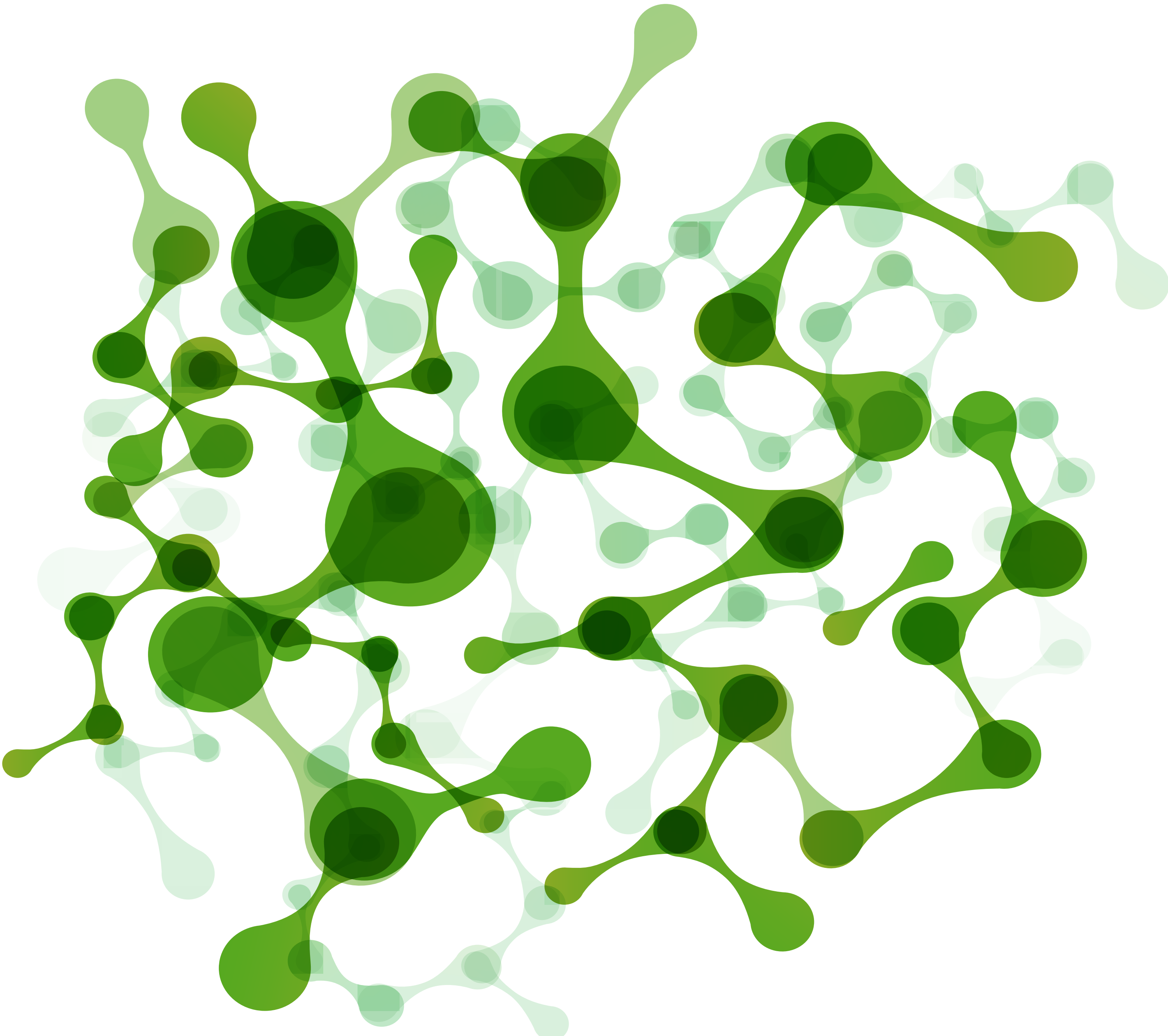
IRENA
International Renewable Energy Agency

Bioenergy for the energy transition

Ensuring sustainability and overcoming barriers



ISBN: 978-92-9260-451-6

Citation: IRENA (2022), *Bioenergy for the energy transition: Ensuring sustainability and overcoming barriers*, International Renewable Energy Agency, Abu Dhabi.

ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

ACKNOWLEDGEMENTS

This report was developed under the guidance of Rabia Ferroukhi (Director, IRENA Knowledge, Policy and Finance Centre) and Ute Collier, and authored by Jinlei Feng (IRENA), Adam Brown (consultant) and Chun Sheng Goh (consultant), with valuable contributions from Diala Hawila, Emanuele Bianco, Abdullah Abou Ali and Hanbit Lee (IRENA).

Valuable external review was provided by Ivan Vera (United Nations Department of Economic and Social Affairs), Toshimasa Masuyama (Ministry of Agriculture, Forestry and Fisheries, Japan), Maria Michela Morese, Constance Miller (Food and Agriculture Organization), Arthur Wellinger (European Biogas Association), Bharadwaj Kummamuru (World Bioenergy Association), Phosiso Sola (World Agroforestry), Daniela Thrän (German Biomass Research Centre), Jack Saddler (University of British Columbia), Julia Tomei (University College London), Suani Coelho (University of São Paulo), Gabriel Blanco, Daniela Keesler (National University of Central Buenos Aires) and Angel Alvarez Alberdi (European Waste-based & Advanced Biofuels Association).

The authors would like to thank Dean Cooper (WWF), Stephan Singer (Climate Action Network International) and Craig Hanson (World Resources Institute) for valuable inputs on the sustainability discussions.

Valuable review and feedback were provided by IRENA colleagues Adrian Whiteman, Arvydas Lebedys, Badariah Yosiyana, Paul Durrant, Paul Komor and Seungwoo Kang.

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ABBREVIATIONS

BECCS	bioenergy with carbon capture and storage
CAD	Canadian dollar
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CHP	combined heat and power
CNY	Chinese yuan renminbi
CO_2	carbon dioxide
COP26	26th United Nations Climate Change Conference of the Parties
ECOWAS	Economic Community of West Africa States
EFB	empty fruit bunch
EJ	exajoule
ETS	emission trading system
EU	European Union
EU-RED	European Union Renewable Energy Directive
EUR	euro
FAME	fatty acid methyl esters
FAO	Food and Agriculture Organization
FFV	flex-fuel vehicles
FIT	feed-in-tariff
FSC	Forest Stewardship Council
GBEP	Global Bioenergy Partnership
GBP	United Kingdom pound
GDP	gross domestic product
GGL	Green Gold Label
GHG	greenhouse gas
GJ	gigajoule
$GtCO_2$	gigatonne of carbon dioxide
GW	gigawatt
ha	hectare
HEFA	hydroprocessed esters of fatty acids
HVO	hydrogenated vegetable oil
ICRW	International Center for Research on Women
IEA	International Energy Agency
ILUC	indirect land-use change
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
ISCC	International Sustainability & Carbon Certification
ISPO	Indonesian Sustainable Palm Oil
KWh	kilowatt-hour
LCFS	Low Carbon Fuel Standard
LPG	liquified petroleum gas
MSPO	Malaysian Sustainable Palm Oil
MSW	municipal solid waste
Mt	megatonne
$MtCO_2$	million tonne of carbon dioxide
MW	megawatt
NDC	Nationally Determined Contribution
NEDO	New Energy and Industrial Technology Development Organization (Japan)
OECD	Organisation for Economic Co-operation and Development
PEFC	Programme for the Endorsement of Forest Certification
PKS	palm kernel shell
PM	particulate matter
POME	palm oil mill effluents
PV	photovoltaic
RBF	results-based financing
RD&D	research, development and demonstration
RED II	Renewable Energy Directive recast
RFS	Renewable Fuel Standard
RNG	renewable natural gas
RSB	Roundtable on Sustainable Biomaterials
RSPO	Roundtable on Sustainable Palm Oil
SDG	Sustainable Development Goal
SFM	sustainable forest management
SOx	sulphur oxide
UCO	used cooking oil
UN	United Nations
US	United States
USD	United States dollar
USDA	United States Department of Agriculture
VAT	value-added tax
VFDS	Viet Nam Forestry Development Strategy

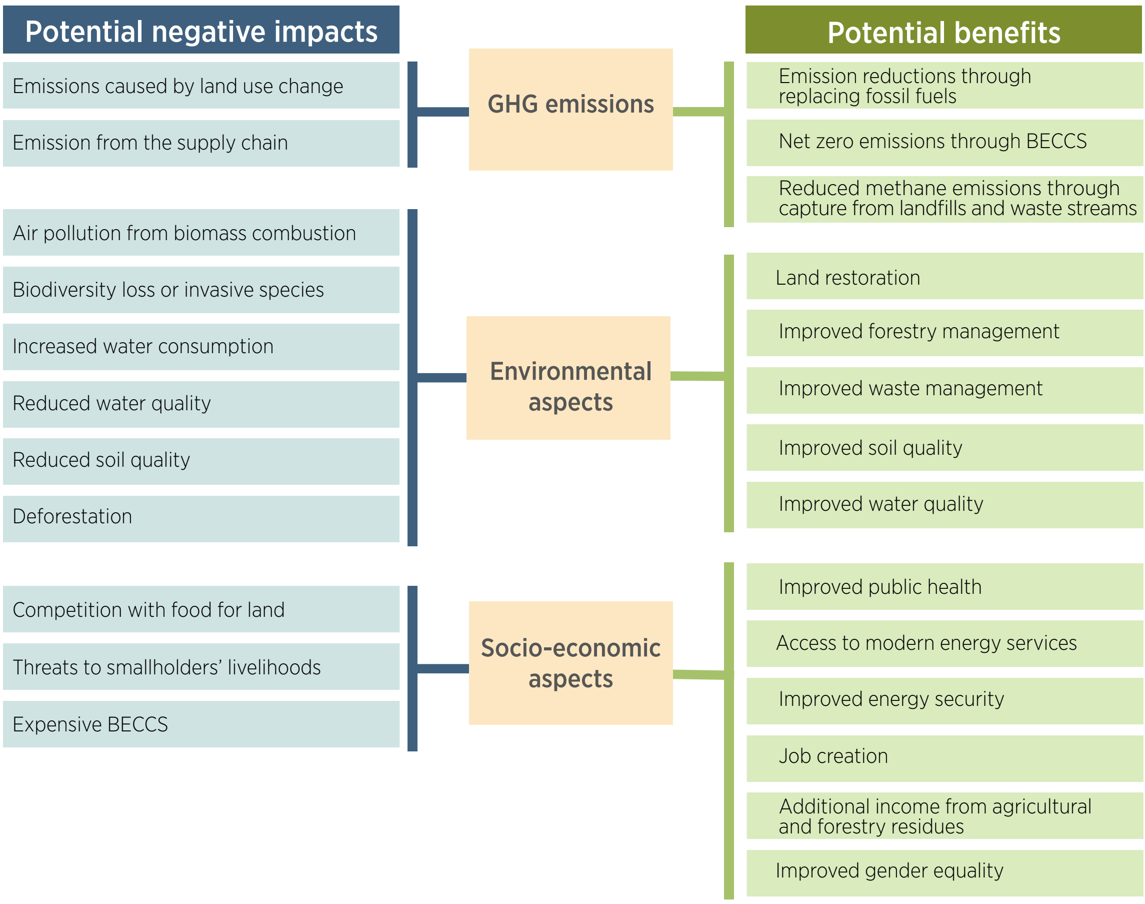
EXECUTIVE SUMMARY

Bioenergy currently contributes the largest share (two-thirds) of renewables utilisation worldwide, when including the traditional use of biomass. A growth in production and use of modern bioenergy will be critical for the global energy transition with low-carbon to net zero emissions scenarios. According to the International Renewable Energy Agency's (IRENA's) 1.5°C Scenario, bioenergy production would need to increase significantly by 2050 to achieve the 1.5°C climate goal. Without the deployment of sustainable biomass for different purposes, achieving this goal may be challenging.

The current deployment of bioenergy remains well below what is needed to achieve the energy transition, even though many technologies are available, and the modern use of biomass and liquid biofuels has been growing significantly in some regions. At the same time, billions of people still rely on the traditional and inefficient use of biomass for cooking and heating, affecting health and gender inequity, while leading to deforestation in many areas and adding to climate change. Modern bioenergy will need to increase significantly in all end uses. Accelerating progress will depend on tackling the traditional biomass use problem by facilitating a shift to alternative sustainable fuels, as well as developing more ambitious policy portfolios for modern biomass use, supported by investments.

Realising bioenergy's role in the energy transition will be a major challenge. For policy makers, bioenergy is a complex area, involving a much wider range of stakeholders and issues than most other forms of renewable energy. It interacts with many other sectors, such as agriculture, forestry, environmental protection and waste management, and can have positive or potentially negative impacts if the supply chain is not managed properly. The potential sustainability risks of the bioenergy supply chain and its deployment are linked to land use, air pollution, water and soil quality, biodiversity, competition with food supply, and effects on indigenous communities and smallholders (see Figure S1).

Figure S1. **Potential aspects related to bioenergy sustainability**



Note: BECCS = bioenergy with carbon capture and storage; GHG = greenhouse gas.

International trade of bioenergy has further increased the complexity of sustainability governance. Wood pellets, biodiesel and bioethanol are major commodities produced by countries in North and South America and Asia, while European countries are main destinations for most of these commodities to support their decarbonisation ambitions. Many drivers along the bioenergy trade have triggered the adoption of certifications and regulations and a wide range of stakeholders to address the sustainability issues.

Ensuring the sustainability of bioenergy along the supply chain, including most notably biomass feedstocks, is the most fundamental element of bioenergy policy making. The aim of this study is to assist policy makers in this complex area. While no one solution fits all, policies and measures should be contextualised and based on engagement with various stakeholders. The policy framework for sustainable bioenergy should consist of sustainability-based target setting and long-term planning, co-ordinated planning across departments, regulations, certification schemes and partnerships. Moreover, the Sustainable Development Goals (SDGs) can also be used to help bioenergy policy making (see Figure S2).

Figure S2. **A policy framework for sustainable bioenergy development**

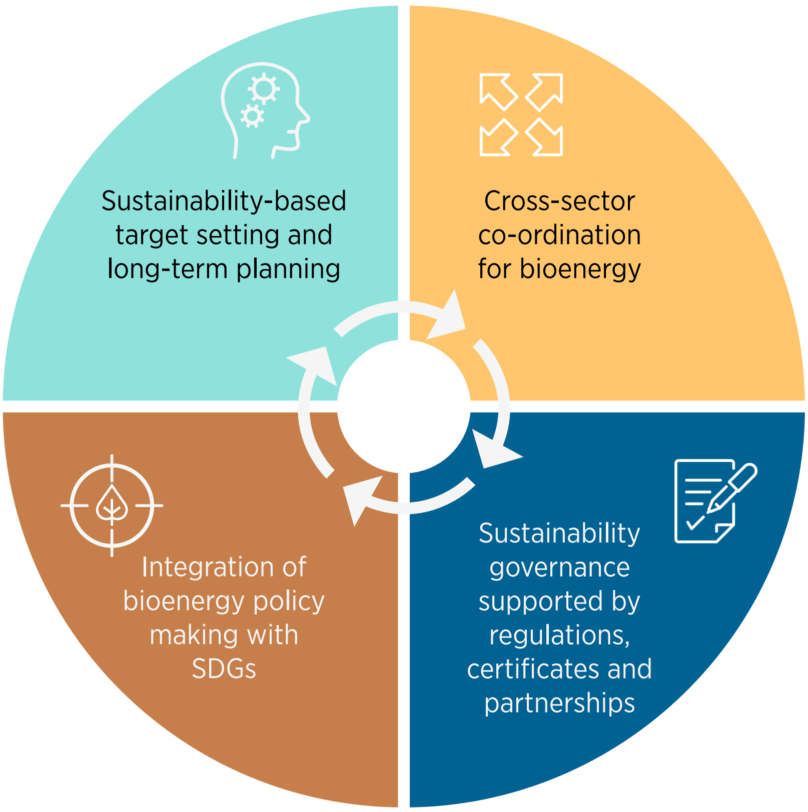


Figure S3. Cross-cutting barriers to bioenergy deployment

Political and institutional barriers

- Policy uncertainty
- Weak institutional structures

Financial and economic barriers

- Fossil fuel subsidies
- High cost
- Lack of access to affordable finance

Technical and infrastructure-related barriers

- Low-level technology readiness
- Reliability of technologies
- Lack of infrastructure

Supply chain-related barriers

- Lack of stable feedstock
- Lack of qualified workers and skills
- Sustainability risks

Information and public awareness-related barriers

- Lack of reliable information
- Low public awareness

Various barriers are impeding the development of sustainable bioenergy use for most applications (see Figure S3). These barriers include policy uncertainty due to a lack of clear or long-term signals given to bioenergy in national energy policy making; institutional and organisational issues, including a lack of co-ordination of policies between relevant departments; the high cost of biomass boilers and advanced biojet fuels and difficulties in securing finance; a low level of technology readiness, reliability and efficiency; and a lack of skilled workers, infrastructure and reliable information.

Policy measures are needed to address those cross-cutting barriers and should be tailored to the local context and align with other sectoral policies and strategies. Generally, these policy measures can include a clear and long-term strategy on bioenergy development. Financial and fiscal measures can be included to fix the energy market distortion incurred by fossil fuel subsidies and to improve bioenergy's cost-competitiveness and access to finance. Measures can also include regulations, obligations and mandates depending on the type of bioenergy. Policy support for research, development and demonstration (RD&D) and loan guarantees can also be used to mitigate the risks of novel bioenergy technologies.

Clean cooking can be achieved through the help of renewables-based solutions, including efficient cookstoves, modern forms of biomass, biogas and biomethane. However, existing investment gaps and clear gender inequity, along with the unaffordable cost of renewables-based solutions for many households, are some major barriers. With the guidance of dedicated clean cooking targets, result-based financing schemes and public awareness-raising programmes, these barriers could be addressed, thereby accelerating the needed progress to achieve 100% coverage of clean cooking.

Modern forms of bioenergy for heating in buildings include injection of biogas and biomethane into gas grids and pellet use in decentralised and centralised boilers. District heating networks supply heat for multiple buildings are likely to be a better cost-efficient technology in urban areas. The high upfront cost of boilers and district networks, weak policy attention to building heating, and high production cost of biomethane compared to natural gas are major barriers. Potential measures to address these barriers include a ban on fossil fuel heating, an obligation on bioenergy heating, and the introduction of appliance standards and connection mandates.

Bioenergy has been increasingly used for power generation, mainly based on pellets, biogas, municipal solid waste, and agricultural and forestry residues. Due to other existing lower-cost renewable electricity options and limited biomass feedstock, bioenergy for power generation only is not a prioritised option. However, bioenergy can still produce renewable electricity based on low-cost waste and residue feedstock and through co-firing as the intermediate solution for the phaseout of coal plants, providing dispatchable electricity to systems with a high share of variable renewable energy, or combined heat and power (CHP) and bioenergy with carbon capture and storage (BECCS) to deliver negative emissions. Weak supply chains and high operation costs are among the major barriers. Renewable obligations and blending mandates for coal plants can secure deployment. Business models and policy support are also needed to incentivise BECCS projects and cover the additional investments.

Biomass has been widely used in the pulp and paper industry and sugar mills to provide industrial heat and cogeneration. It can also be used as feedstock and provide process heat for the chemical and petrochemical sectors, such as the production of bioplastic or biomethanol. Biomass also has the potential to provide high-temperature heat for the cement, steel and iron industries. However, the cost of biomass-based chemical products such as bioplastic and biomethanol is much higher than their fossil counterparts. Heat requirements for high-temperature industries can be high and raise concerns about product quality impacts. Securing a better quality would require matured technologies, qualified workers and needed pre-treatment, neither of which are well developed. To support biomass development, countries have allocated capital subsidies to support biomass CHP in industries, provided funding and grants to RD&D projects, as well as made the procurement of biomass-based products for public organisations mandatory.

Bioenergy, including bioethanol, biodiesel and biomethane, can replace fossil fuels and decarbonise road transport and shipping. Biojet fuels based on hydroprocessed esters of fatty acids (HEFA) or hydrogenated vegetable oil (HVO) and other pathways can also have unique roles in decarbonising aviation. Some of these advanced technologies, especially biojet fuels, are still in the early development stage. Replacing fossil fuels with liquid biofuel will also require necessary fuel transportation and distribution infrastructures. Most importantly, sustainability risks have been the main barrier related to biofuels. Blending regulations have been adopted by dozens of countries and may need to be expanded to the shipping and aviation sectors to secure market viability. Certificates, grants and loan guarantees are available measures to increase the cost-competitiveness of biofuels. Moreover, a holistic policy framework among all the measures is needed to ensure limited sustainable biomass feedstock can be used for the most appropriate options depending on local contexts.

INTRODUCTION

Bioenergy is the energy produced from biological materials such as crops, woody biomass (*e.g.* forestry and agricultural residues) and other organic materials and wastes. Biomass, biofuels, bioliquids and biomethane are related terms (see Glossary). These different forms of bioenergy can be used for cooking, heating, industrial use, to produce electricity and for transport fuels.

Bioenergy is an important contributor to global energy needs. It makes up the largest share of renewable energy use today, accounting for around 12% of the world's total final energy demand. More than half of bioenergy is consumed for cooking and heating buildings in a traditional way. Modern uses of bioenergy include biomass and biogas/biomethane for building and industrial heat and power generation, liquid biofuels and biomethane for transport, and biomass-based material used as industrial feedstocks.

