguards for sustainable production and consistent regulation in the global trade of biofuels.

An overview of biofuel policy tools applied in 15 countries and the European Union is provided in “Implementation Agendas: 2020-2021 Update - Compare and Contrast Transport Biofuels Policies”.

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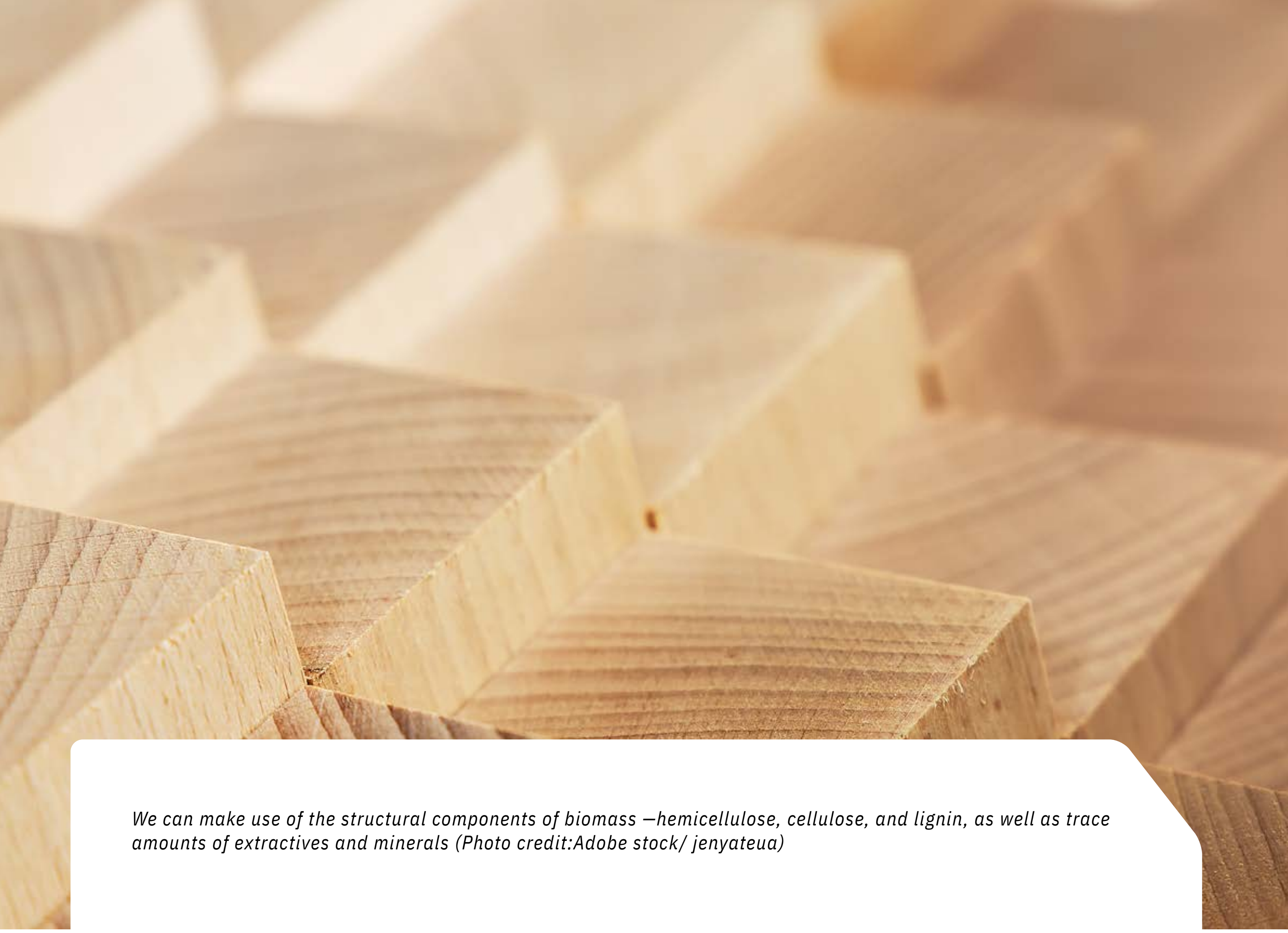
Biorefining