Modern bioenergy has a major role to play in the energy transition. The International Renewable Energy Agency's (IRENA's) 1.5°C Scenario suggests that it could make up a quarter of the total primary energy supply, or 17% of final energy demand, by 2050. Bioenergy would need to be scaled up to provide heat for both industrial processes and buildings, as well as fuels for transport. It is also likely to be needed as feedstock in the chemical industry to produce chemicals and plastics. Combined with carbon capture and storage (CCS) technologies in the power sector and some industrial sectors, bioenergy may deliver the negative emissions needed to achieve the net zero emission goal.

Bioenergy has been growing significantly in recent years in some countries and regions, such as Brazil, China, the European Union (EU) and the United States (US) (IRENA, 2020, 2021a; IEA, 2021a). However, the growth rate is still well below that needed to achieve the decarbonisation goals for a net zero future. Bioenergy only contributes small shares of the final energy consumption of end uses: 8% of energy consumption in buildings and industry and 3% of transport fuels (IRENA, 2022a).

The concept of sustainability must be central to the further development of bioenergy. Concerns have been raised about the sustainability of bioenergy, especially related to land use. These concerns include not only environmental factors like carbon stock and biodiversity but also social issues like food versus fuel and land grabs. While bioenergy can play a positive role in the energy transition, it is important to avoid any unwanted consequences from bioenergy deployment.

This report aims to provide an overview of sustainable bioenergy developments. It focuses on bioenergy's role in decarbonising power and end-use sectors in the energy transition, as well as major sustainability challenges based on the scale of bioenergy deployment depicted in IRENA's 1.5°C Scenario, which would require increased biomass supply. It analyses main opportunities, barriers and policy options to ensure the sustainability and for the deployment of bioenergy for power and each end use.

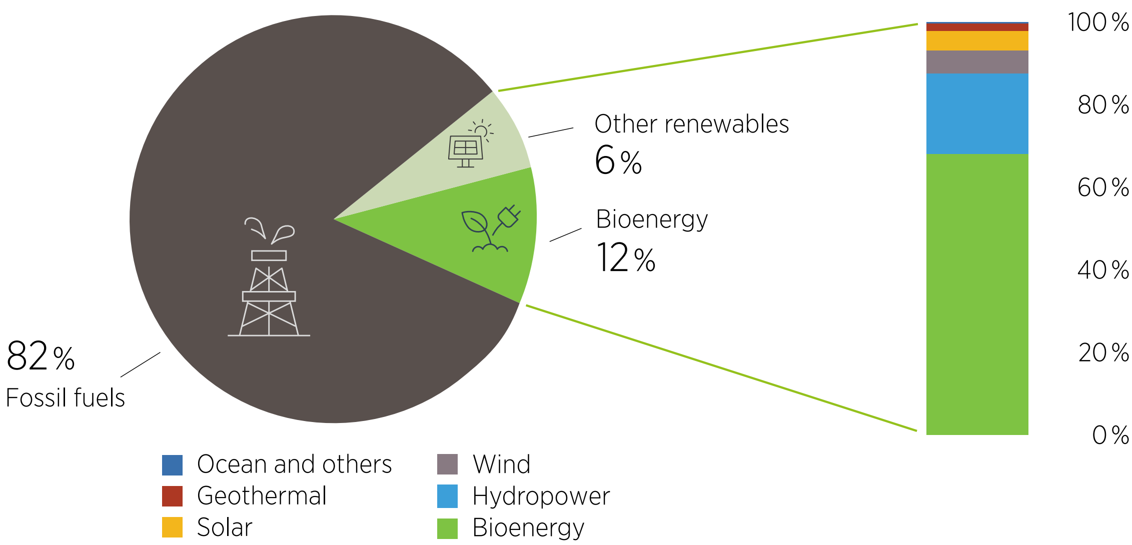
The report is structured as follows. Chapter 1 places bioenergy in the context of the energy transition, describing its current status and role in the future transition. Then, it identifies the key aspects of bioenergy sustainability in terms of emission reduction, environmental protection and socio-economic benefits in Chapter 2. Chapter 3 illustrates the international trade of bioenergy, a major component of bioenergy development. Chapter 4 analyses the policy framework for the sustainability of bioenergy, and Chapter 5 presents selected case studies from Southeast Asia. Cross-cutting barriers and policies to deployment are analysed in Chapter 6, while chapters 7 to 11 analyse barriers and policies specific to end uses, namely cooking, heating in buildings, electricity generation, industry and transport.

1. BIOENERGY IN THE ENERGY TRANSITION

1.1. CURRENT DEPLOYMENT STATUS AND SHARE IN THE ENERGY MIX

Globally, bioenergy remains the largest renewable energy resource, contributing to around 12% of final energy consumption (see Figure 1.1). It can be used for power generation and end uses, including heating, cooking and transport (see Figure 1.2). Currently, more than 80% of bioenergy is used for cooking and heating in buildings and industry. Globally, in 2020, bioenergy provided around 20% of total heat consumption, with 8% from modern forms of bioenergy and 12% from traditional use of biomass (IEA, 2021a; IRENA, 2022a).

FIGURE 1.1. Share of bioenergy and other renewables in global total final energy consumption, 2019



Box 1.1. Limitations in data reporting and definition of traditional biomass

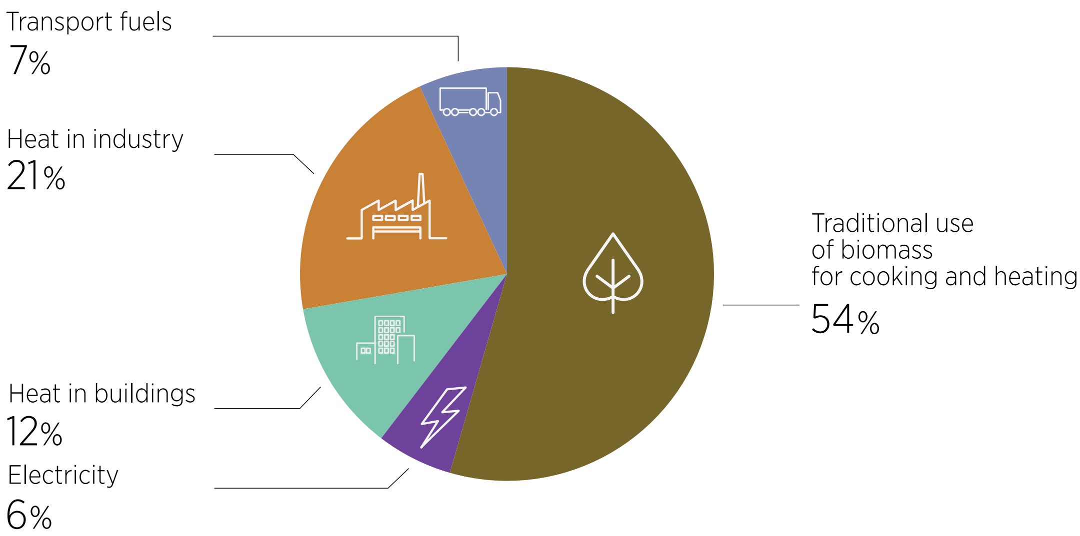
The current data reporting approach and definition of the traditional use of biomass have limitations and may mislead the estimation and forecasting of sustainable bioenergy use in different regions and countries.

The current widely adopted definition of traditional biomass refers to the inefficient uses of solid biofuels – such as wood fuel, charcoal, crop residues and animal dung in open fires – and focuses on these uses in the developing world. However, the reporting of traditional uses of biomass in energy balances developed by main energy institutions is focused only on the residential consumption of primary solid biofuels and charcoal in non-Organisation for Economic Co-operation and Development (OECD) countries. The inefficient uses of biomass in OECD countries by households facing energy poverty may be left out.

Furthermore, these data may not sufficiently capture the adoption of modern forms of bioenergy use in emerging economies, including the increasing consumption of pellets and other modern uses. Data accuracy needs to be improved to provide a better basis for bioenergy policy making as well as to address sustainability issues related to bioenergy.

The inefficient, traditional use of solid biomass, such as firewood, charcoal, crop residues and animal dung, accounted for more than half of total bioenergy consumption. Around 2.4 billion people, mostly in developing regions of sub-Saharan Africa and South Asia with limited access to affordable and reliable modern energy systems, relied on traditional solid biofuels for cooking and residential heating on open cookstoves and fireplaces with very low energy conversion efficiency (around 5-15%). The fuels were often sourced through self-supply or through informal supply chains, and it is difficult to accurately estimate the amount used (see Box 1.1).

FIGURE 1.2. **Share of global bioenergy consumption by end use, 2020**



Based on: IEA (2021b), IRENA (2021b).

Traditional and inefficient use of solid biofuels causes negative health, socio-economic and environmental consequences. It generates a high level of health-damaging air pollutants, inducing acute ambient and indoor air pollution when combined with poor ventilation. This is considered a major cause for around 3.8 million premature deaths every year, mostly in low-, lower- and middle-income countries (WHO, 2021).

Women and children are disproportionately affected by these practices, as they take more responsibility for cooking and have more exposure to indoor air pollution. They are also tasked with the collection of biomass such as firewood or agriculture residues, which could be very time-consuming. In this case, it takes women's time away from other working or economic earning activities and takes children's time from education. For this portion of bioenergy, attention focuses on replacing traditional use of bioenergy with clean fuels and modern technologies. While Sustainable Development Goal 7 (SDG 7) includes a target to achieve universal access to clean cooking fuels by 2030, progress has been slow, with a global annual improvement rate of around 0.2-1.8% from 2010 to 2019, far from the 3% required. Sub-Saharan Africa, home to more than half of the global population without access to clean cooking in 2019, has seen the least progress (IEA, IRENA, UNSD, World Bank and WHO, 2021).

Modern use of bioenergy refers to more efficient use of solid and gaseous biofuels for heating and power generation, as well as liquid biofuels and biomethane for transport and other end uses. In 2019, modern use of bioenergy provided some 6% of total global final energy demand, more than hydropower and other modern renewables. It is estimated that the total market value of solid and liquid modern bioenergy was around USD 79 billion (United States dollars) in 2019, with USD 34 billion from bioethanol, USD 35 billion from biodiesel and USD 10 billion from wood pellets (Globe Newswire, 2021).

The development of modern bioenergy varies by region and sector. The production and modern use of bioenergy in buildings for heating are mainly seen in Europe and North America and to a lesser extent in other temperate countries like Japan and New Zealand. Its use in industry is currently concentrated in the cement industry and wood-based industries, such as pulp and paper, as well as agriculture and food sectors. Brazil and India use bagasse from sugarcane production in combined heat and power (CHP) systems extensively.

Wood pellets are the main biofuel used for power generation. Europe has been the major consuming region, importing wood pellets mainly from the United States, Canada and the Russian Federation, as well as using its domestic supply. The United Kingdom remains the largest pellet consumer, with most of the consumption used for power generation in one big power plant Drax (Bioenergy Europe, 2019; Drax, 2020). Other forms of solid biofuels are also consumed in relatively smaller volumes. East Asia, particularly Japan and the Republic of Korea, has recently emerged as a solid biofuel consuming region for power generation (FAO, 2021).

Most liquid biofuels are used for transport, but some are consumed for CHP and district heating in northern Europe (IEA Bioenergy, 2021a). More than 60% of liquid biofuel for transport is produced by Brazil and the United States. Other major producers include Argentina, China, Indonesia, Malaysia and the European Union (IEA, 2021a; OECD/FAO, 2021).

Biogas can be used directly for heating or power generation. China, Germany, Italy, the United Kingdom and the United States have the largest installed biogas power generation capacities. Biogas can also be upgraded to biomethane and injected into the gas grid to replace fossil gas. Biogas production in 2019 was around 1.5 exajoules (EJ), increasing from 0.8 EJ in 2010.

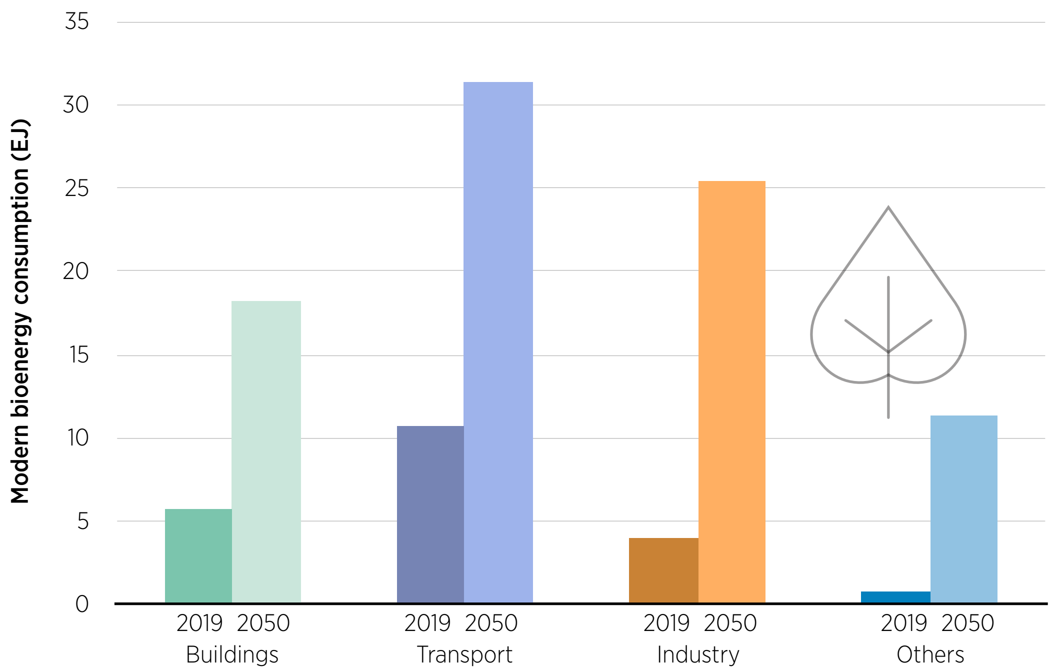
The international trade of biofuels has been developing for decades. In the last five years, Canada, the Russian Federation, the United States and Viet Nam have been the largest exporters of wood pellets. In energy value, biodiesel is the largest traded bioenergy, contributing to the majority of all traded bioenergy commodities in 2020. Europe is the major destination, but Japan and the Republic of Korea are emerging markets. Biodiesel is mainly exported by Argentina, China, Indonesia and Malaysia and imported by the European Union. The United States is the largest bioethanol exporter, with major importers including Canada, Colombia, India and the Republic of Korea. Details of the international trade of bioenergy are discussed in Chapter 3.

1.2. THE ROLE OF BIOENERGY IN THE ENERGY TRANSITION

Bioenergy plays an important role in the global energy transition. In IRENA's 1.5°C Scenario, sustainable bioenergy plays a major role in bringing global carbon dioxide (CO_2) emissions close to net zero by 2050, thus limiting the global temperature rise to 1.5°C. Bioenergy could provide medium and long-term solutions for many sectors for which there are few other renewable options available, such as providing fuels for aviation. It could also provide renewable heat and feedstock for industries (IRENA, 2021b).

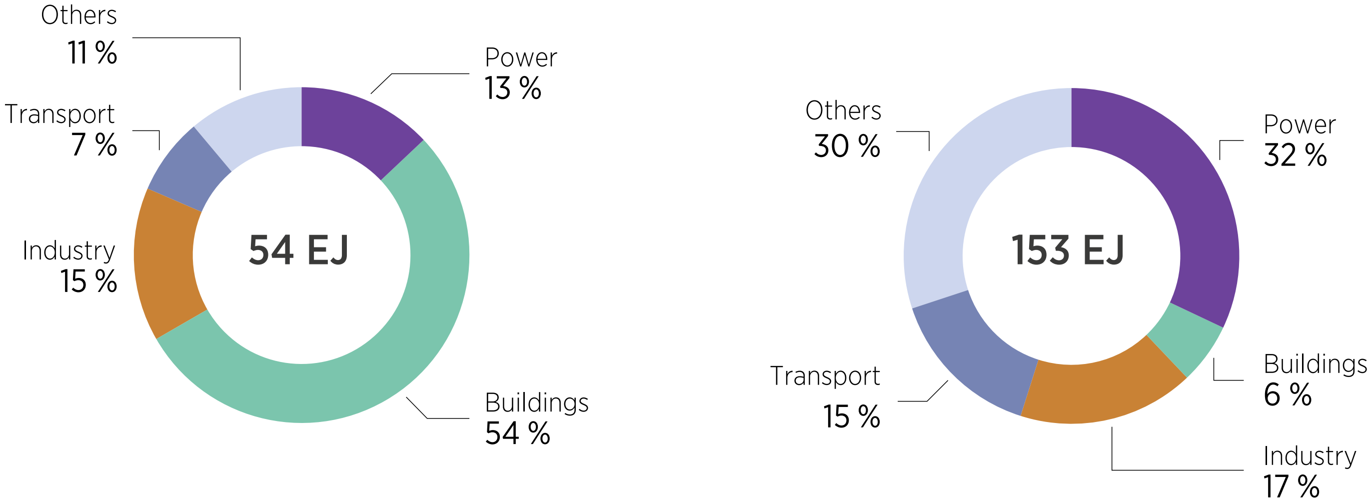
In the 1.5°C Scenario by 2050, bioenergy contributes 17% of total final energy consumption. Modern use of bioenergy would need to increase in all end uses (see Figure 1.3). Biomass accounts for 25% of the total primary energy supply globally. This translates to 153 EJ of biomass, a threefold rise compared to the 2018 level (see Figure 1.4). Achieving the requisite supply in a sustainable manner would be a major challenge. Given that context and resources vary, different solutions are preferable for each region and country (see Box 1.2).

FIGURE 1.3. Modern bioenergy consumption in 2019 and 2050 in IRENA's 1.5°C Scenario, by sector



Note: "Others" includes bioenergy for non-energy use and as chemical feedstock; EJ = exajoule.
Source: *IRENA (2022a).*

FIGURE 1.4. **Primary bioenergy supply in 2018 (left) and 2050 (right) in the 1.5°C Scenario**



Note: "Others" include non-energy use, losses in transformation processes and other uses.
Source: *IRENA (2021b).*

Box 1.2. Estimation of biomass supply potentials

The estimation of biomass potential that could be sourced sustainably varies significantly and covers a huge range because all estimations are based on different criteria and assumptions. For example, IRENA estimates that 153 EJ of biomass supply could be possible by 2050. The International Energy Agency (IEA) estimates that potential supply was likely to be within a range of 130 EJ to 240 EJ (IEA, 2017). Studies also suggest that bioenergy's deployment potential is likely between 50 EJ and 90 EJ (IPBES and IPCC, 2021). The Energy Transition Commission estimates that biomass supply could be 40 EJ to 120 EJ per annum (ETC, 2021). However, this topic is complex and has been at centre of debate for decades.

Based on IRENA analysis, there exists a large physical potential to increase biomass supply based on improved productivity and sustainable management. Realising this potential requires key steps, including:

- Demonstrate cost-effective technologies for production of biofuels from lignocellulosic feedstocks (grasses, wood, farm and forest residues) and from algae.
- Accelerate improvement of crop yields by expanding extension services to promote modern farming techniques and enhance access to seed, water and fertiliser in developing countries.
- Improve logistical approaches for cost-effective harvesting of farm and forest residues.
- Reduce food waste and losses through more flexible labelling to avoid discarding good food and increase investment in refrigeration and transport infrastructure to bring more food to market in a fresh state.
- Accelerate afforestation through incentives to cultivate trees on degraded lands and through sharing best practices for sustainable forest management.
- Expand registers of origin to promote sustainable feedstock sourcing and trade.

It is worth noting that studies of global biomass potential estimated by many organisations and academic articles may provide only limited insight into the local feasibility of supplying large quantities of biomass (IPCC, 2018). A large amount of biomass supply may raise sustainability concerns (see Chapter 2).

Source: IRENA (2016a).

In addition, bioenergy with carbon capture and storage (BECCS) may further provide a "negative emission" option through capturing and storing emissions in geological formations. The 1.5°C Scenario suggests BECCS has the potential to capture around 10 gigatonnes of carbon dioxide ($GtCO_2$) per year in 2050.

Alongside emission reduction, bioenergy can bring a number of social and economic benefits when it involves local suppliers and businesses. In many rural areas, biomass feedstock is abundant. Decentralised modern bioenergy systems, such as biogas digesters or modern and efficient biomass stoves, are among the most accessible and affordable options to decarbonise local energy systems. A properly governed bioenergy system could also provide incentives for local communities to manage forests and land in a sustainable way. Bioenergy can also help improve waste management practices by transforming waste streams into energy.

In summary, the role of bioenergy in achieving the 1.5°C Scenario will be shaped by several actions. One obvious strategy is the phase-out of traditional inefficient and health-damaging uses of bioenergy for cooking, and a shift to cleaner and more sustainable options, including biogas digesters, improved bioenergy cookstoves and renewables-based electric cooking.[1]

In the 1.5°C Scenario, bioenergy provides around 20% of total energy use in industry by 2050. Biomass also replaces fossil fuels for non-energy purposes such as feedstock for the chemical industry. Energy-intensive and high-temperature sectors are in focus, such as iron and steel, cement and lime, and aluminium and chemicals, where bioenergy can replace coke and coal, along with continuing growth in the bio-based industries where bio-based materials are already used to substitute fossil fuels. This is followed by the increased use of biofuels in the transport sector, especially in decarbonising long-haul transport, such as aviation and shipping, and the freight sector with liquid biofuels, complementing the deployment of electric vehicles and other renewable options.

The scenario also includes the increased use of bioenergy for heat and power generation through high-efficient CHP connected to district heating networks and combined with BECCS. While providing renewable heat for residences and industries, bioenergy-based CHP could also provide dispatchable power for the system and accommodate a higher level of variable renewable energy.

Achieving the 1.5°C Scenario would require improved biomass supply chains with diverse feedstock sources. Organic wastes, including sewage, animal manures, liquid organic effluents, fractions of municipal solid waste (MSW) and other similar wastes can be used to produce biogas based on anaerobic digestion or landfill captured gas. Waste animal fats can also be used to produce biodiesel for transport fuels. Forest and agricultural residues can be used for CHP and produce heat for buildings and industries, combined with carbon removal measures. Wide adoption of other practices, such as short-rotation woody crops on degraded and marginal lands, could also improve land productivity.

Most importantly, the 1.5°C Scenario needs to ensure that biomass and bio-based feedstock are sustainable in terms of greenhouse gas (GHG) reductions and biodiversity, other environmental aspects, and social and economic considerations. The sustainability of bioenergy is elaborated in more detail in the next chapter.

[1] *In the near term, traditional use of biomass in cooking will remain in most sub-Saharan African countries due to the slow adoption of improved stoves. However, it would need to be phased out in the medium term, according to IRENA's 1.5°C Scenario.*

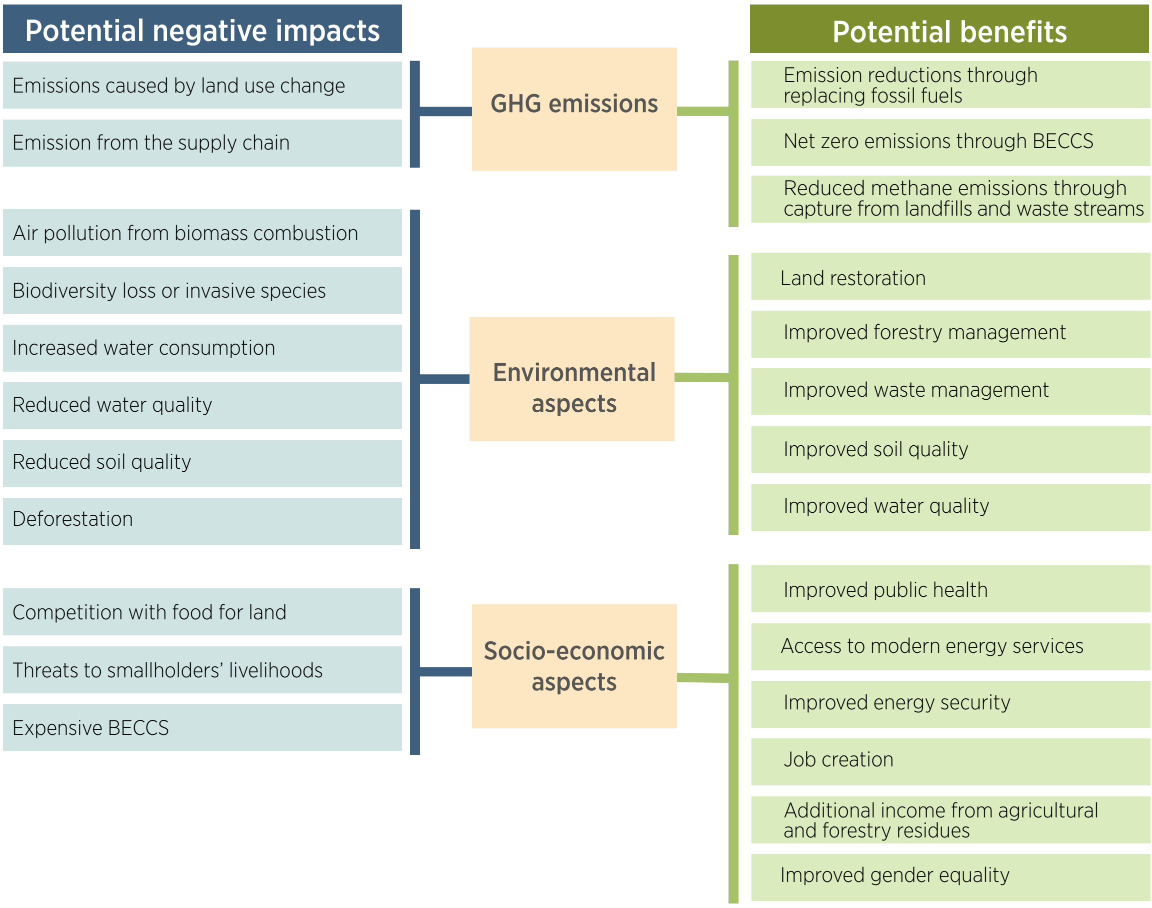
2. SUSTAINABILITY OF BIOENERGY

Bioenergy sustainability is a complex topic. In principle, bioenergy use can provide various benefits, such as avoiding GHG emissions by replacing fossil fuels in power generation, heating, transport and industry. It can also bring environmental and socio-economic benefits such as land restoration and job creation and improved health from clean cooking. However, these benefits can only be realised under specific circumstances. If not managed well, bioenergy supply chains and use could incur negative environmental, social or economic impacts beyond the energy sector due to their strong interactions with a number of important sectors such as agriculture, forestry, rural development and waste management.

Bioenergy's impacts on land-use changes are highly context-, location- and scale-dependent (IPCC, 2018). For example, increased bioenergy supply could cause land-use changes from the current purpose (*e.g.* food production or ecological service) to energy use, raising potential concerns about issues such as food security or biodiversity loss. However, there is also scope for potential benefits by using bioenergy by-products to improve soil quality, plantations for phytoremediation to improve water quality and agroforestry to increase biodiversity (see Figure 2.1). Additionally, the potential for increased carbon sequestration through improved land stewardship measures is considered to be substantial. Evaluating the synergies and trade-offs and the myriad issues related to land-use governance is essential to better understanding the future role of biomass.

Therefore, assessing the positive and negative impacts on sustainability must be based on specific locations and other circumstances that characterise the management of feedstock production (IRENA, IEA Bioenergy and FAO, 2017).

FIGURE 2.1. Potential aspects related to bioenergy sustainability



Note: BECCS = bioenergy with carbon capture and storage.

This chapter focuses on the major sustainability challenges and concerns related to the scale of bioenergy deployment depicted in the 1.5°C Scenario and other low-emission and net zero scenarios, in which large-scale production of feedstocks from agriculture and forestry residues would be a core component. It is important to note that while waste-based and some forms of advanced bioenergy have important roles to play in achieving the targets, they may not share similar issues with land-based bioenergy. This chapter identifies several common lines of inquiry but does not aim to distil a single clear narrative for all, as the issues can only be fully understood when placed in specific contexts.

2.1. REDUCING GHG EMISSIONS

Bioenergy can reduce GHG emissions by replacing fossil fuels in electricity generation and end uses. Available options include efficient bioenergy CHP projects; bioenergy-based district heating networks; liquid biofuels for road transport, shipping and aviation; and biogas and biomethane to replace fossil gas in different uses. Small-scale options also exist, such as household biogas plants as clean cooking solutions. However, decarbonisation through bioenergy should phase out the traditional use of biomass and take into account the carbon stock loss, or emissions from indirect land-use change (ILUC) and from the supply chain.

Transforming traditional bioenergy systems

Inefficient, traditional use of bioenergy remains the largest component of global bioenergy consumption. In some regions, mainly in sub-Saharan Africa, this has close linkages to severe forest degradation due to firewood extraction (GIZ and GBEP, 2014). For example, it is reported that in Zambia alone, extraction of traditional wood fuels is a major reason for deforestation, contributing to around 79 000 hectares (ha) to 150 000 ha of deforestation per year (FAO and Ministry of Energy of Zambia, 2020). The traditional use of biomass has been significantly affecting the resilience of land and populations in the context of climate change and compromised productivity and biodiversity of forest ecosystems (Pirelli, Morese and Miller, 2020). Transforming traditional bioenergy systems to modern ones, coupled with proper land management, may reduce carbon stock loss in this part of the world, further contributing to overall emission reductions. Given its share in the energy mix, addressing the sustainability challenges of traditional bioenergy needs to be a top priority for decarbonising strategies in regions like sub-Saharan Africa and South Asia.

Avoiding carbon stock loss from deforestation and conversion

A major debate surrounding the scale-up of bioenergy use is the risk of converting forest and high carbon stock areas to monocultural agriculture or timber plantations for bioenergy production. Research estimated that the global tropics lost 12.2 million ha of tree cover in 2020 (WRI, 2022). Commodity-driven activities and shifting to agriculture are major reasons for such loss in Latin America, Southeast Asia and Africa, but expanding land conversion for bioenergy would raise more concerns. Almost one-third of the loss of tree cover – some 4.1 million ha, or an area equal to the Netherlands – happened within humid tropical primary forests, which are usually rich in carbon storage and biodiversity. The primary forest loss resulted in 2.64 $GtCO_2$ of carbon emissions, which is equivalent to the annual emission of 570 million cars (WRI, 2022). Plantations generally have much lower carbon stock than natural forests. Carbon stock loss resulting from land conversion may exceed the emission savings from fossil fuel substitution, defeating the purpose of bioenergy development. The risk is considered high in regions relying on land exploitation to induce economic development.

Acknowledging this risk, countries and regions have implemented various measures to monitor and safeguard the sustainability of feedstock production. The European Union's (EU's) Renewable Energy Directive (RED), established in 2009, has set strict requirements to rule out feedstock linked to substantial carbon stock loss, using certification as a tool to monitor the origins of feedstock (see Box 4.1). While the EU-RED has been used as a benchmark, countries or regions may develop their own schemes to regulate their bioenergy production and consumption in local contexts.

Improving carbon sequestration with afforestation and active forest management

Bioenergy development may provide incentives for afforestation activities (timber plantations) that could contribute significantly to carbon stock gain. Viet Nam is an example of a county with rapid afforestation triggered by increasing demand for wood products and bioenergy (see Chapter 5) (Arvola *et al.*, 2020; Van Hung and Thuy, 2020). Furthermore, more intensive management of existing production forests may also improve their stock replenishment and carbon removal rate. For instance, a large area of human-made forests planted in Japan was abandoned in the 1970s, and these forests have now largely stopped growing due to old age. Active harvesting-replanting for bioenergy may greatly improve the forests' stock replenishment and carbon removal rate (Goh *et al.*, 2020).

However, one concern is the temporal gap between emissions from biomass conversion to energy and carbon sequestration in the new biomass that regrows: the so-called "carbon debt". Carbon debt is usually linked to the conversion of forests to biofuel production, which causes significant one-off emissions due to deforestation. This debt would take a long time to "pay off". In this case, a carbon debt is incurred at the establishment of biofuel production. The amount of carbon debt incurred depends on the condition of the land before the biofuel production process and the level of reduction in its carbon storage. For example, converting tropical rainforests to palm oil plantations for biofuels is estimated to incur a carbon debt that would take 86 years to pay back. However, the time period for payback can differ across forest systems and management models (Holmgren, 2021). Furthermore, monocultural timber plantations and intensive management of natural forests may have other negative environmental impacts, such as biodiversity loss and overconsumption of water (Favero, Daigneault and Sohngen, 2020).

Improving carbon sequestration on degraded land

In some cases, biomass cultivation on degraded lands may help restore and reclaim these lands while supplying bioenergy feedstocks. Proper land management can improve carbon sequestration by both the crops and the soil. In November 2021, during the United Nations (UN) Climate Change Conference (COP26) in Glasgow (United Kingdom), more than 140 countries committed to halt and reverse forest loss and land degradation by 2030 (UNFCCC, 2021a). Furthermore, diverting economic activities, such as expansion of agricultural activities or biomass plantation, onto degraded land rather than forests may also avoid carbon stock loss from forest conversion, especially in regions that rely on the land for livelihoods. However, this requires careful mapping of land suitable and available for bioenergy production. Spatially explicit analyses have been conducted around the world to explore the potential of this option (Jaung *et al.*, 2018).

Palm trees plantation at the edge of a tropical forest. ©Rich Carey@Shutterstock.com

Assessing emissions related to ILUC

The concept of ILUC has been a major topic in the debate on the sustainability of bioenergy during the past decade. ILUC occurs when existing agricultural land is converted for bioenergy production – leading to agriculture expansion elsewhere that may involve deforestation – to fill the demand gap in the global market. However, previous work has shown that the forms and dynamics of ILUC related to cash crops with multiple end uses could be extremely diverse and open to alternative interpretations (Goh *et al.*, 2016; Verstegen *et al.*, 2016). The European Union's RED II in 2018 ruled that the European Union will phase out feedstock that may potentially involve ILUC by 2030. The quantification of ILUC remains controversial and under discussion all over the world.

Minimising supply chain emissions

Supply chain emissions are a key component to consider when long-distance transportation of biomass is involved, such as exporting wood pellets from North America to Europe, or liquid biofuels from Latin America to Europe. However, this part of the emissions is highly variable depending on the feedstock production, collection systems, and the distance, volume and transportation methods. Some studies have found that net GHG emission reduction is still possible for long-distance biomass supply chains by improving efficiency, such as increasing energy density through pelletisation or torrefaction, using large ocean vessels, and optimising supply and demand (Vera *et al.*, 2020).

Tapping synergies with waste management

Bioenergy generated from waste streams has extra benefits in emission reduction, especially biogas produced from methane released from landfills, animal manure, food waste and other organic residues. This can be an important way to reduce methane emissions. In an urban context, landfills usually come from municipal waste. This approach can mitigate pressure on urban land from the expansion of landfills and reduce problems stemming from landfill waste. At the same time, producing biogas and biofuels based on waste, animal manure and residues supports better waste management practices and promotes the circular economy. A biogas digester can turn a waste issue into a revenue opportunity for farms, waste treatment industries and rural communities by selling biogas or biomethane to utilities and gas companies or saving on fuel costs. Additionally, the digestate can be used or sold as a fertiliser.

In California (United States), manure from dairy cows accounted for one-quarter of the state's methane emissions and was usually flushed and stored in open lagoons, allowing methane to vent to the atmosphere. To address this issue, the Low Carbon Fuel Standard (LCFS) was designed to incentivise biomethane production from livestock manure (California Air Resources Board, 2017, 2020). Bioenergy production from waste streams may increase the financial feasibility of deploying proper waste management in many parts of the world.

Integrating BECCS

Combining BECCS in bioenergy production and industrial processes (*e.g.* chemicals and cement production) is a possible option to further reduce emissions or, in other words, achieve negative emissions. However, the deployment of BECCS is still limited, and it is a relatively expensive technology. There are several BECCS demonstration projects (see Box 2.1). Stimulating the deployment of BECCS requires policy support such as sustainable governance and financial incentives.

Box 2.1. BECCS

BECCS includes technologies to capture carbon emissions from bioenergy conversion processes, such as biomass-based power generation and CHP, and digestion or fermentation of biomass to produce biogas and liquid biofuels, and to permanently store the CO_2 in geological formations. In this case, BECCS may produce negative emissions. Most 1.5°C scenarios indicate that compliant pathways would rely on CCS technologies including BECCS, which is constrained by sustainable bioenergy potential.

Concerns exist about their low efficiency, life-cycle emissions and sustainability. BECCS projects should consider the emissions from feedstock growing, harvesting, transporting and processing to avoid outweighing the captured and stored emissions. They should also avoid competing with food supplies and intensifying negative impacts on land use. It is also challenging to ensure that BECCS delivers negative emissions in a timely and sustainable manner while also generating energy at an appropriate scale (Fajardy *et al.*, 2018). Therefore, stimulating the deployment of BECCS requires policy support such as sustainable governance and financial incentives.

BECCS faces high costs and requires new investment in necessary infrastructures. The cost of BECCS is estimated to vary depending on the sector, ranging from USD 88 to USD 288 per tonne of CO_2 for bioenergy combustion, USD 20-175 for ethanol and USD 30-76 for biomass gasification. In 2050, the infrastructure for bioelectricity and biofuel would need investments of around USD 138 billion to USD 123 billion per year, respectively (Smith *et al.*, 2016).

There are only a few BECCS demonstration projects based on ethanol production located in Canada (Husky Energy CO_2) and the United States (Kansas Arkalon, Bonanza CCS, Farnsworth). Some projects based on biomass power and CHP plants are operating in Denmark (HOFOR Copenhagen), Japan (Mikawa power plant), Norway (Norwegian full-chain CCS) and the United Kingdom (Drax Power Station).

Large-scale use of biomass for CO_2 removal may raise concerns, including a range of potential consequences, such as greatly increased demand for freshwater use, increased competition for land, loss of biodiversity and/or impacts on food security. The short- versus long-term carbon impacts of substituting biomass for fossil fuels, which are largely determined by feedstock choice, also remain a source of contention.

Source: IPCC (2018, 2022), IEA Bioenergy (2021b), Global CCS Institute (2021).

2.2. PROTECTING THE ENVIRONMENT

Bioenergy production and consumption may impact environments in various ways. When practiced sustainably, bioenergy production and consumption can improve degraded land, benefit biodiversity and improve soil through the by-products of bioenergy production. However, negative impacts also exist, including biodiversity loss caused by monocultural plantations, invasive species from feedstocks grown for biofuel purposes, high water consumption, reduced soil quality and air pollution.

Protecting biodiversity with a focus on invasive species

Bioenergy production shares similar issues with agriculture and forestry in terms of biodiversity conservation. Conversion of the natural landscape to croplands threatens native species due to lost habitat. Large-scale monocultural plantations and other biomass production practices, such as changing forest management to faster-growing species, greater residue extraction and shorter rotations, may also negatively impact biodiversity (*e.g.* single species and low level of diversity). Some feedstock favoured for the production of second-generation biofuels could also be classified as invasive species in some regions; therefore, promoting plantation of these feedstocks could result in a negative impact on biodiversity (FAO, 2008).

In contrast, reforestation of degraded land with native trees can have substantial benefits for biodiversity (IPCC, 2018). However, the impacts of biomass production on biodiversity are difficult to quantify. While preventing conversion of natural forests and areas with high conservation value to bioenergy production sites may avoid forest loss, care must be taken with regard to the introduction of monocultural plantations, which usually have a lower biodiversity value than natural forests.

Adding to the low biodiversity characteristics of monocultures, some of the potential bioenergy feedstock could be classified as invasive species and may negatively impact local biodiversity. Acacia is a typical example of this. It is a potential feedstock for solid biofuels and has become the preferred choice of plantation in some Southeast Asian countries (Koutika and Richardson, 2019). Furthermore, some degraded or abandoned land may bring larger benefits for conservation, such as restoring ecological corridors for animal movement, than they would bring if used for bioenergy production (Evans, Goossens and Asner, 2017).

Reducing air pollution and protecting public health

Combustion of solid biomass could produce air pollutant emissions of the same variety as solid and liquid fossil fuels except for sulphur oxides (SOx) (Ness, Ravi and Heath, 2021). For example, a study revealed that, in 2017, the health impacts (total mortality) of biomass and wood combustion (mainly used for industrial boilers, heating in residential and commercial buildings, and power generation) in the United States were higher than those from the combustion of coal and gas (Buonocore *et al.*, 2021). In the United Kingdom, household combustion of wood fuel accounted for 38% of primary emissions of particulate matter (PM) 2.5 in 2019 (DEFRA, 2021). In Europe, biomass combustion accounted for only 2.6% of energy use but contributed to more than a third of total PM2.5 pollution in the European Union, three times the level emitted by road transport (Amann *et al.*, 2018). In Rome (Italy), biomass burning for domestic heating has been identified as an air pollution source, contributing to 12% of PM10 in peri-urban areas and 6.7% inside the city (Perrino *et al.*, 2019).

Pollutants from solid biomass combustion mainly include products from incomplete combustion and solid particulate matters. However, pollution varies depending on the stoves and technologies used, characteristics of biomass fuels, as well as how the system is operated. In the residential heating sector, modern biomass stoves with high-quality biomass fuels with emission control technologies are likely to significantly reduce air pollutants and can comply with stringent emission limits if operated appropriately (IEA, 2019). Policies to incentivise modern biomass combustion technologies and stoves are necessary to reduce pollution and protect public health.

Improving soil quality

Soil quality improvement can be achieved with some by-products of bioenergy production. For example, digestate, the residue of biogas production, can be used as organic fertiliser to reduce a widely used chemical fertiliser and improve soil quality (Barłóg, Hlisnikovský and Kunzová, 2020). Certain forms of agroforestry[2] can restore soil fertility, enhance water retention in the soils and increase agricultural yields while producing additional biomass (IRENA, 2019a). Furthermore, the use of biochar, the by-product of woody biomass gasification, is useful to return nutrients to soil and stimulate the rehabilitation of degraded and contaminated lands (Pirelli, Morese and Miller, 2020). However, when most agricultural residues are used for bioenergy production, residues returning to field may fall below the needed level and, therefore, impact soil quality and nutrition. Measures should be included to avoid large-sale residue removal practices beyond the sustainable threshold.

Recognising hydrological constraints in bioenergy projects

Similar to other agriculture and tree planting activities, bioenergy production will increase the volume of water consumption. Additional pressure on water resources exerted by bioenergy production must take into account the potential competition with food production. Research estimates that about 2-3% of water consumption in agriculture can be attributed to biofuel production (Rulli *et al.*, 2016). However, there are no accurate global data available to understand the hydrological constraints for bioenergy production if it takes place at the level suggested in various climate scenarios (Rosa *et al.*, 2020). This is crucial in determining the sustainability of bioenergy projects, as these may fail due to low productivity caused by water constraints, as demonstrated by past experience, *e.g.* Jatropha cultivation in Africa (Tufa, Amsalu and Zoomers, 2018).