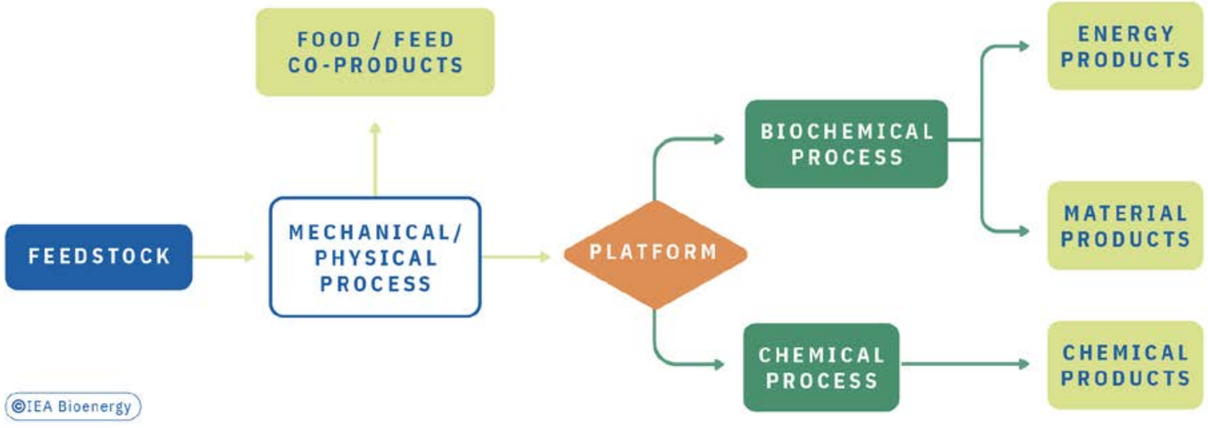


We can make use of the structural components of biomass —hemicellulose, cellulose, and lignin, as well as trace amounts of extractives and minerals (Photo credit:Adobe stock/ jenyateua)

Biorefining

Biorefining is the processing of biomass feedstocks into a spectrum of marketable products and bioenergy. As biomass comprises many components with complex molecular structures, biorefining is well suited to producing not only bioenergy but a wide variety of fibre, protein, and base chemical products. Basing the production of such products on biomasses instead of fossil resources contributes to achieving a more circular economy.

The diversity and complexity of biomass feedstocks offers both strengths and challenges. As almost "everything can be made from everything", it is hard to identify the most promising combinations of feedstocks, processes, intermediates, and products. To shed light on this complex puzzle, experts of IEA Bioenergy Task 42 developed a biorefinery classification system and provided technical, economic, and environmental assessments for a range of biorefinery case studies to examine the status and opportunities of biorefineries focused on producing products for different market segments (chemicals, fibres, proteins, lignin). The classification system distinguishes among feedstocks, conversion processes, platforms (i.e., intermediate products), and products. Rather than producing a primary product and several co-products, a biorefinery produces one or more intermediate products ("platforms") that are valorised through a spectrum of products.



Schematic representation of a biorefinery pathway, following the biorefinery classification system

Within a biorefinery, the focus is on producing “platform chemical” intermediates such as pentose (C5) and hexose (C6) carbohydrates, syngas, lignin, or pyrolytic liquids, and on valorising these intermediates through a range of products, including energy carriers, chemicals, materials, and food and feed constituents. Biorefining involves the processing of renewable biomass feedstocks into a spectrum of marketable energy, chemical, and material products. Examples of biorefineries operational today include:

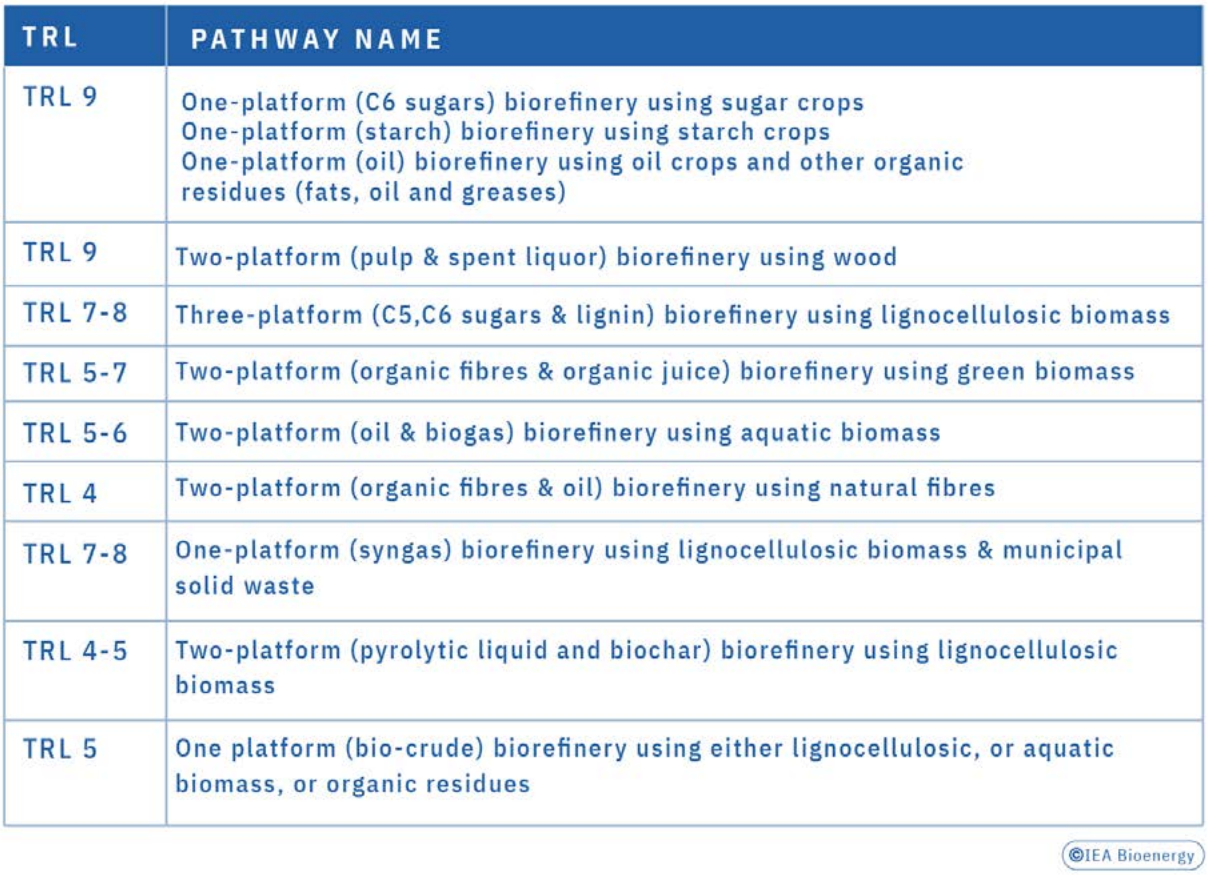
- Utilisation of C5 and C6 sugars from corn stover for the production of ethanol, electricity, and heat (lignocellulose biorefinery);
- Utilisation of C5 and C6 sugars from sugar beet or sugar cane to produce the biopolymer polyhydroxybutyrate (PHB) along with electricity and heat (sugar biorefinery);
- Utilisation of C5 and C6 sugars from food waste to produce polylactic acid (PLA) and animal feed (waste biorefinery);
- Utilisation of black liquor from wood chips for the production of pulp, lignin, and energy (lignocellulose biorefinery).

The terms in brackets indicate the classification of these concepts according to the classification standard VDI 6310 published by VDI, The Association of German Engineers.

Biorefining involves the processing of renewable biomass feedstocks into a spectrum of marketable energy, chemical, and material products.

Technology readiness level and status of implementation

The technology readiness level (TRL) of biorefinery concepts is hard to define. The processes used are often already well established, but just not for the same feedstocks or product slates. Many companies that process biomass feedstocks have diversified into producing a range of products beyond their initial primary product(s); for example, integrated pulp and paper mills not only produce paper but also green electricity and district heat, as well as speciality chemical products, such as tall oil or methanol.



TRL	PATHWAY NAME
TRL 9	One-platform (C6 sugars) biorefinery using sugar crops One-platform (starch) biorefinery using starch crops One-platform (oil) biorefinery using oil crops and other organic residues (fats, oil and greases)
TRL 9	Two-platform (pulp & spent liquor) biorefinery using wood
TRL 7-8	Three-platform (C5,C6 sugars & lignin) biorefinery using lignocellulosic biomass
TRL 5-7	Two-platform (organic fibres & organic juice) biorefinery using green biomass
TRL 5-6	Two-platform (oil & biogas) biorefinery using aquatic biomass
TRL 4	Two-platform (organic fibres & oil) biorefinery using natural fibres
TRL 7-8	One-platform (syngas) biorefinery using lignocellulosic biomass & municipal solid waste
TRL 4-5	Two-platform (pyrolytic liquid and biochar) biorefinery using lignocellulosic biomass
TRL 5	One platform (bio-crude) biorefinery using either lignocellulosic, or aquatic biomass, or organic residues

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Overview of feedstocks and TRL of different biorefinery pathways (Source: "EU Biorefinery Outlook to 2030")

An overview of the current implementation status and outlook to 2030 of biorefineries in Europe is provided in "EU Biorefinery Outlook to 2030". This study focuses on biorefineries primarily producing chemicals or materials—it does not include biorefineries whose major product is bioenergy or biofuel, nor does it include biorefineries focused on pulp and paper and board production. Within Europe, the study found over 400 biorefineries driven by chemicals or materials, more than half of which were utilising food and feed crop feedstocks. Facilities identified in the EU Biorefinery Outlook to 2030 project study are mapped in a database that is accessible here. IEA Bioenergy Task 42 recently launched its Global Biorefineries Atlas Portal which also includes biorefineries that primarily produce biofuels and other energy products; based on further information from the Joint Research Centre (JRC) of the European Union Research Centre (EURC), Bio-Based Industries (BBI), (U.S.) Department of Energy (DOE), and others, it allows users to create their own customised maps and download data. The Global Biorefineries Atlas Portal is accessible here.