2.3. INCREASING SOCIO-ECONOMIC BENEFITS

Bioenergy can produce various socio-economic benefits. Biomass production can generate additional income for farmers and rural communities and improve energy security in the case of abundant local biomass resources. Biogas technology, along with other decentralised energy solutions, can help to support better livelihoods for the poor (IRENA and SELCO Foundation, 2022). Bioenergy, in some cases, can provide a localised solution to transform rural economies while enhancing energy and food security (IRENA, 2015a). Developing bioenergy supply chains and refineries can boost industrial development and create renewable jobs. Bioenergy can also bring multiple economic, health and well-being benefits to the agri-food chains (IRENA, 2016b).

Avoiding competition with food production

Considering population growth and dietary changes, global food demand may increase by 30% to 62% in 2010-2050 (van Dijk *et al.*, 2021). Meeting the growing demand would require both intensifications of existing cropland and cropland expansion for food production. In this case, the large-scale expansion of biomass plantation for energy purposes may compete with other critical and human ecological needs in terms of land-use purpose (Layke *et al.*, 2021).

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[2] *Agroforestry is a collective name for land-use systems and practices where woody perennials are deliberately integrated with crops and/or animals on the same land management unit. The integration can be either in spatial mixture or temporal sequence. There are normally both ecological and economic interactions between the woody and non-woody components in agroforestry.*

Estimates of bioenergy potential, including afforestation for bioenergy production, must take this into account to avoid overlooking the competition for land, water and resources between food and bioenergy production. Policies also need to consider that large amounts of agricultural products have been used for non-food purposes. For example, about half of global vegetable oil production is used as industrial feedstock (*e.g.* to produce detergents) (FAOSTAT, 2021). A more efficiently managed food system, especially in terms of equitable food distribution, low-carbon diets and reductions in food loss may free up resources for bioenergy purposes. This must, however, be carefully put in local contexts considering the differences in climates, agro-ecological factors, society and culture. If designed properly, bioenergy projects may also become important income sources for communities to adopt sustainable land-use practices. Economic reasons play a major role in determining land uses in the current globalised production system. Therefore, a more thorough understanding of local contexts is necessary to avoid over- or under-estimation of the potential for sustainable bioenergy.

Providing decent job opportunities

In 2020, biogas, solid biomass and liquid biofuels supported over 3.53 million jobs globally (see Figure 2.2), a number that could reach 13.7 million by 2050, according to IRENA's projection. Liquid biofuel contributed the largest share of bioenergy jobs, creating around 2.4 million jobs in 2020. In Brazil, the bioenergy sector, particularly sugarcane ethanol, supports around 871 000 jobs (IRENA and ILO, 2021). However, the bulk of bioenergy jobs are in the agriculture sector, planting and harvesting feedstock of various types and gathering agricultural waste. Many of these harvesting jobs are typically seasonal in nature, rather than full-time jobs (ILO, 2017).

In many developing countries, a large share of the supply chain for bioenergy employs low-paid agricultural labourers. Their working conditions may be tough, and most of these jobs are performed by men. Therefore, to ensure a just and inclusive energy transition, it is important to develop a supportive policy framework to provide decent working conditions, improve workers' skills and wage levels, and ensure gender equality. In some cases, manual labour for agricultural harvesting is increasingly being replaced by a greater reliance on machinery, providing fewer but more highly skilled and better-paid jobs. Policies can be considered to help workers through skill development and proper training.

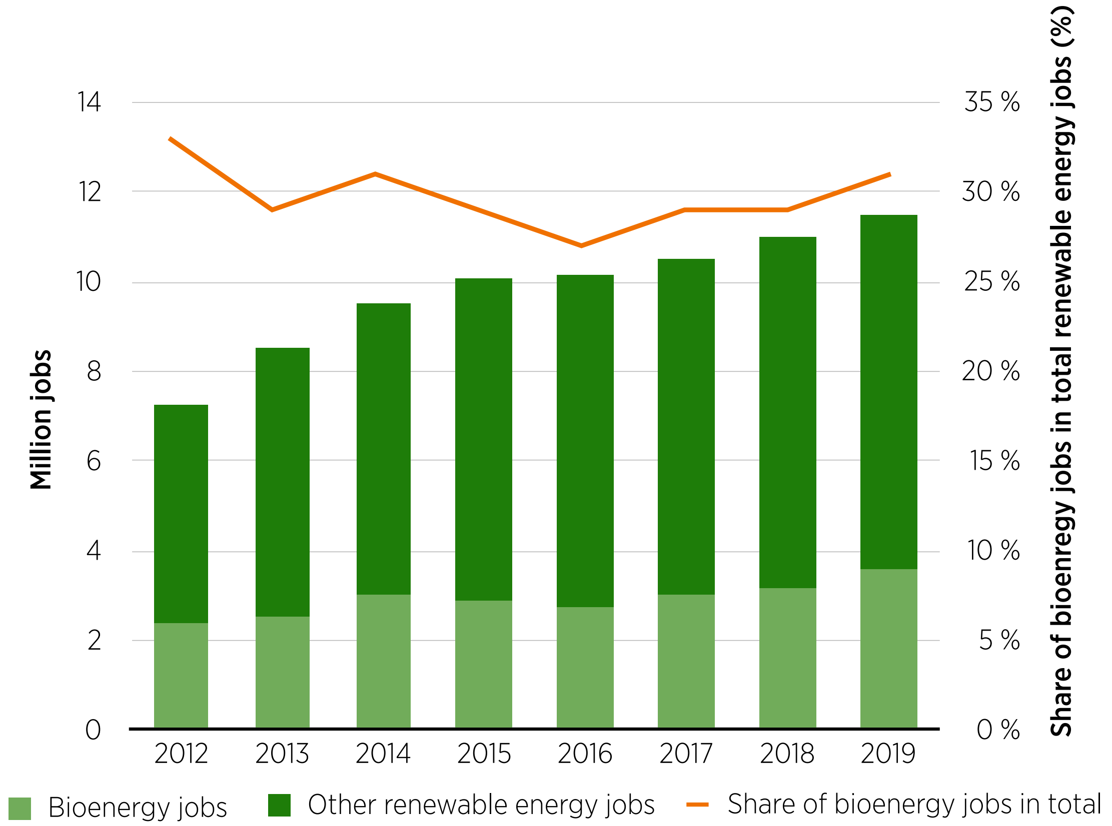
Ensuring fair and equitable rural development

While bioenergy has been promoted for job and income creation, benefits can vary in different parts of the world. In developing regions where communities rely heavily on land for livelihoods, bioenergy development is expected to provide additional income and improve energy security. However, in some cases, large-scale expansion of cash crop and timber plantations for bioenergy production may raise concerns over conflicts between bioenergy companies and local communities in terms of land tenure and land access, distribution of revenues, and disruption of traditional lifestyles (Tomei, 2015).

Strengthening energy security with local biomass resources

In some regions, bioenergy is deemed the most accessible renewable energy source. For example, woody biomass from surrounding manmade forests may be the most sustainable way to heat households in rural Japan, where kerosene has been the main fuel (Goh *et al.*, 2020). Transforming traditional bioenergy systems into modern ones is an option to ensure energy security in regions like sub-Saharan Africa that avoids shifting to imported fossil fuels. For countries that are large agricultural producers and where biomass can be sourced sustainably, bioenergy may have an important role in fuel price control and energy security.

FIGURE 2.2. **Numbers of bioenergy jobs and share in total renewable energy jobs, 2012-2019**



Source: IRENA and ILO (2021).

2.4. PLACING SUSTAINABILITY OF BIOENERGY IN CONTEXT

A specific bioenergy production model may be considered sustainable in one location but not in another due to, for example, climatic and biophysical differences. Socio-economic factors like demography, politics (*e.g.* when involving land ownership) and culture also determine the suitability of bioenergy deployment in a particular site. There are place-specific and temporal elements, *i.e.* the growth and harvesting rate of biomass, to be accounted for in the carbon balance of bioenergy systems. In some cases, the governance framework for biofuel inputs may not be able to capture all potential issues that matter to the local community in production countries, depending on each country's local enforcement. A sustainability framework in importing countries may have driven many changes in the producer countries but could also be failing to regulate practices in reality, which may strengthen the position of powerful actors and further marginalise vulnerable communities (Tomei, 2015). Therefore, different systems are also interconnected in a larger system, with linkages to outside influences and processes. One major trend to be taken into consideration is the international bioenergy trade presented in Chapter 3.

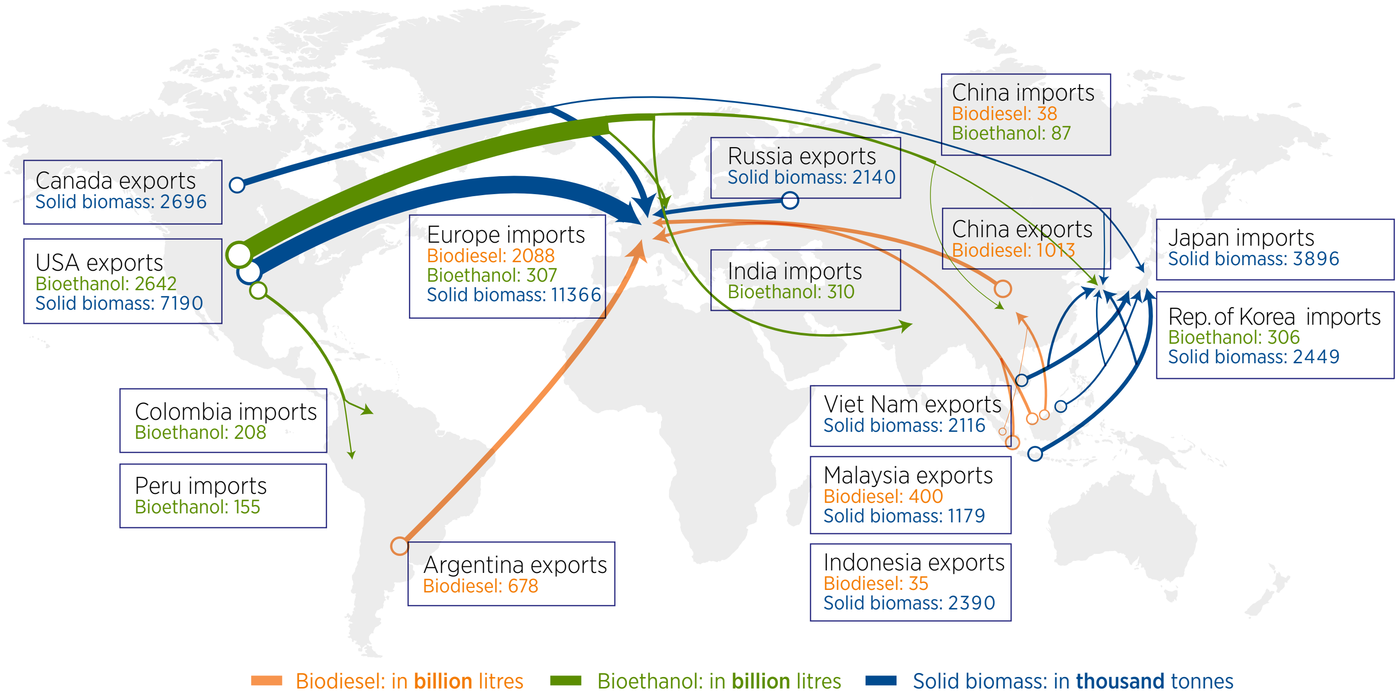
Given its high contextual setting, substantial investment in understanding how different bioenergy systems and land-use models can be made sustainable in different geographical regions is required. Importantly, a comprehensive sustainability framework has to be put in place to aid decision making and ensure sustainability. This is discussed in Chapter 4. Mitigating the potential risks from bioenergy production may require (re-)designing existing land-use models, supply chains and energy systems. These are put into regional perspectives through three case studies in Southeast Asia presented in Chapter 5.

3. INTERNATIONAL BIOENERGY TRADE

In recent decades, the global trade of bioenergy has increased due to the unbalanced distribution of biomass resources and demands. Major bioenergy commodities include wood pellets, biodiesel and bioethanol. The European Union is the main destination due to clear strategies to substitute fossil fuels with renewables, and targets on biomass for heating and liquid biofuels for transport. Bioenergy exporting countries diverse, for example, Argentina, China and Indonesia are all major biodiesel exporters but use different biomass feedstocks. A similar situation applies to solid biomass exported from North America and Southeast Asia (see Figure 3.1). Given the current status and likely trends in the energy transition, international bioenergy trade may be linked to sustainability concerns (see Chapter 2). Therefore, policies and measures need to be in place to improve governance.

Based on available data, this chapter analyses the status of major bioenergy commodities (biodiesel, bioethanol and solid biomass), trade among major importing and exporting countries and regions, and possible links with sustainability concerns. It then proposes policy options to improve the governance and practices of bioenergy trade.

FIGURE 3.1. Global bioenergy trade in major markets in 2020



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.
Note: The figure does not include all bioenergy trade due to limited data. Other international trade of bioenergy may exist but is not shown in this figure.

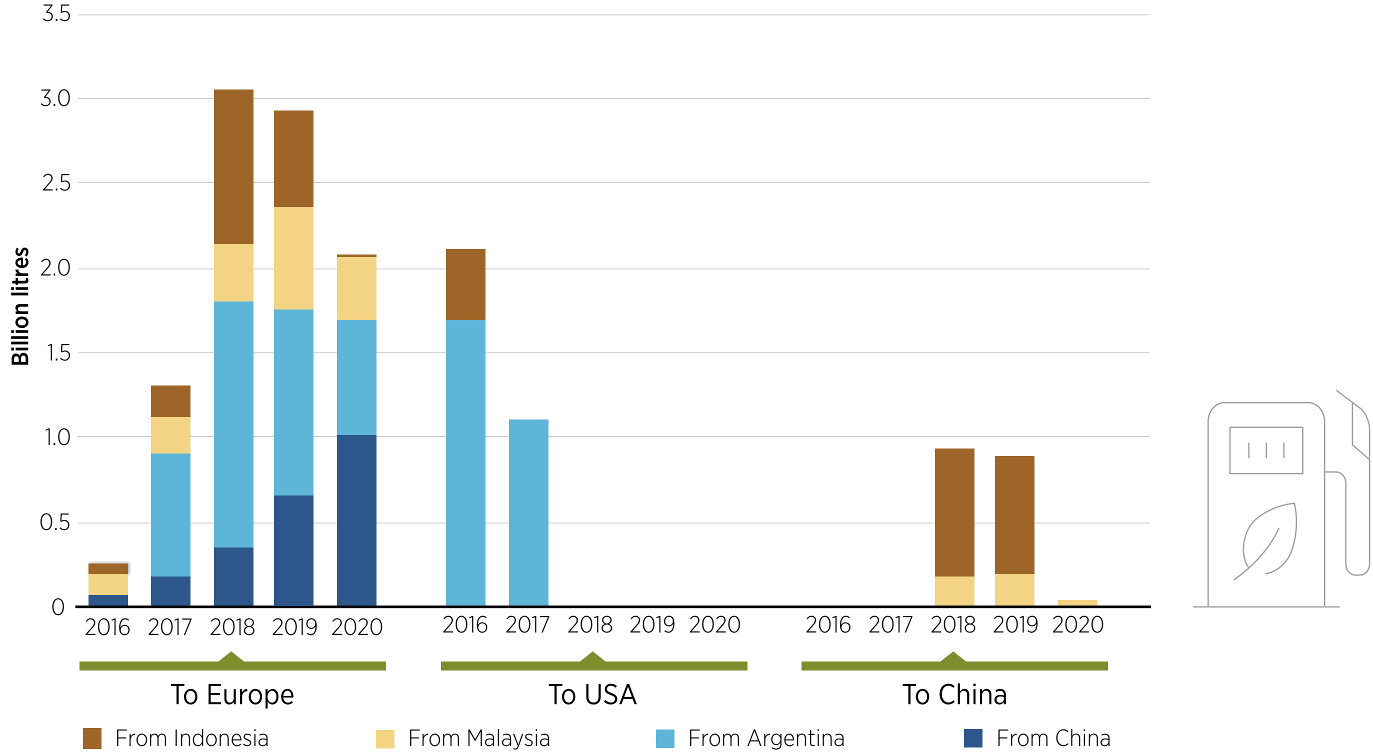
3.1. OVERVIEW OF GLOBAL TRADE OF LIQUID BIOFUELS

Biodiesel

The international trade of biodiesel has changed significantly in the past few years, as shown in Figure 3.2. The trade of biodiesel in 2019 was estimated at around 4.2 billion litres, accounting for around 10% of total global production. Three types of biodiesels, categorised by feedstock, were traded in relatively large volumes compared to biodiesel made of other feedstocks, *i.e.* soy-based biodiesel from Argentina, palm-based biodiesel from Indonesia and Malaysia, and used cooking oil (UCO)-based biodiesel from China. The exported volume of these three types of biodiesels in 2019 was about 90% of the total global trade volume (IEA, 2020a).

Europe has been a major destination for biodiesel from the aforementioned countries. Biodiesel exports to Europe grew significantly and peaked in 2018. A significant decline was observed in Europe in 2020, mainly due to diminishing Indonesian exports caused by countervailing duties. In the same year, biodiesel exports from Argentina and Malaysia also almost halved. These declines were probably caused by the COVID-19 pandemic. One exception was the export of UCO-based biodiesel from China to Europe, which continued to grow in 2020. In 2020, the export volume from China to Europe had reached 1 billion litres and surpassed the other countries.

FIGURE 3.2. Estimated export volumes of biodiesel from major producers, 2016-2020



Source: UN Comtrade (2021).

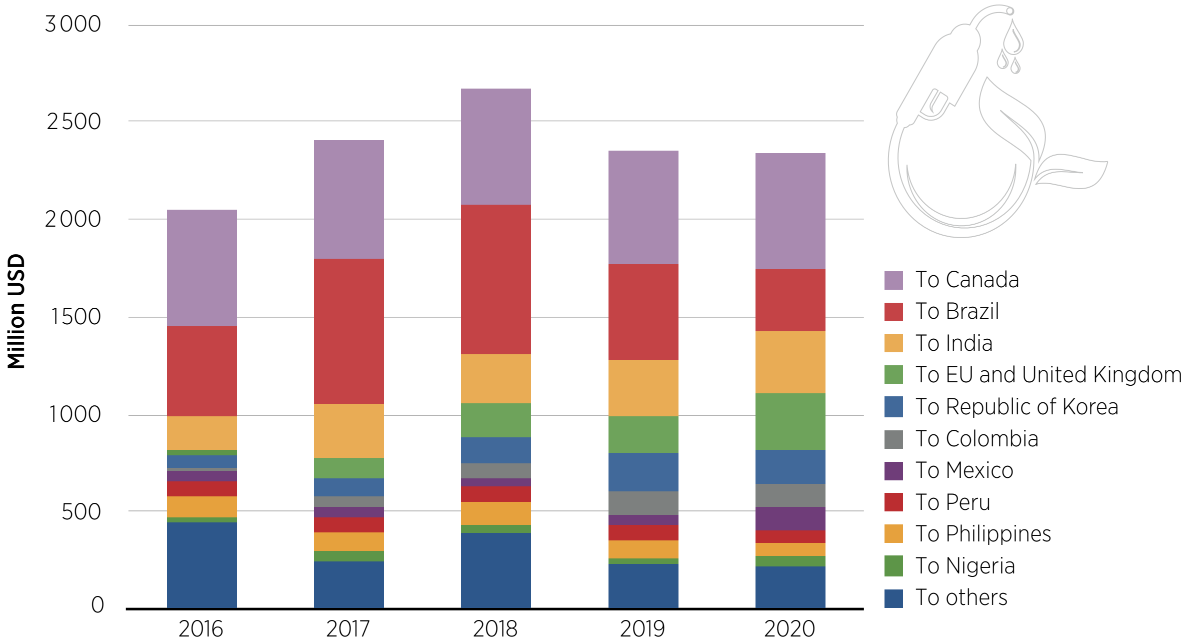
Note: All data are extracted under the harmonised system (HS) code (HS 382600), which is internationally accepted to identify traded products. Commodities under the code HS 382600 include biodiesel and mixtures thereof not containing or containing less than 70% by weight of petroleum oils or oils obtained from bituminous minerals.

The situation in the United States was the opposite: exports to the country totalled more than 2 billion litres in 2016 but then almost disappeared in 2018 as the United States imposed anti-dumping and anti-subsidy duties on biodiesel from Argentina and Indonesia over the next five years. Meanwhile, China recorded substantial volumes of both exports to Europe and imports from Indonesia and Malaysia in 2018 and 2019 (see Figure 3.2). As the country does not have a surplus of vegetable oil production (it is a net importer of vegetable oils), UCO, also known as "gutter oil" collected from oil brokers, was used to produce biodiesel (Chase, 2020). The UCO-based biodiesel was largely exported to Europe and the volume grew significantly throughout 2016-2020 (see Figure 3.2).

Bioethanol

The global trade of bioethanol was estimated to be around 2.5% of total production in 2020. The United States was the largest exporter of bioethanol in 2016-2020, followed by Brazil. In 2020, the United States exported around 2.9 billion litres of bioethanol for transport fuels (USDA, 2021a). The largest share of US exports of bioethanol went to Canada to meet the country's federal and provincial mandatory renewable fuel standards, which require a specific share of bioethanol for gasoline (5% to 8.5%) (c2es, 2021). Brazil is another major destination, but the volume has declined since 2019 due to several factors, including sugar and oil prices and a volatile exchange rate (see Figure 3.3).