IEA Bioenergy Task 42 is mapping biorefineries globally

Technical, economic, and environmental (TEE) assessments

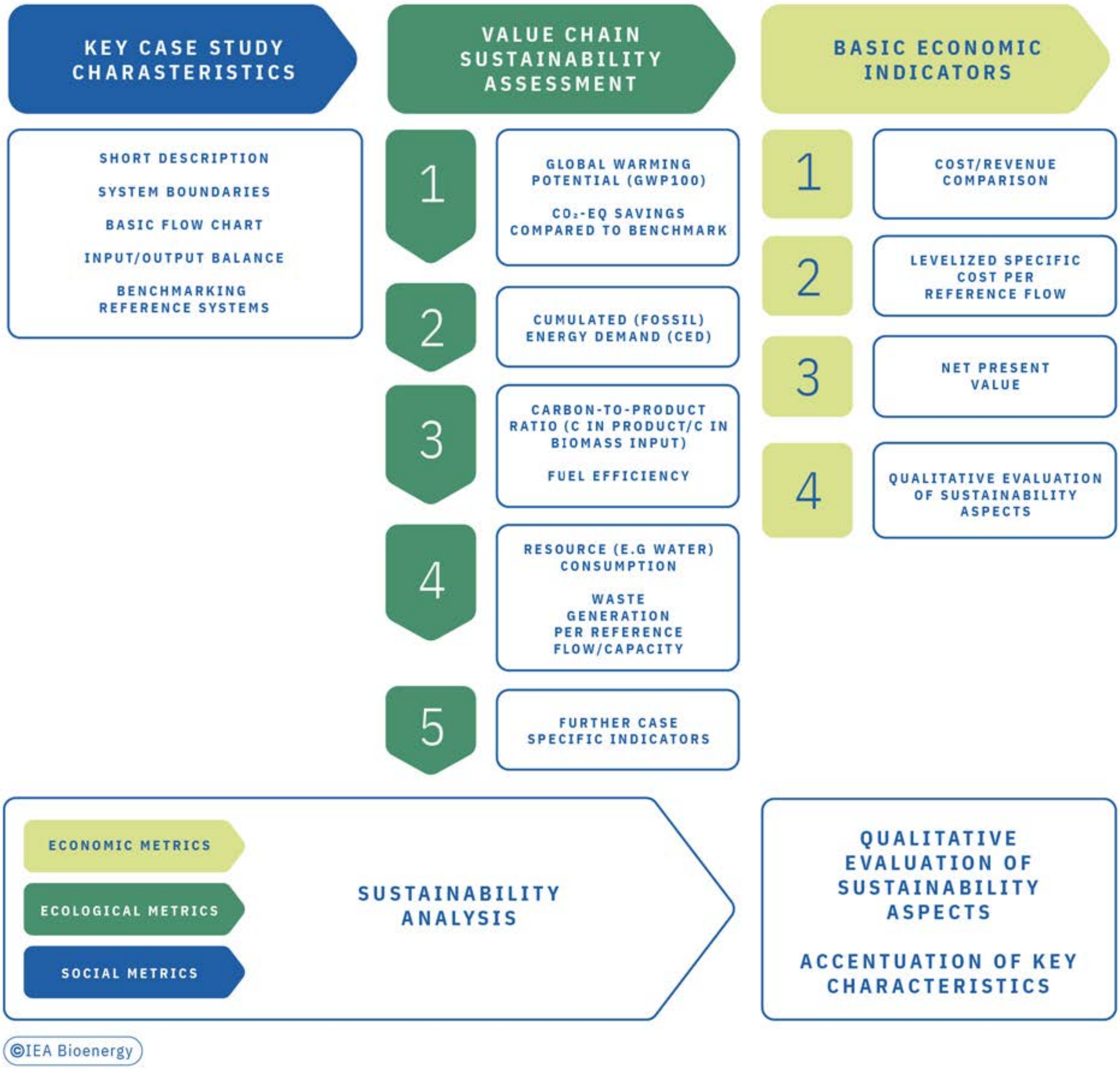
Experts of the IEA Bioenergy Task 42 have developed a methodology for making comparative technical, economic, and environmental assessments of biorefineries, conducting a series of case studies published as biorefinery fact sheets. The first four case studies, performed in 2019, showed that these biorefineries generated GHG emissions that were less than half of the fossil reference system, clearly indicating their benefits regarding global warming reduction. Feedstock costs were the main contributor to overall costs. Some cases struggled with economic feasibility based on simplified cost versus revenue comparison of an annual operation, as the fossil-derived products are on the market at lower prices.

Biorefinery production costs in general are expected to decrease through technological learning and by future biorefineries achieving greater economies of scale. For the moment, however, targeted supportive policy measures and programmes are required to drive the development.

The following biorefinery fact sheets, named according to the biorefinery classification system in which “platform” stands for “intermediate product” are available here:

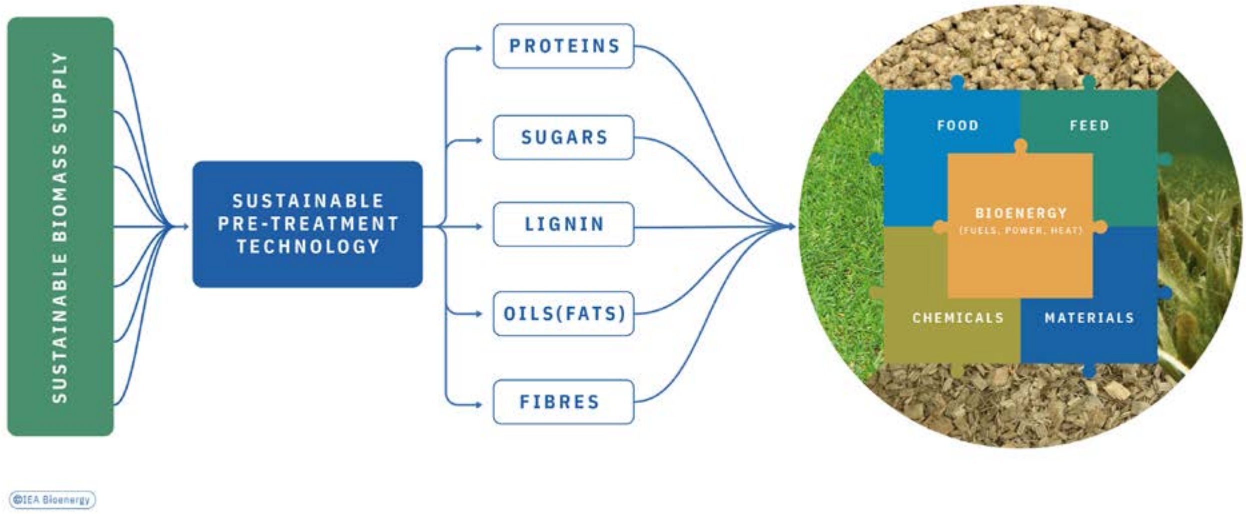
- platform (C6 sugar, lipids) biorefinery to produce the biopolymer PLA and animal feed from food waste;
- platform (C5 and C6 sugars, lignin) biorefinery to produce bioethanol, electricity, and heat from corn stover;
- platform (C5 and C6 sugars, biogas) biorefinery to produce the biopolymer Polyhdydroxybutyrate (PHB), electricity, and heat from sugar beet or sugar cane;
- 1platform (black liquor) biorefinery to produce pulp, lignin, and energy from wood chips;
- 3-platform (C5 and C6 sugars, electricity and heat, lignin) biorefinery using wood chips for bioethanol, electricity, and phenols;

- 4-platform (biogas, green juice, green fibres, electricity and heat) biorefinery using grass silage and food residues for bioplastic, insulation material, fertiliser, and electricity;
- 3-platform (pyrolysis oil, syngas, electricity and heat) biorefinery using straw for FT-diesel and methanol with oxygen gasification;
- 2-platform (electricity and heat, syngas) biorefinery using wood chips for FT-diesel, FT-gasoline, heat, and waxes with steam gasification; and
- 3-platform (vacuum gas oil, pyrolysis oil, electricity and heat) biorefinery using wood for renewable gasoline and diesel, biochar, and pyrolysis oil.



Primary metrics used in the technical, economic, and environmental assessments of IEA Bioenergy Task 42 biorefinery fact sheets. Source: IEA Bioenergy Task 42

Current research gaps and opportunities



Biorefineries allow for the production of food, feed, chemicals, materials, and bioenergy
Source: IEA Bioenergy Task 42

Chemicals

Biobased chemicals could potentially be co-produced with secondary energy carriers in integrated biorefinery facilities. In 2010, Bozell and Petersen identified the following bio-based chemicals building blocks (or “2 platforms”) as being most promising for future development of biorefineries: succinic acid, furanics, hydroxypropionic acid/aldehyde, glycerol and derivatives, sorbitol, xylitol, levulinic acid, biohydrocarbons, lactic acid, and ethanol. When analysing the market potential for bulk chemicals from renewable sources, the BREW project found that under favourable market conditions the production of bulk chemicals from renewable resources could reach 113 million tonnes by 2050, representing 38% of all organic chemical production. Under more conservative market conditions, the market could still reach 26 million tonnes (17.5% of organic chemical production).

The biopolymers market volume was estimated to be 2.11 million tonnes globally in 2020 (bioplastics market data), representing only about 1% of global annual plastic production. Strong growth has been seen for polylactic acid (PLA), bio-based polypropylene (PP), and polyhydroxyalkanoate (PHA). Markets for biopolymers include flexible as well as rigid packaging, consumer goods, textiles, agriculture and horticulture, automotive and transport, building and construction, coatings and adhesives, and electrics and electronics.

Fibres

Applications for bio-based fibres are found in paper, fibre-based boards, textiles, composites, insulation materials for buildings, and in food and feed industries. Emerging market opportunities include the production and use of micro- and nano-fibrillated cellulosic materials for films, nanocomposites, coatings etc.; lightweight, high-performance materials for electric vehicles;

carbon fibres from lignin; cellulose fibres for so-called fair fashion (see “Natural Fibres and Fibre-based Materials in Biorefineries” for details).