FIGURE 3.3. Top ten export markets for US bioethanol, 2016-2020



Source: USDA (2021a).

Recent trends in trade policies linked to sustainability

The international trade of liquid biofuels has directed policy makers' attention to the issue of its sustainability, especially for the European Union as a major importer (see Box 3.1). The EU's biofuel policy has been developed since the mid-1990s (Londo and Deurwaarder, 2007). It has driven structural changes in governing supply chains of biofuels and brought enormous changes to global trade. The EU-RED was established in 2009, setting mandatory criteria for the sustainability of biofuels. Its reformulated version, RED II, came into force in July 2021 (European Commission, 2019a). The standards excluded biofuels made of raw materials produced at the expense of areas with important ecosystem services like primary forests, nature protection areas or highly biodiverse grassland. Biofuel producers have to participate in certification schemes that are recognised by the European Commission to gain entry into the European Union's biofuel market. Many certification schemes go further than the mandatory criteria and extend to social and other environmental criteria.

Box 3.1. International liquid biofuel trade and sustainability

International liquid biofuel trade has raised discussions on sustainability of biomass supply chains. South America is the world's leading region in terms of soybean production. Soy-based biodiesel is considered a by-product of soy production, which mainly serves as food and feed. Soybean and soy-based biodiesel has been questioned for its link to deforestation in this region. Rapid cropland expansion and a massive loss of natural rainforest were both observed in the past three decades (FAO, 2021). However, the linkages between various end uses of soybeans with deforestation are complex (Barona *et al.*, 2010; Morais, Martins and Mata, 2010).

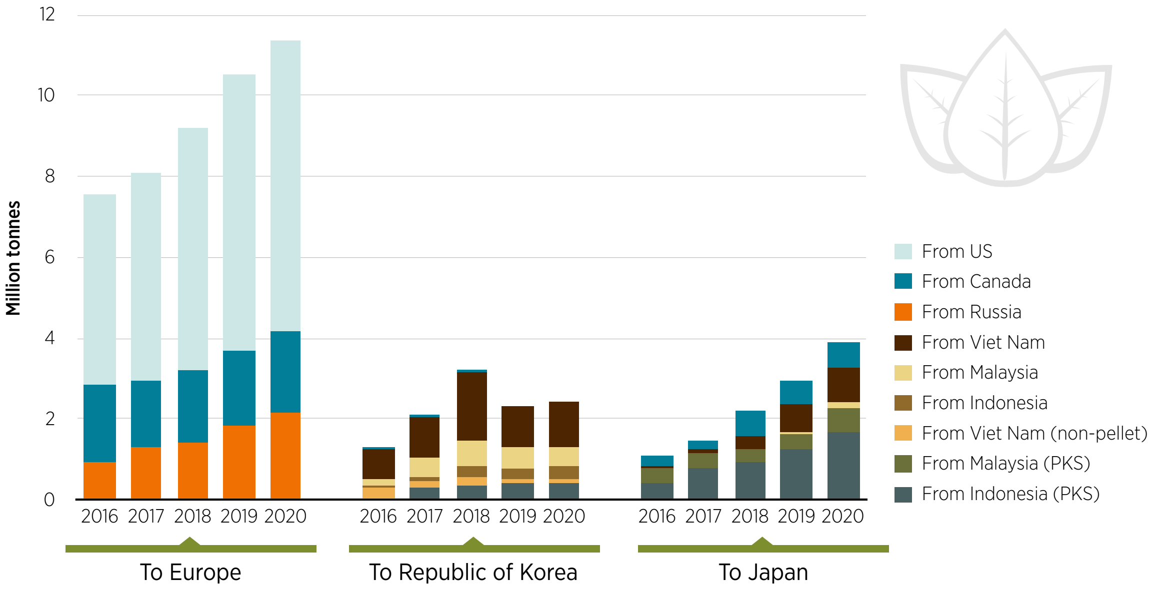
ILUC is another concern regarding the sustainability of liquid biofuels (see discussion in Chapter 2). While previous works revealed that it is extremely difficult to quantify the impacts of ILUC, it remains a major consideration in European biofuel policies. The revised Renewable Energy Directive II (RED II) states that it will gradually decrease the import of high-ILUC risk biofuels from the end of 2023 to zero by 2030 (European Union, 2018). Studies have also revealed that oil palm, like soybean, is a "flex crop". It has multiple end uses, making it very difficult to point to any one market as the driver of ILUC (Tomei and Helliwell, 2016).

China has become a competitive biodiesel producer due to the strong incentives given to waste-based biofuels in Europe. In 2018, the food industry generated about 11 billion litres of UCO. However, only about 10% of the UCO was used for biodiesel production. During the COVID pandemic in 2020, a reduction in UCO supply from industry and an increase in acidified UCO from households were observed, as visits to restaurants were largely replaced by home cooking (Mcgrath, 2020). This may change the dynamics of the supply chains not only in collection but also in processing, as not all plants are capable of processing acidified UCO. However, the total production and export of UCO-based biodiesel continued to grow in 2020.

3.2. OVERVIEW OF GLOBAL TRADE OF SOLID BIOFUEL

Global trade of major solid biofuels, including wood pellets, wood chips and palm kernel shells (PKSs), reached around 18 million tonnes in 2020, accounting for 30% of total production (REN21, 2021; FAO, 2021). While woody biomass has long been consumed in Europe for residential heating, the region has seen a surge in demand for wood pellets to replace coal for power generation in the past decade. Meanwhile, in East Asia, the consumption of solid biofuels in power plants has also grown significantly. These new demands have greatly spurred the production and export of wood pellets to both regions in the past few years (see Figure 3.4).

FIGURE 3.4. **Estimated export volumes of wood pellets and other solid biofuels from major producers in 2016-2020**



Source: Wood pellets data are based on UN Comtrade (2021), HS code 440131 include wood; for fuel, sawdust and wood waste and scrap, agglomerated in logs, briquettes, pellets or similar forms; wood pellets. Wood pellets (Russian Federation to Europe in 2020) is based on Argus (2021a). Non-wood pellets data are based on UN Comtrade (2021), HS code 440139 include wood; for fuel, sawdust and wood waste and scrap, agglomerated in logs, briquettes, pellets or similar forms; other than wood pellets. PKS to Japan is based on Japan Forestry Agency (2019) and Argus (2021b). PKS to Republic of Korea is based on Argus (2019).

The United States was the largest exporter of wood pellets in 2016-2020. Canada, Russian Federation, and Viet Nam are the next three countries with significant export of wood pellets, but the sum of these three was still lower than the export volume from the United States alone, which has been growing steadily and reached 7.2 million tonnes in 2020, or 53% of the global wood pellet trade excluding intra-Europe trade. Europe was the major destination for wood pellets. It absorbed almost all pellets from Canada, Russian Federation and United States. The total volume of wood pellets entering Europe continued to grow.

The trade of wood pellets has also been active in East Asia, mainly as exports to Japan and the Republic of Korea, although the total traded volumes were far lower than those shipped to Europe. The two countries largely rely on supply from Southeast Asia, *i.e.* Indonesia, Malaysia and Viet Nam, and partly on Canada as their major suppliers. The total volume shipped to the Republic of Korea remained around 2 million tonnes in 2019 and 2020, while total exports to Japan reached nearly 1.8 million tonnes in 2020.

Palm kernel shell (PKS), a form of residue from the palm oil industry from Indonesia and Malaysia, turned out to be the largest stream of solid biofuels entering Japan in the past five years. In 2020, total exports of PKS to Japan reached more than 2.1 million tonnes. Exports to the Republic of Korea were smaller, fluctuating at around 0.3 million tonnes. Apart from that, there were also small amounts of non-pellet woody biomass exported from Viet Nam to the Republic of Korea for fuel purposes.

Concerns over impacts of global trade of solid biofuel on sustainability

The intensive use of forests for export-oriented wood production, particularly in the southeastern region of the United States, may generate unwanted environmental consequences, although it also can stimulate job and income creation (Aguilar *et al.*, 2020). The sustainability assessment of wood pellets from the United States and other places that produce wood pellets has been challenging due to the number and diversity of supply chain actors, as it requires spatially explicit analysis of both feedstock production and logistics to better capture the impacts on sustainability (Visser *et al.*, 2020). While the performance in both emission reduction and economics may be further improved with technologies like torrefaction,[3] conventional pellets remain the major types of bioenergy traded across the Atlantic Ocean (Yun, Clift and Bi, 2020).

The concerns over the sustainability of wood pellets from Viet Nam are essentially linked to the entire forestry sector in the country. In the past decades, Viet Nam has emerged as a major player in the global trade of wood products through a rapid expansion of timber plantations, especially monocultural acacia plantations under the "reforestation" programme. Much of the wood pellets exported are made of acacia woods. Such expansion could be challenged as the non-native, monocultural plantations offer much fewer environmental benefits than native forest ecosystems. While establishing timber plantations on degraded land may help to improve carbon sinks and ecosystem services, proper and sustainable management practices must be put in place to tap the benefits. Although studies have been conducted to develop more sustainable ways of managing the plantations, the actual implementation has been difficult. One important factor is that many of these plantations are in the hands of small growers eyeing short-term livelihoods rather than long-term sustainability, and existing policies may not be effective enough to facilitate needed financial means or support them to adopt more sustainable practices (Phuc, 2021; Flanagan *et al.*, 2019).

Both Indonesia and Malaysia have ambitious plans to utilise more of the abundant agricultural residues generated from their oil palm industries. These residues include PKS and empty fruit bunches (EFB) that can be pelletised and potentially used in power plants like wood pellets. The export business of PKS has been prosperous, with substantial growth observed in the past few years, but the large-scale processing and exports of EFB and other residues have not been realised. The latter may be linked to potential competition with mulching, *i.e.* returning nutrients to the soil by applying the EFB back to the plantations.

Recent trends in trade policies linking to sustainability

Policies of importers, such as Europe as the major destination for wood pellets, have more influence on the global trade of solid biofuels. Recommendations on sustainability criteria are given for solid biofuels at the EU level. Certification schemes are expected to be a means to facilitate and enable the biomass producers and power generators to demonstrate compliance with the standards. As of mid-2022, 13 voluntary schemes have been recognised by the European Commission under the RED II (European Commission, 2022)..

A similar development has been observed in Japan. As of 2022, third-party certifications like Green Gold Label (GGL), Roundtable of Sustainable Palm Oil (RSPO) and Roundtable on Sustainable Biomaterials (RSB) are required for biofuels subject to the feed-in-tariff (FIT) system (Aikawa, 2020). These include agricultural residues like PKS, most of which are not certified.

[3] *Torrefaction is a thermochemical process typically at 200-350°C in the absence of oxygen, at atmopsheric pressure with low particle heating rates and a reactor time of 1 hour. This process can improve biomass to higher energy content per unit volume. Its use could reduce problems associated with decomposition of biomass during storage (EBTP, 2016).*

The Republic of Korea relies mainly on wood pellets, with no measure put in place to monitor sustainability. On the producer's side – Viet Nam, in this case – tools used in forest governance, especially certifications like the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC), will likely be the major references for monitoring the sustainability of biofuels made of forest feedstocks, as there are no specific systems created for solid biofuels.

While Europe, North America and South America continue to be the key players in the bioenergy sector, East Asia and Southeast Asia have also seen rapid development in the use and trade of bioenergy in the past few years. Until now, most of the bioenergy traded was produced from land-based feedstocks with close linkages to agriculture and forestry. In the last decade, the growth in international bioenergy trade has triggered the development of transnational sustainability governance of bioenergy through instruments like certification. A policy framework and measures are urgently needed to deal with the sustainability issues discussed in Chapter 4.

A front-loader piles wood chips. ©Tricky Shark@Shutterstock.com

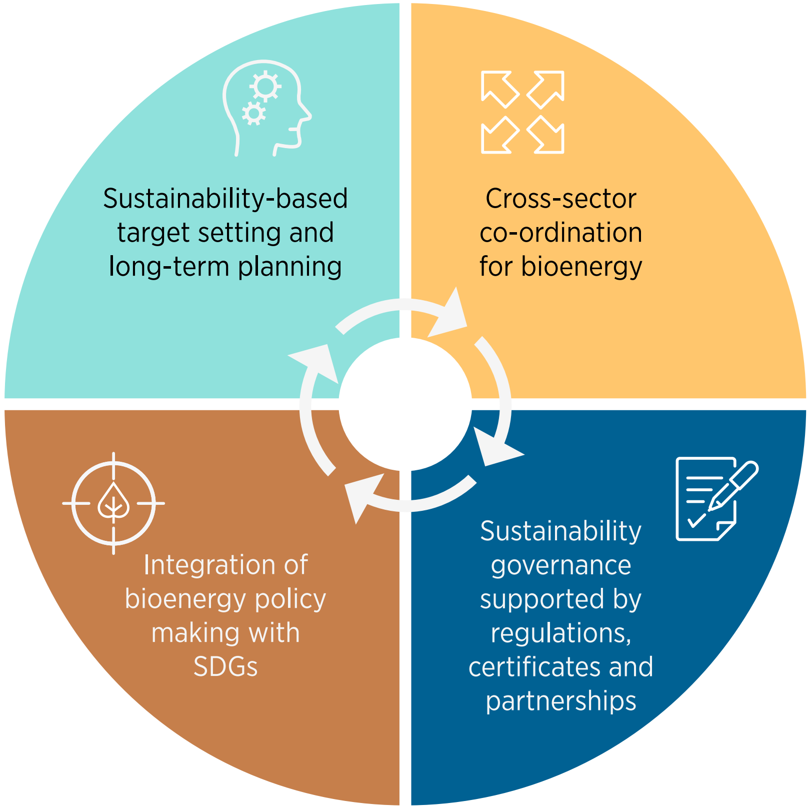
4. POLICY FRAMEWORK FOR SUSTAINABLE BIOENERGY DEVELOPMENT

As the sustainability of bioenergy is complex and highly context-specific, a policy framework is necessary to ensure that bioenergy plays its role in achieving the 1.5°C target effectively and appropriately. The policy framework should include sustainability-based target setting and long-term planning, cross-sector co-ordination for bioenergy, and sustainability governance supported by regulations and certificate schemes, as well as integration of bioenergy policy making with the SDGs (see Figure 4.1).

4.1. SUSTAINABILITY-BASED TARGET SETTING AND LONG-TERM PLANNING

Bioenergy target setting should be based on a sound understanding of sustainability in the context where the targets apply. This includes spatial and temporal characteristics of different options – the types and availability of feedstocks, supply chains, and end uses – in all environmental, social, and economic aspects. If bioenergy targets are set without considering sustainability, policy implementation may face challenges because of potential conflict with other sectoral targets. Various studies have been trying to map the availability of bioenergy feedstock at a global or national level, mainly based on agro-ecological indicators (IRENA, 2016a; IEA, 2017; ETC, 2021). However, more efforts are needed to integrate bioenergy targets with a better understanding of the sustainability and suitability of different bioenergy options in local contexts, considering the social and economic factors.

FIGURE 4.1. A policy framework for sustainable bioenergy development



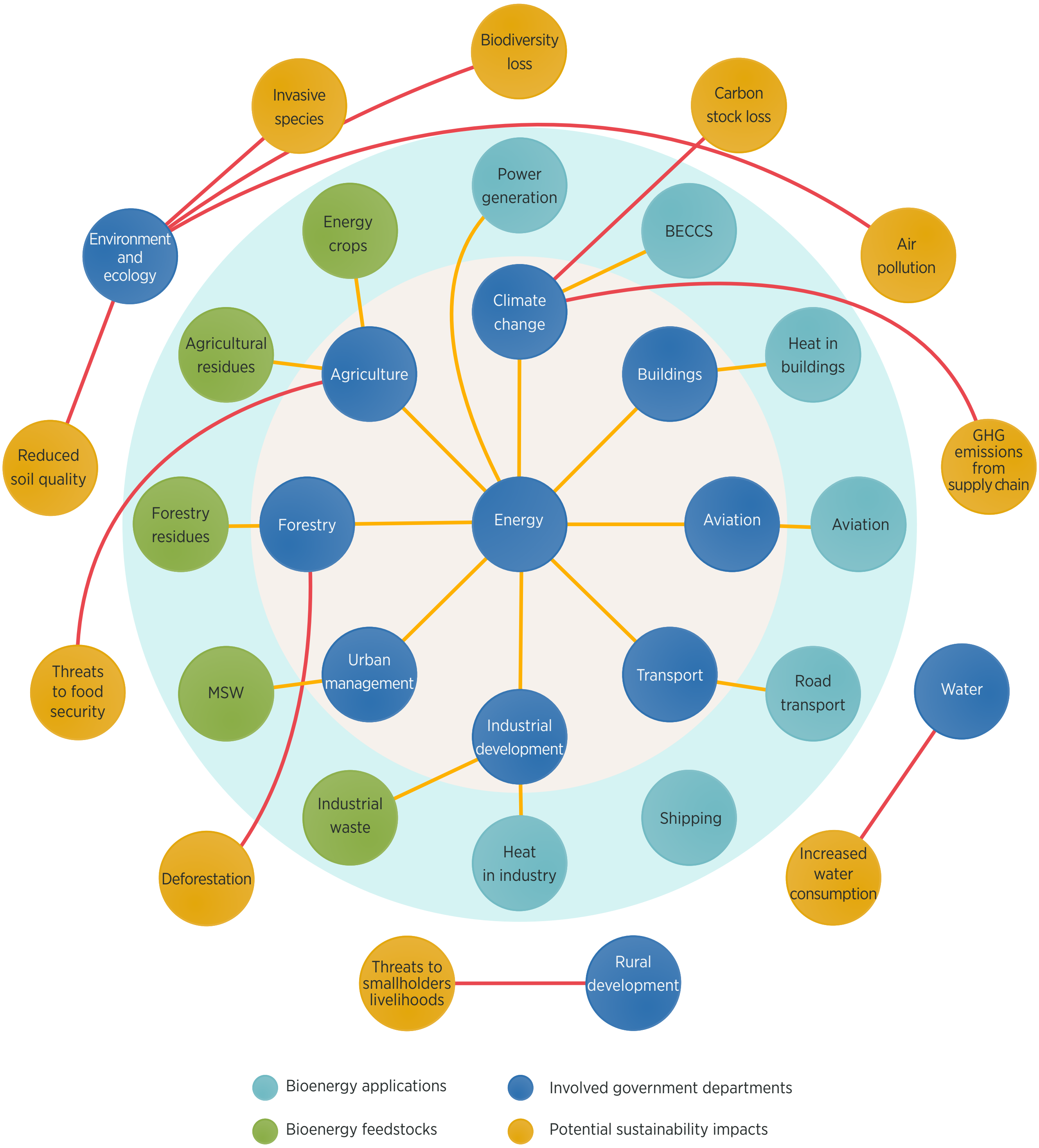
A long-term strategy for bioenergy development built upon a sound understanding of sustainability can provide a consistent policy signal to guide policy makers and build the confidence of investors and project developers. Long-term planning could enable improved land management instead of focusing on short-term gains from rapid extraction of biomass or unsustainable intensification overusing chemicals and water. This demands comprehensive monitoring systems on a landscape scale.

Bioenergy targets and policies should include consideration of socio-economic dynamics – *e.g.* labour availability, migration and energy access, especially in the context of rural development – before setting targets for large-scale bioenergy production (Goh *et al.*, 2018). Engagement with local stakeholders to seek suitable land-use and business models is necessary to ensure bioenergy development is beneficial for communities.

4.2. CROSS-SECTORAL CO-ORDINATION FOR BIOENERGY

Bioenergy policy making requires substantial cross-sectorial collaboration between agriculture, forestry, industry, environment, rural development and energy to align with broader plans beyond the energy sectors. Complex institutional structures and misalignments in dealing with sustainability issues across multiple policy domains have been key barriers in many countries. For example, energy agencies usually examine bioenergy purely from an energy balance perspective. Agriculture and forestry departments emphasise bioenergy as one of the options for rural development. Environmental ministries set rules for conservation beyond just carbon but may neglect local livelihoods. Industrial divisions focus solely on downstream development with little understanding of feedstock supply-related issues. Sustainable bioenergy development lies in the authorities of all these departments, which are usually lacking proper co-ordination or consistency.

FIGURE 4.2. Government departments' involvement in bioenergy production and consumption



Note: Government department names used in this figure are for illustrative purposes only. Actual government structure and department names vary depending on context.

Sustainable bioenergy development may have to be blended within the larger policy frameworks that cut across sectors, from upstream to downstream, depending on national or regional development plans. Bioenergy deployment should not focus solely on emission reduction as its primary goal. The deployment of bioenergy should complement economic activities like producing food, feed and fibre, all of which play major roles in socio-economic development. Positioning bioenergy in a broader socio-economic perspective may be challenging, considering the institutional barriers across departments and levels. For energy agencies, bioenergy is usually positioned as one type of renewable energy governed by uniform policy measures, such as FITs.

The concept of a "bio-economy" covers all bio-based sectors from upstream to downstream and from land use to end use (Fritsche *et al.*, 2020). It intends to link agriculture, forestry, energy and industrial development because they share many similarities in terms of supply chains, technologies and, most importantly, sustainability. However, the scope of the bio-economy can be very different in countries with different backgrounds.