Proteins

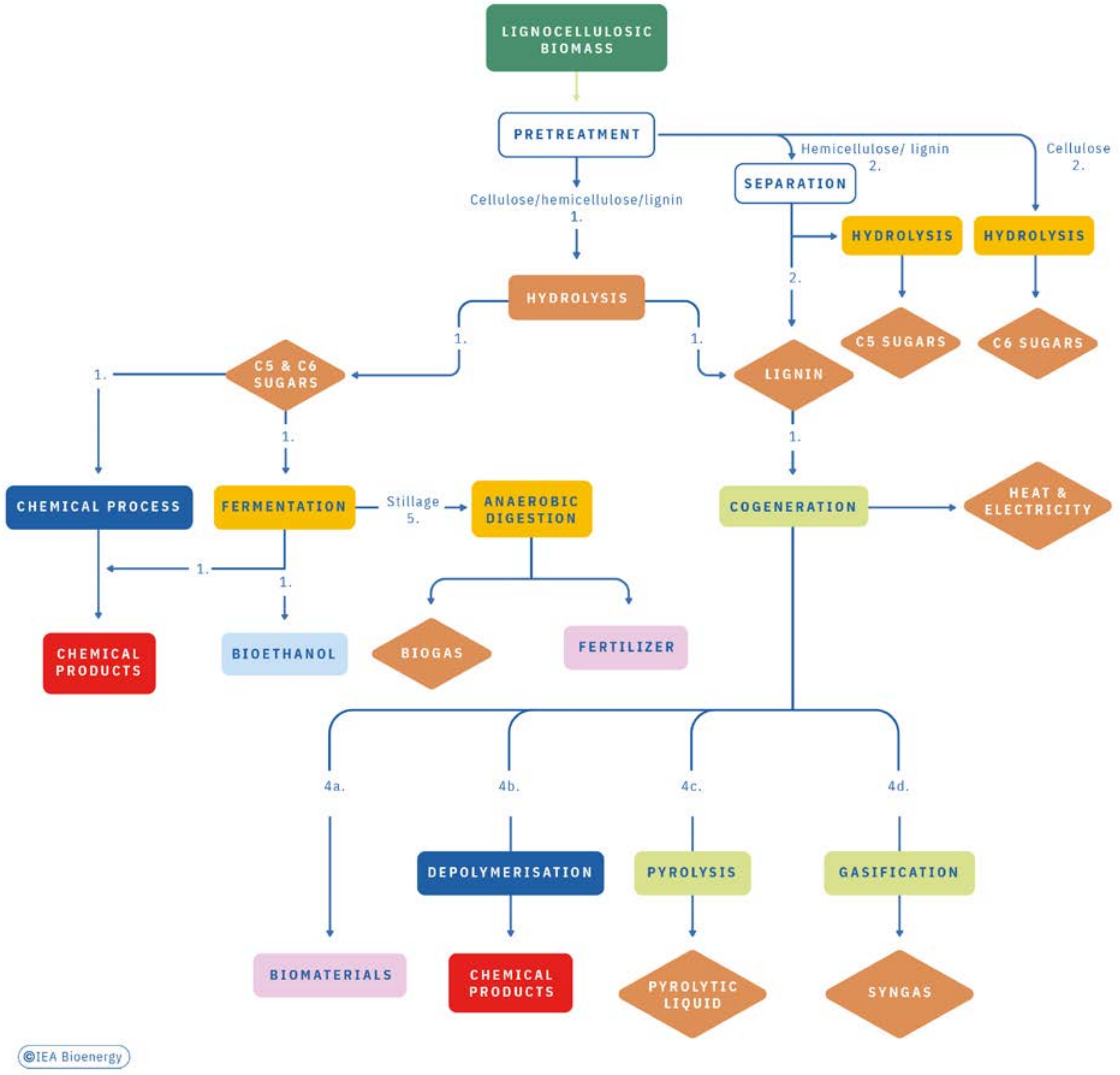
Protein-rich biomass sources such as agricultural crops, crop residues, agricultural product processing residues, and post-consumer residues can be refined into marketable products for food, feed, and technical applications. While food applications and animal feed are the most important markets for proteins, they can also be used in technical applications such as coatings, adhesives, surface active agents, and as so-called green chemicals.

To increase the use of proteins for such products, research and development is still needed in several areas, for example, mild fractionation, separation/isolation and purification technologies, to allow protein-derived intermediates with the required functionalities to be produced.

Powerful policy instruments

The transition to a circular, bio-based global economy requires the establishment of strong, internationally aligned policies. The use of biomass for the production of foods, feeds, chemicals, materials, and bioenergy products will benefit from the following developments:

- Removal of subsidies on fossil fuels;
- High price for emitting net GHGs;
- Incentives for carbon capture and storage;
- Mandatory sustainability guidelines for forestry and agriculture;
- Mandatory circular economy–based production and reutilisation;
- Removal of restrictions on using sustainably sourced biomass feedstocks; and
- High social acceptance of the climate threat and the need for strong climate policy.