Cross-sectoral co-ordination and integration can ensure policy consistency, avoid potential sustainability issues and seek synergies among departments. For example, the US's Biomass Research & Development Board was operational from 2000 to 2020 to co-ordinate research and development activities relating to bio-based fuels, products and power across different federal agencies, maximising the benefits and coherence of national-level planning. It set a quarterly meeting mechanism involving members from national departments on energy, agriculture, transportation, interior, defence and environmental protection (Biomass Research & Development, n.d.). It was then terminated and taken over by the Fuels for Future Advisory Board with similar functions for alternative fuels such as bioenergy and hydrogen (Biofuels Digest, 2021).

4.3. SUSTAINABILITY GOVERNANCE SUPPORTED BY REGULATIONS, CERTIFICATES AND PARTNERSHIPS

A regulatory framework dedicated to bioenergy can play a critical role in the sustainability governance of bioenergy. The key landmark was the introduction of sustainability criteria for bioenergy in the EU-RED, which sparked global responses as the European Union serves as the largest importer of bioenergy. While other regulatory frameworks like the Renewable Fuel Standard (RFS) in the United States and the Brazilian Biofuels National Policy (RenovaBio) are also important in terms of the volume of bioenergy regulated, the evolving EU Renewable Energy Directive to 2030 (RED II) has been the key component in discussions about bioenergy sustainability as it greatly influences the international trade and production of bioenergy around the world (see Box 4.1). However, currently, there are substantial gaps between the consumption (bioenergy) and production ends (agriculture and forestry) in terms of the regulatory framework and enforcement. There have been ongoing efforts to close these gaps by recognising the linkages between different end uses and supply chains (Iriarte, Fritsche and van Dam, 2021).

Box 4.1. Bioenergy within the EU Renewable Energy Directive to 2030 (RED II)

The EU-RED is the overall framework that sets rules and targets on the production and promotion of renewables, both in the medium and long term. The EU-RED was released in 2009, setting targets for renewables in the European Union by 2020. In 2016, the European Commission proposed an update of RED for the period from 2021 to 2030, which is called EU-RED II. The EU-RED II was consolidated in 2018 and continues to be developed and revised.

The EU-RED II requires all woody biomass to be used according to its highest economic and environmental added value in the following order of priority: wood-based products, extending their service life, reuse, recycling, bioenergy and disposal. It also includes a series of sustainability and GHG emission criteria for biomass and liquid biofuels use in power, heating and transport. Relevant targets and measures to reduce the sustainability risks include:

- Biofuels must not be produced from raw materials grown on land with high carbon stocks or high biodiversity and avoid the use of whole trees.
- Transport biofuels should achieve 65% of minimum GHG savings thresholds from 2021.
- Caps should be introduced on the share of biofuels for transport and liquid biofuels for power and heating, and bioliquids that are produced from crops grown for food and feed crops (such as ethanol from corn or cereals or biodiesel from virgin vegetable oils). In each member state, the level must be at least 1% below that being used in 2020 and at a maximum of 7% of final energy consumption in the road and rail transport sectors.
- Limits should be placed on the use of fu els produced from feedstocks with high ILUC risks for which a significant expansion of the production area into land with high-carbon stock is observed, and finally be phased out by 2030.
- Targets include both 14% renewables in transport and sub-targets for advanced biofuels (produced from indicated feedstock) at 1% in 2025 and 3.5% in 2030.

In July 2021, the European Commission further revised RED II. The proposed revision includes tightened bioenergy criteria that are in line with the EU biodiversity strategy, which will:

- prohibit sourcing biomass for energy production from primary forests, peatlands and wetlands
- provide no support for forest biomass in electricity-only installations as of 2026
- prohibit national financial incentives for using saw logs (a felled tree trunk suitable for cutting up into timber) or veneer logs, stumps and roots for energy generation
- require all biomass-based heat and power installations to comply with minimum GHG reduction thresholds
- apply EU sustainability criteria to smaller heat and power installations (equal or above 5 megawatts [MW]).

Source: European Commission (2021a-d).

Voluntary certification schemes may be employed to demonstrate compliance with sustainability regulations. For example, numerous schemes have been developed to allow companies and producers to prove that the bioenergy that they are producing, purchasing or consuming meets a specific set of sustainability criteria with various evidence, especially in tracing the origins of the feedstock (see Table 4.1).

An independent voluntary certification body usually establishes a set of practicable indicators on sustainability and then audits the supply chain to assess whether the criteria are fulfilled. Bioenergy certification schemes are often aligned with systems already put in place in other bio-based industries. Most are built upon existing schemes in agriculture and forestry.

It is worth noting that certification systems require additional effort and expertise to understand and meet the sustainability requirements, as well as to prepare evidence and documentation. These may increase the overall cost of bioenergy, creating barriers to smaller players, especially small farmers in developing countries (Stupak *et al.*, 2016; de Man and German 2017). Therefore, policies and measures are necessary to relieve the cost burden of certification fees on smallholders, as well as actions to close the expertise gap needed for various schemes.

TABLE 4.1. Certification schemes for bioenergy

Schemes	Year	Scope
Forest Stewardship Council (FSC)	1994	Sustainable forest management (SFM)
Sustainable Forest Initiative (SFI)	1994	SFM
Canadian Standards Association's SFM standards (CSA)	1996	SFM
GlobalGAP	1997	Good agricultural practices
Sustainable Agriculture Network (SAN)	1997	Good agricultural practices
Programme for Endorsement of Forest Certification (PEFC)	1999	SFM
CertFor, Chile	2002	SFM
CertFlor, Brazil	2002	SFM
Green Gold Label (GGL)	2002	Solid biomass supply chain
Roundtable on Sustainable Palm Oil (RSPO)	2004	Palm oil supply chain
Bonsucro	2010	Sugar and ethanol supply chain
International Sustainability & Carbon Certification (ISCC)	2010	Biomass and bioenergy supply chain
2BSvs	2011	Grain biofuel supply chain
Roundtable on Sustainable Bioproducts (RSB)	2011	Biofuels & biomaterials supply chain
RoundTable for Responsible Soy (RTRS)	2011	Soy biofuel supply chain
REDcert	2011	Biomass & liquid biofuels supply chain
ENplus	2011	Pellet
Initiative Wood Pellet Buyers (IWPB)	2012	Wood pellet supply chain
Sustainable Biomass Programme (SBP)	2013	Woody biomass supply chain
Sustainable Resources Verification Scheme (SURE)	2020	Solid biomass and biogas supply chain

Source: Stupak *et al.* (2016), Bioenergy International (2020), REDcert (n.d.), ENplus (n.d.).

Sustainability governance also requires global collaboration, especially when it involves international trade. Efforts have been made in harmonising the numerous certification schemes for bioenergy (Mai-Moulin *et al.*, 2019; Cucuzzella, Welfle and Röder, 2020). International platforms and partnerships have also been established for this purpose. For example, the Global Bioenergy Partnership (GBEP) was established in 2006, aiming to bring together public, private and civil society stakeholders in a joint commitment to promote bioenergy for sustainable development. It now has more than 70 members with an expanded range of activities in different countries (GBEP, 2017, 2020). The set of 24 sustainability indicators agreed by GBEP include water quality availability, land-use tenure and labour rights, including child labour and safe working conditions. These indicators have been applied or tested by more than a dozen countries, including some of the major bioenergy production countries such as Argentina, Brazil, Indonesia and Viet Nam, among others, to help national and local stakeholders monitor and develop sustainable bioenergy policies (GBEP, 2020). These international platforms and partnerships could play an active role in building capacity, raising the awareness of policy makers and complementing voluntary certification schemes.

4.4. BIOENERGY AND THE SDGS

The SDGs can be used to guide countries to achieve the sustainable deployment of bioenergy and the bio-economy in more coherent ways. Since their adoption by all UN member countries in 2015, the SDGs have played a role in serving as a comprehensive framework for developing holistic policies that address environmental, social and economic priorities. They are also important for sustainable biomass production to maximise positive benefits and avoid negative impacts on sustainability (Blair *et al.*, 2021).

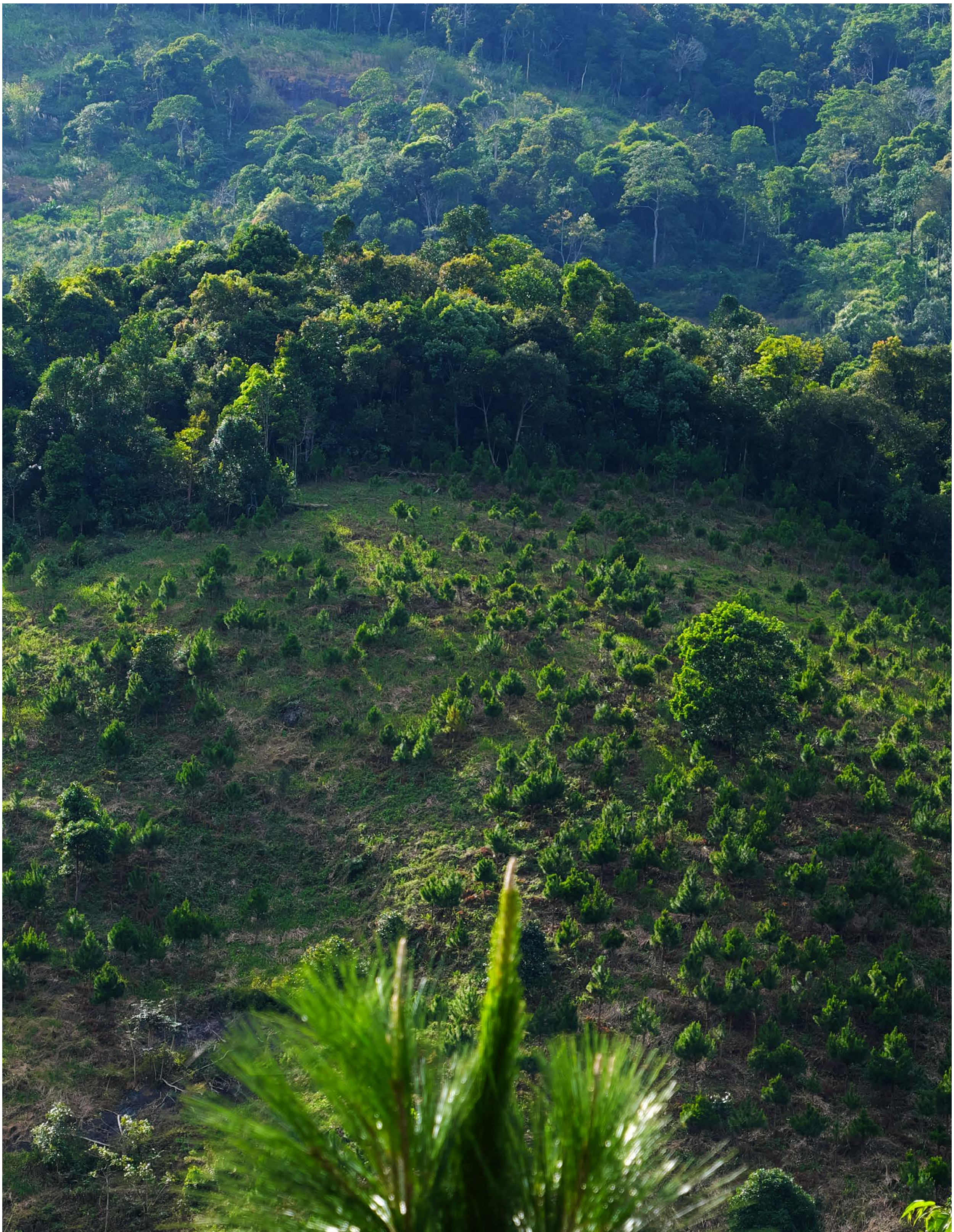
SDGs are intended for global action in various dimensions. Bioenergy and biomass sustainability have clear linkages with at least 12 of the 17 goals (see Table 4.2). All these linkages can be translated to policies and measures that should help national and local governments in identifying the most appropriate policy framework to deploy sustainable bioenergy. As most national governments have set up structures to work towards meeting SDGs, these goals may also be integrated into bioenergy policy making, with active engagement with regional and local policy makers, non-government organisations, international agencies, and private sectors.

TABLE 4.2. Maximising synergies between bioenergy and the SDGs

Goal	Linkages with positive impacts	Linkages with negative impacts	Policies and measures to maximise synergies
Goal 1: Zero poverty	Bioenergy provides a means to increase the income of the population working in land-based sectors, such as agriculture and forestry.	Bioenergy production can also impact smallholders' tenure rights of land (Target 1.4).	Financial and fiscal incentives. Regulations to protect the land tenure for smallholders.
Goal 2: Zero hunger	Sustainable biomass production can increase land productivity and smallholder incomes, including those of small food producers who sell by-products (Target 2.3).	Bioenergy crops can potentially compete for land with food production.	Regulations and incentives for smallholders selling agricultural and forestry residues for bioenergy production. Co-ordinated policies for bioeconomy to avoid competition with food production.
Goal 3: Good health and well-being	A switch to modern bioenergy use can have major health benefits.	Traditional biomass use causes a high level of air pollution, linking to high mortality numbers (targets 3.1 and 3.9).	Investments to transition households completely from inefficient and polluting biomass use. Regulations to reduce air pollution from biomass combustion from power generation, heating, cooking and industry (*e.g,* appliance emission standards).
Goal 5: Gender equality	Sustainable bioenergy may create new economic opportunities to empower women (Target 5.4).	Traditional biomass cooking is disproportionally undertaken by women.	Legislation, regulations and other measures to recognise domestic work by women and give women equal rights to economic resources and finance.
Goal 6: Clean water and sanitation	Waste-based bioenergy production could improve wastewater treatment and reduce water pollution (Target 6.3).	Large-scale production of biomass feedstock may increase water stress levels (Target 6.4).	Integrated assessment of water footprint for bioenergy targets. Targets and incentives to increase the utilisation of manure and sewage for bioenergy production.

Goal 7: Affordable and clean energy	Bioenergy can provide clean and affordable renewables, including for power, heat and transport fuels. Sustainable bioenergy development also needs to transition households relying on traditional bioenergy to modern fuels (all targets).		Targets and incentives to accelerate deployment of sustainable bioenergy. Mandates for bioenergy use for buildings and transport. Investments in clean cooking solutions.
Goal 8: Decent work and economic growth	Bioenergy can create significant employment opportunities and create markets for small to medium businesses, such as clean cooking enterprises.	Sustainability also requires decent work for workers along the biomass value chain (Target 8.5). Sustainability requires biomass producers' compliance with labour rights (Target 8.8).	Regulatory framework on work conditions for jobs along the biomass production supply chain and protection of labour rights.Programmes for training and capacity building of workers.
Goal 9: Industry, innovation and infrastructure	Biomass provides opportunities to decarbonise industrial heat and provide sustainable feedstock for industries such as the chemical industry (Target 9.4).		Investment for research and development of bio-based technologies. Targets and incentives to use bio-based feedstock to replace fossil fuel use in industries.
Goal 11: Sustainable cities and communities	Sustainable bioenergy could improve the management of MSW and reduce pollution (Target 11.6).	Solid biomass combustion can increase air pollution problems in cities.	Incentives for utilising MSW to replace fossil fuels and capturing landfill gases for heating and power generation. Regulations on the environmental performance of biomass appliances.
Goal 12: Responsible consumption and production	Reducing food waste and food losses along the supply chain (Target 12.3) is key to expanding sustainable biomass supply.		Regulations and incentives to encourage reducing food waste and food loss.
Goal 13: Climate action	Bioenergy is a key part of integrated national climate policies and plans (Target 13.2) to reduce emissions.	Some bioenergy supply chains have negative climate impacts.	Nationally determined contributions (NDCs) integrating policies and plans on bioenergy. Regulation of bioenergy supply chain.
Goal 14: Life on land	Sustainable practices can help restore degraded land (Target 15.3).	Biomass production can negatively impact forest area biodiversity and bring invasive species and therefore require sustainable forest management (targets 15.1 and 15.8).	Integrated long-term planning and targets on bioenergy, land, forest management and biodiversity conservation.

Source: IRENA analysis based on UNDESA (2022).



Reforestation at Bao Loc mountain, Viet Nam. ©xuanhuongho@Shutterstock.com

5. SELECTED CASE STUDIES ON SOUTHEAST ASIA

5.1. SUSTAINABILITY CHALLENGES OF BIOENERGY IN SOUTHEAST ASIA

The development of bioenergy in Southeast Asia has been largely motivated by potential economic opportunities and other benefits such as energy security and climate change mitigation. Since the 2000s, numerous bioenergy projects with ambitious targets have been proposed. Some concerns about these projects have been raised due to their impacts on the environment, societies and economies, despite their potential benefits (Pratiwi and Juerges, 2020). Policies and targets were then adjusted to take more factors into consideration. Importantly, the role and implications of bioenergy in the region were re-examined beyond the energy sector as it has close linkages to agriculture and forestry. Therefore, to understand the sustainability challenges of bioenergy in the region, one must place these in the larger context of the land-based sectors.

Southeast Asia is home to nearly 15% of the world's tropical forests. In the second half of the 20th century, the region underwent forest destruction on an unprecedented scale. Large-scale exploitation of timber resources was deemed a rapid way of jumpstarting economies. Rapid timber extraction has resulted in severe deforestation and environmental degradation (Stibig *et al.*, 2014). Many valuable tropical woods were logged and exported, either as raw logs or plywood, especially to other Asian countries (UN Comtrade, 2021). The trend has continued into the 21st century, with the region losing more than 22 million ha of natural regenerating forests in the first two decades, mainly in Indonesia (10 million ha), Myanmar (7 million ha) and Cambodia (3 million ha) (FAO, 2021). Meanwhile, about 6 million ha of new plantation forests were established, mainly in Thailand and Viet Nam, and to lesser extents in Cambodia, Indonesia and Myanmar.

As the region houses some of the most important forests and carbon stocks in the world, increasing the use of wood, including for bioenergy, may trigger concerns over the risk of forest degradation and deforestation. Timber plantations have been considered an option of afforestation to increase tree covers in the region. Acacia and eucalyptus are two major types of planted trees, which may offer fewer environmental benefits than naturally regenerating forests (FAO 2021). The expansion of monocultural timber plantations can affect existing ecosystems in terms of biodiversity, carbon storage and soil protection (Cunningham *et al.*, 2015). The demand for wood pellets could further drive the expansion of such monocultural plantations in Southeast Asia, as already observed in Viet Nam.

Furthermore, the sustainability issues with land use have become more complex in the past few decades, especially oil palm cultivation in Indonesia and Malaysia (Gaveau *et al.*, 2019). The conversion of large areas of natural regenerating forests to plantations in both countries has resulted in concern about environmental degradation and climate change. Critically, the conversion of peatland to plantations in this region has also greatly escalated the risk of land fire (IFAD, 2021). Recurring land fire events have led to enormous carbon stock loss and transboundary haze that exerted detrimental health impacts over the entire region.

5.2. GOVERNING SUSTAINABILITY OF BIOENERGY SUPPLY CHAINS

Recognising the complexity of intra- and extra-value chain governance in the land-based sectors is a key factor in understanding the governance of bioenergy sustainability in Southeast Asia. Bioenergy involves a wide range of stakeholders with diverging interests and perspectives on sustainability, including feedstock growers and land users (both large- and small-scale), downstream manufacturers (with bioenergy as one of the potential products), retailers (especially large buyers of raw materials located overseas), governments (different levels and departments), financial institutions (including foreign banks and investors), international organisations and agreements (on trade, climate change, etc.), and civil society organisations (on the environment, poverty, indigenous people, human rights, etc.). Bioenergy is only one of the components embedded in this "complex" with myriad instruments employed for sustainability governance. Three broad approaches are described below.

Regulations

Demarcation of protected areas is one of the common approaches used by Southeast Asian countries to shield forests from disturbance. In 2020, about 68 million ha of forests were located within protected areas (excluding Thailand, for which there was no data) (FAO, 2021). These areas, in principle, are not allowed to be used for bioenergy production. Countries also implemented various regulations and legislation to support sustainable forest management.

Certifications

For solid biofuels from the forestry sectors, certifications like the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) have been used to monitor the origins and sustainability of imported wood pellets. These schemes are recognised by the governments, but the adoption rates differ widely among countries and territories depending on the local context.

A range of voluntary schemes was developed for liquid biofuels from the agricultural sectors based on the EU-RED requirement. In practice, certifications designed specifically for biofuels may overlap with various legal frameworks in producing countries. For example, Indonesia and Malaysia have embarked on developing their own national schemes for palm oil, *i.e.* Indonesian Sustainable Palm Oil (ISPO) and Malaysian Sustainable Palm Oil (MSPO), which were mainly based on compliance with existing laws and regulations in the countries.

Furthermore, stakeholders may have different perspectives and demands. The emergence of different standards, schemes, and legal requirements may increase the cost, which might make it difficult for smallholders to prove compliance and therefore exclude smallholders from adopting sustainability certification.

Jurisdictional approach

A jurisdictional approach has recently gained interest throughout Southeast Asia. It is defined as an integrated landscape approach that aims to reconcile competing social, economic and environmental objectives through participation by a full range of stakeholders across sectors, implemented within government administrative boundaries, and with a form of government involvement at the national and sub-national levels of public administration (JCAF, 2021). This approach focuses on the political aspect of land-use decision making, providing an official platform to align governments, businesses, communities, civil society organisations and other stakeholders to work together on conservation and other development goals. In the context of certification, it will be the jurisdiction that obtains certification. In other words, all related products within the jurisdiction's boundaries will be considered to comply with the standards.

A jurisdictional approach can be used to strengthen the enforcement of environmental regulations and mitigate the certification cost burden on smallholders. Importantly, a comprehensive land cover and land-use map with a formal jurisdictional basis could also contribute to spatial planning on a territorial scale. This may effectively address the multiple issues in monitoring and improving the sustainability of bioenergy. However, implementing and ensuring the process is properly carried out in developing countries might be challenging due to the complexity of governance involved and possible long procedures needed.

Workers harvest palm fruit. ©Yogie Hizkia@Shutterstock.com

5.3. CASE STUDIES IN INDONESIA, MALAYSIA AND VIET NAM

Case 1: Palm-based bioenergy in Indonesia and Malaysia

Oil palm is a crucial cash crop in Southeast Asia, mainly planted in Indonesia and Malaysia and to a lesser extent in Thailand. Oil derived from palm fruits can be used as cooking oils and as raw materials for a wide range of additives and non-edible products like detergents and cosmetic products. Palm oil is the main feedstock for liquid biofuel production in Indonesia and Malaysia, while residues from mills and plantations are potential feedstock for solid biofuels for power and heat generation. Biogas and biofuels can also be produced from the treatment of palm oil mill effluents (POME), which is critical to prevent water pollution and methane emission. In 2018, more than one-third of the global vegetable oil demand was fulfilled by palm oil and palm kernel oil. It contributed to 16% of global food use and 21% of non-food use, with the latter including the 6% devoted to biofuel production (FAOSTAT, 2021).

Palm-based products have received heavy criticisms as they may directly add further pressure on highly biodiverse forests in the region, with a particular concern about the impacts on iconic species such as the orang-utan. Possible environmental risks associated with oil palm plantations include degradation, increased forest fire hazard, social conflicts between palm oil companies and local community, as well as issues related to land tenure and unjust benefit distribution for rural people (CIFOR, 2020; Field *et al.*, 2016; Abram *et al.*, 2017; Sanders *et al.*, 2019; Majid Cooke, 2012; Cramb, 2016). However, biodiesel only accounts for a small share of palm oil consumption. The majority of palm oil is used for non-energy uses (Ritchie and Roser, 2021).

Governance of bioenergy sustainability can be highly complex for the case of palm oil as it involves complex land-use dynamics. The actors involved may be broadly divided into several domains: energy, oil palm (agriculture), forestry, environmental protection, climate mitigation, and socio-economic development. The first three domains may involve international trade and investments that have links to other countries. The next two domains focus on various local and global environmental impacts, such as biodiversity and climate change, among others. Another domain, socio-economic development, involves actors and efforts in driving rural development and industrialisation (downstream). These domains overlap with each other significantly with a common set of actors that may or may not directly participate in land-use activities. For example, the energy sector involves local and international bioenergy stakeholders and actors from other domains, including oil palm companies, climate agencies, environmental non-governmental organisations, local governments, indigenous groups, financial regulators, etc. These actors interact with each other, directly or indirectly, via complex webs of governing structure not only in different domains but also at different administrative levels (Pacheco *et al.*, 2017).

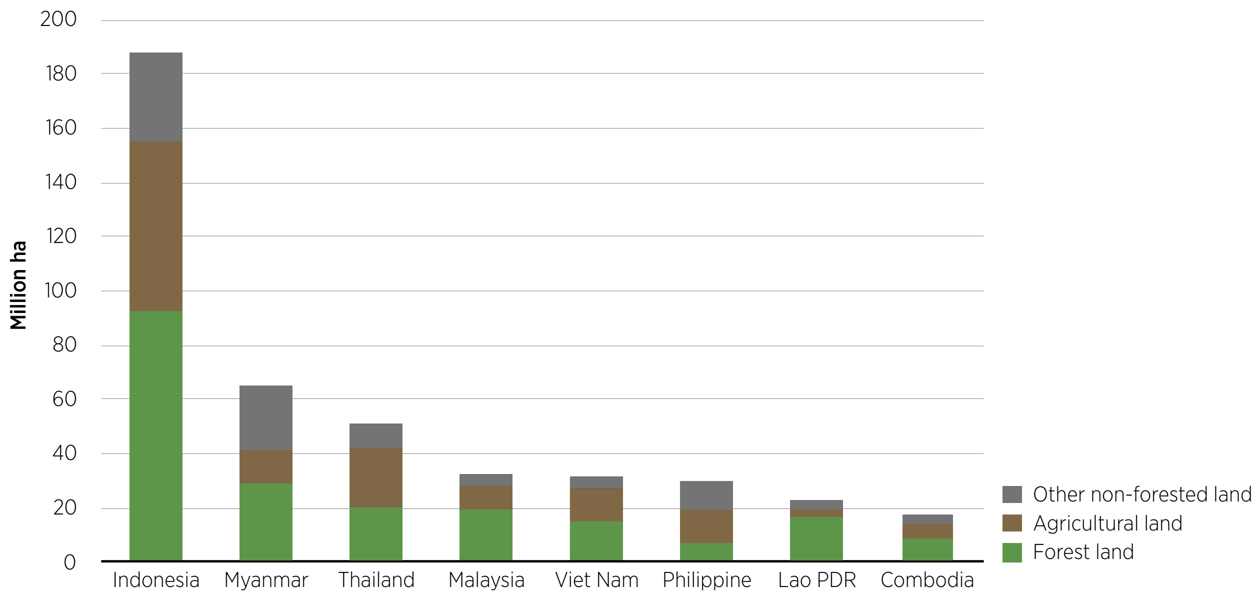
While the sustainability of palm-based bioenergy remains controversial, the sector is regarded by both Indonesian and Malaysian governments as an important component in driving downstream expansion and industrialisation. Plans like Malaysia's National Biomass Strategy were introduced to upgrade the oil palm industries, including proposals for advanced biorefineries, with products spanning from basic products such as liquid biofuels to high-end products like biopolymers. Both countries are now more flexible in setting the blending targets, considering the changes in the palm oil market (Wahab, 2019; Rahmanulloh, 2020). However, the concerns and solutions over the sustainability of biodiesel need to be placed in a broader context of the entire palm oil and vegetable oil industry beyond the energy sector.

Case 2: Biofuels from under-utilised and degraded land in Indonesia

A potential strategy to expand biomass supply is to actively use under-utilised and degraded land for bioenergy production. The strategy has been discussed in Indonesia, which has abundant non-forested land that is currently not actively used for agriculture. Figure 5.1 provides an overview of non-forested land that is currently not used for agriculture in some Southeast Asian countries. Roughly more than 93 million ha of non-forested land is not under intensive agricultural use, with about one-third of that located in Indonesia. Utilising these land resources may effectively avoid carbon stock loss from forest conversion in comparison to the expected business-as-usual scenario. Also, active management, if done properly, can help to avoid further land degradation and potentially replenish lost carbon stock.

This must, however, also take social factors into account. In Indonesia, substantial areas of land are occupied by local communities for small-scale farming. These lands may fall under the "under-utilised" land category solely based on agro-ecological and environmental criteria but may not be deemed under-utilised by the occupants, although the productivity is low (Baka, 2014; Shortall, 2013). In many places in Indonesia, shifting agriculture is still being practised. These areas were not properly captured in the agricultural statistics. Furthermore, most of the claimed land ownerships by local communities are largely undocumented. Activating these lands for biofuel production may need to be done with care to avoid potential conflicts (Majid Cooke, 2013; Lunkapis, 2013).

FIGURE 5.1. An overview of land use in some Southeast Asia countries



Note: Brunei Darussalam, Singapore and Timor-Leste are not included here due to their relatively small land area.
Source: FAOSTAT (2021).

Various names, definitions and criteria have been proposed in the past two decades to identify and quantify potential land areas for bioenergy production in Indonesia. Officially, the forestry and agricultural departments in Indonesia use the terms *lahan kritis* ("critical land") and *lahan sub-optimal* ("sub-optimal land") to describe land that has experienced degradation. The classification needs to be carefully and clearly defined to avoid misled expectations and unintended consequences in policy making. For example, in some cases, land classified as "degraded land" may still be rich in carbon stock and biodiversity (Obidzinski and Dermawan, 2010). Based on sets of agro-ecological criteria, multiple studies show that there are still millions of hectares of land that can potentially grow crops for bioenergy (Milbrandt and Overend, 2009; Hadian *et al.*, 2014; Jaung *et al.*, 2018).

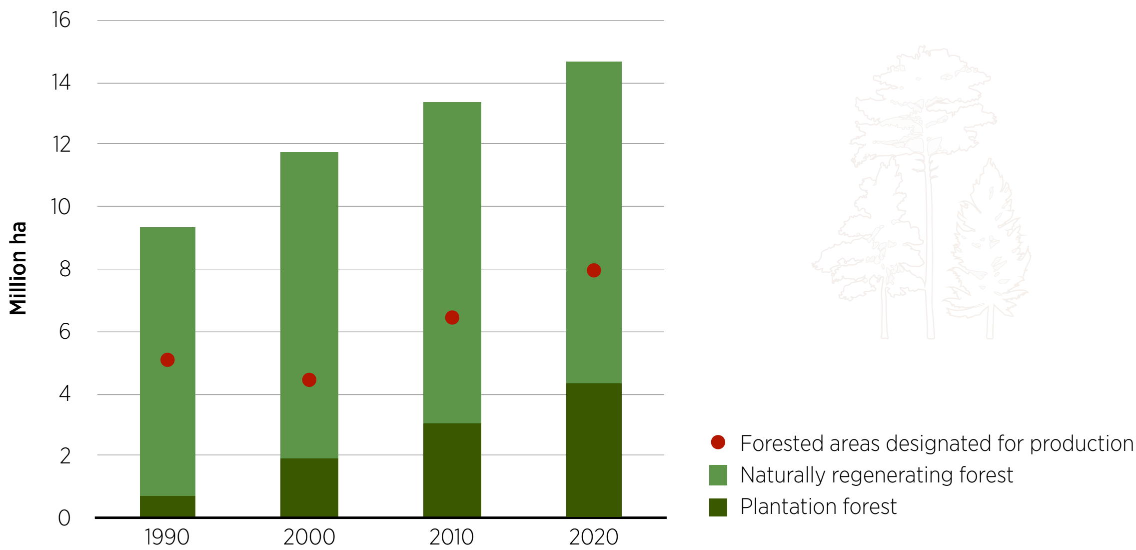
With suitable business models, the incentives from biofuel production on degraded land may provide new income sources for local communities and thus reduce the risk of unsustainable agricultural expansion (Goh *et al.*, 2017; Rahman *et al.*, 2019). A wide range of crops suitable for cultivation on degraded land were proposed and trialled in different parts of the country (Jaung *et al.*, 2018). However, the potentially high cost of using degraded land, mainly due to land quality and accessibility, has become a major barrier. Substantial early stage investments may be needed to replenish the land and improve accessibility. Studies have proposed to combine biofuel projects with other funding for land restoration, like carbon credit mechanisms (Kanematsu Corporation, 2011; Van Rooijen, 2014).

Producing bioenergy on degraded land requires careful consideration of suitable business models that take local conditions into account. To date, most biofuel projects proposed for local communities in Indonesia remain small and tend to have multiple objectives (with biofuel as just one of multiple outputs) (Rahman *et al.*, 2019). It is unlikely that there will be large-scale production of biofuels from degraded land in Indonesia in the near future.

Case 3: Wood-based bioenergy in Viet Nam

The forestry and wood processing industry has been a major contributor to Viet Nam's economic growth and job creation for decades. By 2020, the country had designated about 8 million ha out of its 14.6 million ha of forested areas as production forests (see Figure 5.2), supplying 28 million cubic metres of wood materials per annum. Slightly more than half of the production forests are plantation forests, and the rest are natural forests. Viet Nam is the region's largest wood pellet producer; about 10% of woody biomass harvested is processed into wood pellets and exported for bioenergy (UN Comtrade, 2021; FAO, 2021). The wood processing industry in Viet Nam also utilises imported wood materials in significant amounts. About 5 million cubic metres of timber and logs were imported to Viet Nam in 2019, with about one-fifth coming from the United States (Vo and Nguyen, 2020).

FIGURE 5.2. Changes in forested areas in Viet Nam, 1990-2020



Source: FAO (2021).

While furniture, plywood and wood panels are among the key export items, the export volume of wood pellets for bioenergy purposes grew substantially to nearly 2.8 million cubic metres in 2020 (UN Comtrade, 2021). One characteristic of the wood industry in Viet Nam is that foreign direct investment plays a major role in the sector. More than 50% of the total investment of USD 6 billion came from East Asia, with China leading at about USD 2 billion. This trend corresponds to the major destination of wood products from Viet Nam. Almost all wood pellets from Viet Nam are exported exclusively to East Asia, mainly to the Republic of Korea and a smaller amount to Japan.

Various initiatives have been implemented since the Viet Nam Forestry Development Strategy (VFDS) was introduced in 2006 to increase forest coverage (Van Hung and Thuy, 2020). While the area of natural regenerating forests has shown a significant increase of 1.7 million ha over the past three decades, the area of timber plantations has almost doubled. These timber plantations are dominated by acacia and eucalyptus, which are non-native species but can be harvested in five-year cycles (FAO, 2021). While the furniture industry demands high-grade timber, these fast-growing trees may be suitable for wood chip and pellet production. However, the rapid afforestation through the expansion of acacia and eucalyptus plantations may not deliver the same environmental benefits as natural regenerating forests.

To ensure more sustainable wood production, other productive native species should be considered for the plantations and afforestation projects (Crowther *et al.*, 2020). Payment for ecosystem services was promoted in the 2010s to encourage stakeholders to shift from monocultures to more biodiverse plantations, including various native species with longer rotations, in the form of community-managed forests (Moeliono *et al.*, 2017).

Viet Nam has no large private forestry companies; its forestry sector is household-based. Through VFDS, the government has prioritised households and household groups, especially the poor and forest-dependent ethnic minorities, in allocating forest land. These household-based small growers have low financial resilience (Zhunusova *et al.*, 2019). They prefer short-rotation plantations that can generate quick cash to mitigate risks like natural disasters, family matters and other unexpected expenses (Cuong *et al.*, 2020). Diversification of plantation forests may require more suitable business models like public-private partnerships in combination with various incentives from the government and other sources.

Certification of SFM is still lagging. By 2021, the FSC had awarded certificates that covered slightly more than 220 000 ha in Viet Nam (FSC, 2021). This is only a small fraction of the 8 million ha of productive forests in the country. The complexity and cost of certification might be barriers as most production forests are managed by small growers in the country. Until 2019, only less than 2% of the small Vietnamese growers had obtained certification for forest management (Flanagan *et al.*, 2019).

To ensure sustainable bioenergy production in Viet Nam, additional investment in sustainability, increased knowledge transfers and more long-term partnerships are needed for small growers. Also, gaining a better understanding of the low rate of conventional forest certification in Viet Nam may provide lessons to further improve sustainability governance. Importantly, maintaining progress in poverty reduction will be key to ensuring sustainable forestry and bioenergy in Viet Nam.

5.4. LESSONS LEARNT AND EXPERIENCES

The case studies of bioenergy development in Southeast Asian countries demonstrate that the sustainability of bioenergy depends to a great extent on the context of local agriculture and forestry, especially the scale of bioenergy deployment. As such, bioenergy development involves a much wider range of stakeholders and issues than most other forms of renewable energy.

Biofuel production levels remained constant in 2019 and 2020 in Indonesia and Malaysia, despite a decline in exports, as local consumption increased due to increased blending targets in both countries. The adjustment of blending targets creates a buffer to supplement the palm oil industry. In this context, the overall global consumption level of vegetable oils, whether for food or non-food purposes, will have a much larger impact on the sustainability of the oil palm sector. In April 2022, Indonesia announced a halt to the export of some of palm oil products (accounting for 30-40% of Indonesia's total palm oil exports) due to concerns about a local supply shortage (Raghu and Listiyorini, 2022). The export ban was then lifted in May 2022 (Maulia, 2022).

The case of wood pellets is different because almost all pellets are meant for export. The ratio of woody biomass used for different purposes is also market dependent. While the area of plantation forests is steadily increasing in Viet Nam, there is no quantitative study showing the extent of the ecological limits, *i.e.* the optimal area suitable for growing short-rotation trees without incurring unwanted consequences like increased water consumption, soil degradation, potential pollution, etc. The sustainability of the future pellet supply thus depends to a great extent on determining a scale of production that takes ecological limits into consideration.

Balancing the production scale has also been the key factor for producing bioenergy from degraded land. Recent proposals for generating bioenergy from degraded land are smallholding-centric and prioritise rural development objectives over emission reductions. Landscape sustainability has also been prioritised to avoid the creation of monocultural landscapes.

In short, the sustainability of bioenergy in Southeast Asia is dependent on the overall development in the agriculture and forestry sectors. Bioenergy deployment has to be placed in a wider canvas of sustainable development that cuts across multiple goals in the sectorial and local contexts. Targets for bioenergy must be carefully set in the sectoral contexts of agriculture and forestry. Coherent government policies, cross-sector collaboration and innovative business models are needed to capitalise on the synergies generated from integrating various strategies and benefits.

Sugarcane field. ©Namomooyim@Shutterstock.com

The future of bioenergy in Southeast Asia is likely to be dependent on the following factors:

- **Utilising agricultural and forestry residues and waste:** The agriculture and forestry sectors of Southeast Asia can generate a considerable volume of residues and waste, including POME, cassava pulp, and residues from major crops such as rubber, teak and eucalyptus. These residues and waste remain underutilised and can play a significant role in decarbonising this region's industry and transport sectors (IRENA, 2022b).
- **Boosting productivity:** Sustainable yield intensification is especially important for smallholders with lower productivity due to low-quality seedlings and poor management practices (FAO, 2014). The question for bioenergy development is how much can be further produced for energy purposes through intensification without triggering unwanted environmental consequences. Technological innovation, especially the enhancement of existing biological and chemical methods, may allow a further breakthrough.
- **Activating under-utilised and degraded land:** Degraded land in Southeast Asia may be under-utilised due to low productivity and the high cost of replenishment. These land resources may be reactivated with the right incentives and suitable business models that carefully consider the perspectives of local communities and stakeholders. Bioenergy projects can be integrated with rural development policies, land restoration projects or carbon credit mechanisms to improve financial feasibility.
- **Improving sustainability governance:** Sustainability governance of bioenergy in Southeast Asia is highly complex. It requires holistic thinking that goes beyond just "land" or "energy" to cover multiple aspects of a place or territory. Sustainability certification of agricultural and forestry products is thought to be a key solution in addressing sustainability concerns, but it needs to be coupled with other instruments. Potential options such as the jurisdictional approach could also be very challenging to implement because they require the consolidation of efforts from a wide range of actors in different lines of inquiry. How bioenergy can be synergistically embedded in territorial development plans is worth further exploration.
- **Upgrading and diversifying downstream development:** Creating new added value through developing, upgrading and diversifying downstream activities – particularly through the concept of "biorefinery" – may make bioenergy development more feasible in the long term. A biorefinery is characterised by its ability to process multiple types of feedstocks, including residues and waste streams, and to produce multiple products such as conventional and advanced biofuels, biopolymers, drop-in and novel chemicals, and other co- and by-products. It represents future development and innovation in the biotechnology industries.

Other possible options for sustainable bioenergy development in this region also exist. However, achieving sustainability is a major challenge. Bioenergy development also faces various cross-cutting barriers in most subsectors. Some key cross-cutting barriers and policies to address them are discussed in Chapter 6.

A truck carries wood in Viet Nam.

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6. BIOENERGY CROSS-CUTTING BARRIERS AND POLICIES

In addition to sustainability concerns, bioenergy deployment faces various barriers. Some of these barriers cut across bioenergy applications, such as biomass, biogas and biomethane for heating and power generation, and liquid biofuels for transport. This chapter focuses on the main cross-cutting barriers and policy measures to address them.

6.1. BARRIERS TO THE DEPLOYMENT OF BIOENERGY

As is the case for other renewable energy technologies, a number of barriers (see Figure 6.1) also inhibit more widespread deployment of bioenergy. At a global level, the main barriers include the higher cost of bioenergy compared to fossil fuel options and a distorted energy market due to unlevied externalities of fossil fuel use. In addition, weak supply chains are unable to provide a stable feedstock supply, a situation that will significantly hinder the development of bioenergy industry if policy measures are not put in place. Technology readiness is another barrier, especially for advanced technologies such as liquid biofuels for aviation, and biomaterial used for chemical industries. Those technologies may play an important role in achieving the 1.5°C Scenario, but presently remain in their early stages. Some barriers also link into each other, such as policy uncertainty and difficulty attracting investment. Weak supply chains also can be a reason for high production costs, which are impacted by feedstock costs.

FIGURE 6.1. Cross-cutting barriers to bioenergy deployment

Political and institutional barriers

- Policy uncertainty
- Weak institutional structures

Financial and economic barriers

- Fossil fuel subsidies
- High cost
- Lack of access to affordable finance

Technical and infrastructure-related barriers

- Low-level technology readiness
- Reliability of technologies
- Lack of infrastructure

Supply chain-related barriers

- Lack of stable feedstock
- Lack of qualified workers and skills
- Sustainability risks

Information and public awareness-related barriers

- Lack of reliable information
- Low public awareness

Political and institutional barriers

Policy uncertainty has been a main barrier to developing renewables, including bioenergy, due to the lack of long-term policy commitments and targets. This uncertainty usually translates into weak policy attention and ambition in national energy strategies and planning or frequent changes in relevant policies and regulations. It may impede investment in bioenergy supply chains and pertinent infrastructures that need a long time to make a return. For some uses of advanced bioenergy, creating the markets and demand for product also takes time and therefore requires long-term policy signals.