Biorefinery pathways are very complex, as multiple products are produced. This example shows the conversion of lignocellulosic biomass into a spectrum of chemical products, biomaterials, bioethanol, and fertiliser. Source: IEA Bioenergy Task 42

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Glossary

Term	Definition/context
Agroecology	Agroecology is a holistic and integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of sustainable agriculture and food systems. It seeks to optimize the interactions between plants, animals, humans, and the environment while also addressing the need for socially equitable food systems within which people can exercise choice over what they eat and how and where it is produced.
Baseload power	Baseload power is the minimum demand on an electrical grid over a span of time. This demand can be met by power plants, dispatchable generation, or by smaller intermittent energy sources, depending on costs, availability, and reliability. The remainder of demand (time-variable) is met by dispatchable generation (load following power plants, peaking power plants, or energy storage).
Bio-based	The term bio-based is typically used with regard to products and services based on biomass.
Biodiversity loss	Biodiversity loss includes not only the worldwide extinction of different species, but also the local reduction or loss of species abundance in a certain habitat.
Bioeconomy	The bioeconomy covers the industrial and economic sectors that produce or process biomass feedstocks or use biological resources for food, materials or energy, plus their associated services.
Bioenergy	Bioenergy is energy derived from any form of biomass or its metabolic by-products. Bioenergy comprises the heat, electricity, cooling, and transport fuels produced from biomass.
Biofuel	A biofuel is a solid, liquid, or gaseous energy carrier, based on biomass, that can provide heat, electricity, or transport services.
Biogenic	A biogenic substance is one that is derived from biomass.

Term	Definition/context
Biomass	Biomass is renewable organic material that comes from plants and animals. Biomass sources for energy include: • Wood and wood harvesting and processing residues and wastes—firewood, wood pellets, and wood chips, lumber and furniture mill sawdust and waste, and black liquor from pulp and paper mills • Agricultural crops, residues and waste materials—corn, soybeans, sugar cane, switchgrass, woody plants, and algae, and crop and food processing residues—mostly to produce biofuels • Biogenic materials in municipal solid waste—paper, cotton, and wool products, and food, yard, and wood wastes • Animal manure and human sewage for producing biogas/renewable natural gas
Bioenergy with carbon capture and storage (BECCS)	BECCS is the process of capturing and storing CO2 from processes that use biomass feedstocks to produce heat, electricity, or biofuels (e.g., in biomass combustion, gasification, biogas plants, ethanol plants, pulp mills for paper production; lime kilns for cement production; and biorefineries). Biomass absorbs CO2 as it grows, releasing it during processing or burning. The released CO2 is captured and injected into storage such as deep geological formations, thus removing it from the natural carbon cycle.
Biorefining	Biorefining is the processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat), using a wide variety of conversion technologies in an integrated manner.
Carbon capture and storage (CCS)	CCS is a process in which a relatively pure stream of carbon dioxide (CO2) from industrial and energy-related sources is separated (captured), conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as carbon dioxide capture and storage, or carbon dioxide removal (CDR).
Carbon capture and utilization (CCU)	CCU is a process in which CO2 is captured and then used to produce a new product. If the CO2 is stored in a product for a climate-relevant time horizon, this is referred to as carbon dioxide capture, utilisation, and storage (CCUS). Only then, and only combined with CO2 recently removed from the atmosphere, can CCUS lead to carbon dioxide removal. CCU is sometimes referred to as carbon dioxide capture and use.

Term	Definition/context
Carbon dioxide (CO2) emissions	Fossil fuel use is the primary source of CO2, but the gas can also be emitted from direct human-induced impacts on forestry and other land use, such as deforestation, land clearing for agriculture, and degradation of soils. Likewise, land use can also remove CO2 from the atmosphere through reforestation, improvement of soils, and other activities. CO2 makes up the majority of greenhouse gas emissions (GHG) and is therefore the primary driver of global climate change.
Carbon dioxide removal (CDR)	CDR covers anthropogenic activities that remove CO2 from the atmosphere before durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO2 uptake not directly caused by human activities.
Carbon intensity	Carbon intensity is the amount of emissions of carbon dioxide (CO2) released per unit of another variable such as gross domestic product (GDP), output energy use, or transport.
Carbon dioxide removal (CDR)	CDR covers anthropogenic activities that remove CO2 from the atmosphere before durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO2 uptake not directly caused by human activities.
Cascadic use/ Cascadic chain	Cascadic use or a cascadic chain refers to the reuse, at least once, of biomass materials that have already been processed into a bio-based final product for energy purposes or use as a material.
Circular bioeconomy	A circular bioeconomy is a new economic model that emphasises the use and reuse of renewable natural capital; it focuses on minimising waste, increasing circular material use, and replacing the wide range of non-renewable, fossil-based products currently in use with renewable bio-based products.
Circular economy	A circular economy is a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible to extend the life cycle of products. This is a departure from the traditional, linear economic model, which is based on a take–make–consume–throw away pattern.
Climate change	Contemporary climate change refers to both global warming and its impacts on Earth’s climate and weather patterns.

Term	Definition/context
CO2 equivalent (CO2eq) emissions	A CO2 equivalent is a metric measure used to compare emissions from various greenhouse gases on the basis of their global-warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.
Commoditisation	Commoditisation is the creation of an interchangeable and standardized or certified good which is traded on a transparent and efficient physical market allowing for equilibrating price dynamics.
Decentralization	Decentralisation is a process whereby activities are distributed or delegated away from a central, authoritative location or group. Concepts of decentralisation are applied to political science, law, public administration, economics, and technology.
Eutrophication	Eutrophication is a process by which an entire body of water, or parts of it, becomes progressively enriched with minerals and nutrients, particularly nitrogen and phosphorus.
Feedstock	Feedstocks are raw materials before processing/conversion.
Geographic information system (GIS)	A GIS is a type of database containing geographic data (that is, descriptions of phenomena for which location is relevant), combined with software tools for managing, analysing, and visualising those data.
Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth’s surface, the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary GHGs in the Earth’s atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO2, N2O and CH4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).
GHG emission intensity	GHG emission intensity is the emission rate of a given pollutant relative to the intensity of a specific activity, or an industrial production process; for example, grams of carbon dioxide released per megajoule of energy produced.
Landscape management	Landscape management, from a perspective of sustainable development, comprises actions to ensure the regular upkeep of a landscape, so as to guide and harmonise changes brought about by social, economic, and environmental processes.

Term	Definition/context
Life-cycle assessment (LCA)	Life-cycle assessment is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service. For instance, for a manufactured product, environmental impacts are assessed from raw material extraction and processing, through manufacturing, distribution and use, to the recycling or final disposal of the materials.
Low carbon intensity fuel	A low carbon intensity fuel is an energy carrier with a low content of fossil-based carbon or energy from a lifecycle analysis perspective.
Mixed waste	Mixed waste is any combination of waste types with different properties. Commercial and municipal wastes are typically mixtures of plastics, metals, glass, and biodegradable waste, including paper and textiles.
Modern bioenergy	Modern bioenergy refers to biomass use alongside modern heating technologies, power generation and transport fuels. It excludes traditional uses of biomass in simple pit fires and inefficient heating devices.
Negative emissions technologies (NET)	Negative emissions technologies remove GHG gases from Earth's atmosphere and store them on a permanent or long-term basis. Most NET are CDR, as CO2 is the major GHG gas. NETs include bioenergy with carbon capture and storage (BECCS), reforestation, forest management, wood use, soil management (e.g. with biochar) and direct air capture.
Post-consumer wood	Post-consumer wood is woody material or finished product that has served its intended use and has been discarded for disposal or recovery, having completed its life as a consumer item.
Residues	Residues are divided into four subcategories: agricultural, forestry, aquaculture and fisheries, and processing residues. Residues can be used for further processing, for energy recovery (via combustion, gasification, pyrolysis) or disposed of.
Scaling effect (economy of scale)	Economies of scale are the cost advantages that enterprises obtain due to increasing their scale of operation.
Sustainable	Sustainability has been defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” (WCED, 1987). There are three pillars of sustainable development—economic, social, and environmental.

Term	Definition/context
Sustainable agriculture	Sustainable agriculture is an integrated system of plant and animal production practices aiming at environmental health, economic profitability, and social and economic equity. The overall goal is to meet society's present food and textile needs, without compromising their availability for future generations.
Sustainable avenues	Scenarios/Pathways/Strategies on how to attain the 2030 Sustainable Development Goals (SDGs) or the targets of the Paris Agreement on climate change.
Sustainable bioenergy	Sustainable modern bioenergy systems are those that meet the following criteria: • Technical merit, including technological soundness and accessibility of technology; • Financial and economic merit, including cost-effectiveness, sound cost–benefit ratios, and coherence with local and national development priorities; and • Ecological soundness, bearing in mind that traditional biomass use is not sustainable; that modern bioenergy can be sustainable; and that sustainable bioenergy is always modern bioenergy.
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987) and balances social, economic and environmental concerns.
Sustainable forest management	Sustainable forest management is defined as: “The stewardship and use of forest lands in a way and at a rate that maintains their productivity, biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil now and in the future relevant ecological, economic and social functions at local, national and global levels and that does not cause damage to other ecosystems."

Term	Definition/context
Technology readiness levels (TRL)	TRLs are a method of estimating the maturity of technologies. The following definition was used by the European Commission for the Horizon 2020 Work Programme 2014-2015: TRL 1 – basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept TRL 4 – technology validated in lab TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
Traditional bioenergy/ traditional use of biomass	Traditional bioenergy/use of biomass refers to the burning of woody biomass or charcoal or agricultural residues in simple fire pit stoves and other inefficient heating devices, and is still a major element in many developing and emerging economies.
Transport biofuel	Transport biofuel is produced from biomass and burned in vehicle engines to provide transport services; it may be liquid or gaseous.
Variable renewable energy (VRE) sources	Variable renewable energy sources are ones that that are not dispatchable due to their fluctuating nature, such as wind and solar power; this is in contrast to controllable renewable energy sources, such as dammed hydroelectricity or bioenergy, or relatively constant sources, such as geothermal energy.
Waste	Waste is any substance which is discarded after use, or is worthless, defective, and of no use. Examples include municipal solid waste, hazardous waste, radioactive waste. Depending on their origin, wastes are used for energy recovery (via incineration) or disposed of.