Complex institutional structures and misalignment in dealing with cross-sectoral issues across multiple policy domains create additional barriers. Bioenergy policy making usually involves different departments, such as agriculture, forestry, rural development, waste management and energy. When it comes to end uses, policies for bioenergy development need to be co-ordinated between transport departments (for liquid biofuels and biomethane), industrial development departments (for biomass to replace fossil fuels for industry) and building departments (for biogas, biomethane and biomass for residential heat).

Ensuring the sustainability of bioenergy requires the involvement of sectors and departments, such as departments and policies relevant to biodiversity, environmental protection, climate change, water management, air pollution and labour rights. Policy priorities and targets in these sectors and departments do not always have proper links or alignment with bioenergy policy making and therefore raise concerns about sustainability (see Chapter 2). The trend of international bioenergy trade further increases this institutional complexity (see Chapter 3).

The misalignment of bioenergy-related policies implemented by different departments may create additional difficulties in deploying bioenergy. A lack of co-ordination among these departments remains a critical challenge for bioenergy deployment, together with the absence of a robust and conducive institutional structure.

Financial and economic barriers

Fossil fuel consumption causes environmental and social externalities such as air pollution and climate change. All these costs should be levied from polluters. Additionally, many governments directly subsidise fossil fuel production or consumption. These are called fossil fuel subsidies. Fossil fuel subsidies are defined by the International Monetary Fund (IMF) as the gap between existing and efficient fossil fuel prices, which should take into consideration the economic cost of supplying fuel to consumers; the environmental and social costs associated with fossil fuel consumption such as local air pollution, global warming and other costs associated with fuel use in road vehicles; and general revenue-raising considerations (IMF, 2019). The IMF estimated that global fossil fuel subsidies were USD 5.9 trillion in 2020, accounting for 6.8% of global gross domestic product (GDP). The share is expected to rise to 7.4% of global GDP in 2025. The majority (92%) of fossil fuel subsidies in 2020 were for undercharging for environmental costs and foregone consumption taxes (Parry, Black and Vernon, 2021). Fossil fuel subsidies have created energy market distortion linked with the dominance of fossil fuels. These subsidies therefore make bioenergy solutions less cost-effective than fossil fuel options and have disincentivised the production of bioenergy and other renewables.

In the absence of measures (*e.g.* emission trading systems or carbon taxes) that account for the costs of negative environmental and social impacts from fossil fuel burning, most bioenergy options have a higher cost than fossil fuels. For example, the cost of biomethanol, even with a lower feedstock cost, can be 1.3 times to 7.7 times the cost of fossil fuel-based methanol, with the range influenced by the difference in capital and operation costs as well as conversion efficiency (IRENA and Methanol Institute, 2021). The cost of advanced biofuels used for aviation is three to six times that of fossil-based aviation fuels (IRENA, 2021c).

When bioenergy is used to produce other products for industrial purposes, the high cost of bioenergy-based fuel or feedstock decreases the competitiveness of industrial products. For example, high cost is the main barrier to using biomass-based coke in the steel industry, for which the products have a low margin (Lenz *et al.*, 2020). In addition, small-scale biofuel companies and scattered farmers may not be able to afford the extra costs of pre-treatment technologies that are usually required by biomass CHP plants and biorefineries (EUBIA, n.d.).

Lacking access to affordable finance remains another major challenge for sustainable bioenergy deployment. It is usually difficult to secure finance for bioenergy projects, programmes and investments at reasonable rates. For example, finance companies may see bioenergy investments as high risk due to the unstable biomass feedstock supply for industries or low level of technology readiness of high-level technologies, such as advanced biofuels for aviation (see chapters 10 and 11).

Technical and infrastructure-related barriers

Low-level technology readiness remains an urgent barrier to the deployment of more advanced liquid biofuels (Doliente *et al.*, 2020). Liquid biofuels have a promising future role in the decarbonisation of the aviation sector. Most of biojet fuel technologies are far from mature, except the hydroprocessed esters and fatty acids (HEFA) pathway (IRENA, 2017). As one of the second-generation biofuels, lignocellulosic ethanol-related technology is expected to play an important role in the next decade. But this technology has not been considered mature for large-scale deployment. The low technology readiness of liquid biofuel technologies can further amplify production costs due to small-scale production (IRENA, 2019b).

The same issue also slows down biomass utilisation for high-temperature industrial processes. There are some low-temperature biomass applications (such as biomass for the pulp and paper industry). Still, technologies – for example, some of those used to replace coal and coke through gasification, for high-temperature industrial processes (above 400°C, such as iron and steel) – have not been fully developed at a commercial scale because challenges need to be addressed to ensure product quality is not affected.

Lack of infrastructure constrains the scaling up of bioenergy utilisation. For biofuels in the transport sector, a lack of adequate transport and storage infrastructure constitutes a significant issue for long-distance transport to deliver liquid biofuels when biofuel production is located at a distance from market demand. This barrier is relevant to most common liquid biofuels (*e.g.* fatty acid methyl ester [FAME], ethanol) and related crude products (*e.g.* pyrolysis oil). Along with increasing global and regional trading, expansion of storage and transportation infrastructures will be necessary (IRENA, 2019b).

Issues related to gas grid infrastructures can hinder biomethane use for heating. Because biomethane can be injected into the existing gas grid, limited grid capacity could inhibit the absorption of locally produced biomethane for replacing natural gas. In the European Union, on-site storage of biomass is another major infrastructure barrier (together with high capital costs and a lack of suitable feedstock) that limits bioenergy deployment for industrial process heat (Malico *et al.*, 2019).

Supply chain-related barriers

Weak bioenergy supply chains – including feedstock cultivation, harvesting and collection; pre-treatment or upgrading – have been the most dominant barrier for bioenergy development, especially for large-scale plants or projects. For example, agricultural residues could be a major feedstock for liquid biofuels for aviation, but the supply chains are not well established due to the complexity of effective collecting, storing and utilising these residues (IRENA, 2021c). Bioenergy systems require reliable and consistent supplies of feedstocks. In most regions, agricultural residue-based biomass power plants or lignocellulose biofuel projects must contend with an unstable supply of biomass stock, mainly because of seasonal availability, low bulk-density and dispersion of many small-scale farms scattered across a large area. Furthermore, bioenergy systems need to be carefully planned, designed, installed, operated and maintained to ensure efficient operation and to avoid high emissions levels to air and water. This may be affected by the lack of qualified workers with appropriate skills in the bioenergy supply chain.

Developing bioenergy supply chains needs to involve actors in the forestry, agriculture and waste management sectors, most of which may be unfamiliar to the bioenergy industry and reluctant to change current practices. Potential supply chain approaches are blocked by limited access to finance in some contexts. For example, some new practices, such as short-rotation woody crops and catch and break crops, may expand biomass feedstock availability but require significant changes in crop production and rotation patterns, including a shift from annual crop production to perennial crops such as miscanthus and other grasses or short rotation forestry (*e.g.* coppiced willow or poplar), as well as crops suitable for use in anaerobic digestion. These changes require large investments in novel planting and harvesting machinery and major changes in the skills and knowledge of the farmers and producers. However, the supply chain has not been established due to investors' low confidence in profitability.

Moreover, if bioenergy supply chains are not carefully developed and operated, there may be negative environmental, social and economic impacts. Concerns about the sustainability risks of bioenergy production may also slow down deployment. These sustainability-related challenges are discussed in Chapter 2. More specific issues related to the weak supply chain in each end use are discussed in the following chapters.

Information and public awareness-related barriers

Limited information on bioenergy products and their benefits may impact the engagement of stakeholders (*e.g.* potential users or feedstock providers) along the supply chain. For example, householders (especially in regions without a history of using wood fuels) may be unaware of modern and clean bioenergy solutions such as biogas or pellet-based boilers. Industrial players may either be unaware of potential bioenergy opportunities or lack reliable information on the benefits and risks of the specific bioenergy options. Farmers may be unaware of the potential value and additional income from residues and waste as feedstock for bioenergy. Furthermore, if reliable information is not available, policy makers may hesitate to get involved in bioenergy due to concerns about sustainability.

Policies need to address those barriers. The following section will discuss some measures that can tackle cross-cutting issues associated with bioenergy. Additional measures that target issues affecting specific technologies or end uses – cooking, heat, transport, electricity production and non-energy use in industry – will be elaborated on in the following chapters.

6.2. CROSS-CUTTING POLICIES TO ADDRESS COMMON BARRIERS IN ALL USES

Some of the policy measures apply to all renewable technologies, and therefore policy experience can be based on the policies for deployment of solar and wind projects. For instance, targeted efforts have been made to reduce investment risks associated with utility-scale solar photovoltaic (PV) and wind projects through dedicated procurement programmes, long-term power purchase agreements and payment guarantee mechanisms. Other policies need to be tailored for addressing bioenergy-related barriers, such as the sustainability of feedstock and improving supply chains.

A wide range of policies and regulatory instruments are needed to tackle barriers to bioenergy development. These policies should help create a positive enabling environment for adoption, strengthening the supply chain while maximising social and environmental benefits and avoiding potential risks. These policies can be categorised according to the targeted barriers (see Table 6.1).

TABLE 6.1. **Cross-cutting policies and the targeted barriers**

Categories	Barriers	Policy measures
Political and institutional barriers	Policy uncertainty	Long-term national strategy/plan
		Bioenergy targets
		Mandates and obligations
		Ban on fossil fuel use
	Complex institutional structures	Cross-sectoral co-ordination and integration
Financial and economic barriers	Fossil fuel subsidies	Phaseout of fossil fuel subsidies
		Carbon pricing policies
	High cost	Grants, subsidies and other financial support
		Reduced levies and duties
		Other financial and fiscal incentives
	Lacking access to finance	Loan guarantee and other measures to facilitate affordable financing options
Technical and infrastructure-related barriers	Low technology readiness level	Incentives and support to RD&D
	Lack of infrastructures	Financial and fiscal incentives and mandates to enable infrastructures
Supply chain-related barriers	Unstable feedstock supply	Measures to strengthen bioenergy supply chains
	Lack of qualified workers and skills	Quality control, training and skill development
	Sustainability risks	Sustainability-based targets and long-term planning, cross-sector co-ordination, sustainability governance, and integration with SDGs
Information and public awareness-related barriers	Lack of reliable information	Information sharing and public awareness activities
	Low public awareness	

Policies to address political and institutional barriers

Long-term strategy and plan

A long-term national strategy and plan for bioenergy development can provide a consistent and long-term policy signal to guide policy makers and ensure confidence for investors and project developers. Since bioenergy developments are relevant to various sectors, including energy, environment, waste management, agriculture and forestry, the national strategy development process should involve a wide range of departments and stakeholders to ensure consistency and appropriate ambition based on the context in its jurisdiction. Long-term roadmaps with multiple targets are vital to facilitating more investments in technologies and accelerating the steps towards commercialisation and scaling up. For example, the Kenyan government released its Bioenergy Strategy (2020-2027) in 2020, aiming to promote sustainable bioenergy production and consumption, accelerate the transition to clean cooking technologies and fuels, and provide potential investors with the requisite information for international co-operation and trade in bioenergy. The strategy also highlights co-ordination mechanisms as a crucial support for the strategy (Ministry of Energy, Kenya, 2020).

The strategy should be aligned with broader plans of end-use sectors to prioritise the best suitable bioenergy applications and technologies under the given context and maximise the long-term benefits. For example, the long-term strategy on climate mitigation for the Netherlands includes biomass for industries and advanced biofuels for the transport sector (MEACP, 2019). This is significant for developing novel technologies and needed infrastructure and for strengthening supply chains, most of which would take a relatively longer time to generate a return on the investment.

National strategy and plan development should not only be based on modelling results because models are always imperfect and need to be complemented with other measures. The national strategy and pathways should reflect national and regional contexts and include sustainability governance. They should also be based on assessed biomass potentials, considering infrastructure development (Thrän, Cowie and Berndes, 2020).

Targets on bioenergy

Clear medium- and longer-term **targets** for bioenergy can strengthen long-term policy certainty with the support of concrete plans and incentives. Targets usually are included in the national strategy or other action plans. Bioenergy targets can also strengthen the synergy with **nationally determined contributions** (NDCs) indicating expected GHG emissions and potential technology approaches. For example, by the end of 2019, some 14 NDCs had set targets on liquid biofuels, and 11 NDCs had targets for non-power-sector biogas (IRENA, 2019c). In 2021, the Laos People's Democratic Republic submitted an updated NDC, aiming to increase biomass capacity to 300 MW by 2030, with international support (IRENA, 2022c).

However, bioenergy targets should be based on the limit of feedstock that can be sourced sustainably. In that way, the target will not bring additional negative impacts on environments and society (see Chapter 2). Moreover, back-to-back policies are needed to support or make the best use of domestic potentials, including residues and waste, to avoid relying on imports to reach the targets, which may be detrimental to the development of a domestic supply chain and may create additional concerns about sustainability (see Chapter 3).

Cross-sectoral co-ordination and integration

The long-term development of bioenergy requires co-ordinated and integrated policies and action plans across different sectors, including industry, environment, forestry, agriculture and energy. Cross-sectoral co-ordination and integration can ensure policy consistency, avoid potential sustainability issues and seek synergies among departments. It is an important pillar for the sustainability of bioenergy (see Chapter 4). Effective cross-sectoral co-ordination and integration rely on the clear positioning of bioenergy within the larger policy and institutional framework according to a specific national context.

Mandates and obligations

Mandates and obligations can increase demand for bioenergy and attract investments. These include requirements on the use of renewables in providing heat or biofuels blending obligations for biofuels in transport fuels. They could also include policies such as licences, permits and quotas for the production or transportation of bioenergy. However, mandates and obligations should be decided subject to biomass potential assessments to avoid creating potential sustainability concerns.

Bans on the use of fossil fuels

Commitments and measures to ban the use of fossil fuels for specific end-use sectors could also create long-term signals and support the development of the bioenergy industry. For example, commitments to fossil fuel bans in specific industries, such as the chemical industry, may help create early development opportunities for biomass-based feedstock. A ban on fossil fuel boilers and fossil fuel heat is an important enabling condition for accelerating bioenergy's share in heating. Studies suggest that achieving the net zero target requires banning fossil fuel boilers beginning in 2025 (IEA, 2021b). A number of European countries, including Germany and the United Kingdom, are moving to stop using coal for power generation. At COP26, at least 23 countries made commitments to phase out coal power, including Chile, Egypt, Indonesia, Republic of Korea, Nepal, Poland, Singapore, Spain, Ukraine and Viet Nam (UNFCCC, 2021b). Several countries are also moving to ban the use of oil for heating and constrain the use of natural gas (see Chapter 8).

Wooden pellets boiler.

Policies to address financial and economic barriers

Financial and fiscal support measures can ensure that the production and use of bioenergy sources are profitable for enterprises and affordable for final consumers. These include measures to remove main drivers of the energy market distortion (*e.g.* the phaseout of fossil fuel subsidies, carbon pricing policies), policies to reduce the burden on bioenergy (reduced levies and duties) or raise its competitiveness (*e.g.* FITs, grants, subsidies), and measures to facilitate the financing.

Phaseout of fossil fuel subsidies

Phasing out subsidies to the production and consumption of fossil fuels is urgently needed – especially for G20 countries, which account for the bulk of the subsidies – to fix the energy market distortion and level a playing field for renewables. The phaseout should be guided by a clear timeline and guidance and could be a key component of countries' commitment to NDCs. Moreover, the phasing out of fossil fuel subsidies could save significant government resources, which could be used to accelerate the clean energy transition and help vulnerable populations impacted by high energy prices (IISD, 2019).

Carbon pricing policies

Carbon pricing policies, including carbon taxes and emission trading system (ETSs), can be an important measure to internalise the cost of GHG emissions, which mainly come from fossil fuel burning. With significant roles to play in achieving a zero-carbon future, carbon taxes have boosted the development of biomass for district heating in Nordic countries. In 2021, carbon pricing policies had covered around 21.5% of global GHG emissions (World Bank, 2022). As the country with the largest initiative, China officially launched its national ETS in 2021, covering 30% of its national GHG emission or around 4000 million tonnes of carbon dioxide ($MtCO_2$) (World Bank, 2021). In 2020, the carbon pricing initiatives generated USD 53 billion in revenue, which provided additional resources and could be used to invest in renewables and ensure a just transition.

Landfill captured biomethane in Italy. ©newphotoservice@Shutterstock.com

Carbon pricing policies must be well designed to reflect the local context and should be supported by other policies to avoid worsening the situation of low-income people and energy-poor households. Low carbon prices could also weaken the effect of ETS, for which additional measures such as a guaranteed carbon price floor are necessary. For example, the United Kingdom set floor prices for its ETS to ensure prices do not fall below a threshold and discourage investment (UK Parliament, 2018).

The carbon price needs to be high enough to make bioenergy cost-competitive compared to fossil fuel options. For example, in 2019, a USD 50 per tonne of carbon tax would have increased the levelised cost of heating with gas boilers by 20% in Canada, but pellet heating was still over three times higher than gas heating (IEA, 2021c). However, the recent steep rise in fossil fuel prices has reduced this gap.

Reduced levies and duties

Reduced levies and duties such as value-added tax (VAT) on bioenergy producers and import tariffs on liquid biofuels can improve the cost-competitiveness of bioenergy products compared to fossil fuel options. Such taxes vary widely between countries. Within the European Union, residential energy prices vary by a factor of three, with the differences being largely due to the differences in taxes and environmental levies (UK BEIS, 2020). Lower VAT rates on biomass boilers for residential customers can also significantly influence consumer choice. Sweden exempted liquid biofuels from energy taxes for the transport sector to encourage biofuels and reduce fossil fuel consumption (European Commission, 2020a). Tax exemption is also key for clean cooking progress. In July 2021, Kenya updated its policy to reinstate VAT exemptions on renewables, including clean cookstoves, biogas and biomass briquettes (Gogla, 2021).

Capital grants and subsidies

Capital grants and subsidies are the most common way of supporting bioenergy and other renewable solutions by reducing upfront investment and operation costs. They can support both small and large-scale projects for different applications, such as power plants, heating projects, biomass as feedstock for chemical industries, liquid biofuels and BECCS projects. Specific policy examples can be found in chapters 7 to 11.

Facilitating affordable financing schemes

Facilitating affordable financing schemes for bioenergy projects through special investment funds or the provision of loan guarantees can ensure access to the necessary finance at reasonable terms. It is estimated that reducing the financing rate by 2% (from 10% to 8%) and extending five more financing terms (from 15 years to 20 years) would reduce 5-16% of the advanced biofuels' cost (IEA, 2020b).

Policies to address technical and infrastructure-related barriers

Support for RD&D

Support for innovation through technical RD&D can raise technology readiness and accelerate the commercialisation of novel biofuels such as biofuels for aviation and bioenergy used for industries. Policy support for RD&D is usually included in the grant and subsidies package and should be complemented by long-term targets because development and commercialisation of novel bioenergy technologies may take many years, even decades, for which a long-term policy signal will be necessary.

Support for infrastructure development

Policies such as municipal direct investment or mandatory connection can promote investment in necessary infrastructure, such as district heating schemes or biofuel distribution systems. For example, municipal heating companies may play a role in investing in district heating networks, which may take a long time to generate a return. In some cases, cities can also mandate the integration of district networks in new development areas to ensure necessary heat demand from consumers and avoid overlapping investments in decentralised applications in the same area. More examples of measures for infrastructure are introduced in the following chapters.

Policies to address supply chain-related barriers

Quality control and standardisation

Regulations and measures for quality control and standardisation can improve product quality and the operational efficiency of bioenergy technologies, as well as accelerate commercialisation and market acceptance. These cover equipment, feedstock, production, testing, storage and delivery.Such quality control measures can achieve synergy with financial support to channel resources to qualified projects or installers.

For example, the QM *Holzheizwerke* (biomass heating) programme, a joint Swiss-Austrian-German initiative on quality management, was implemented in Switzerland in 2000. It covers the entire process of designing, procuring and installing a biomass heating system, from initial brief to end of life and disposal. It has helped to raise performance across the biomass sectors in Austria, Germany and Switzerland by providing clarity of responsibilities across the supply chain and measurable minimum standards (QM for Biomass DH Plant, n.d.).

These measures usually involve independent institutions. For example, the European Committee of Standardisation, the International Organisation for the Standardisation and the American Society for Testing and Materials are usually involved in reviewing the quality of biodiesel to make sure the use of biodiesel would not harm the vehicle/equipment performance and durability of vehicles' engines or other combustion equipment (Carrero and Pérez, 2012).

Training and skill development

Training, education, capacity building and skill development initiatives and related policies can improve workers' skills to properly design, install, operate and maintain bioenergy systems in the whole supply chain. Training and skill development can create an appropriate skill base and further cultivate and strengthen the local supply chain. In some African countries, training is conducted to help cookstove installers install efficient biomass cookstoves and help reduce the negative impacts (see Chapter 7).

Policies to address information-related barriers

Information sharing activities

Governments at the national and regional levels have an important role to play in providing precise and reliable information on bioenergy to consumers and potential investors. This can help improve awareness of the benefits and challenges associated with bioenergy and encourage technology adoption.

Local governments can play an important role in organising such initiatives and public campaigns to promote biomass fuels and other low-carbon alternatives. Information on the availability and location of bioenergy resources and public information on energy infrastructure can help project developers in targeting bioenergy feedstocks and the best project locations.

For example, the Food and Agriculture Organization (FAO) provided training on the sustainability of bioenergy to stakeholders in the African countries of Ghana and Togo through the Global Bioenergy Partnership and in collaboration with the Economic Community of West Africa States (ECOWAS) (FAO, 2019). The Upper Austria Energy Agency provides information and financial incentives to energy consumers wishing to switch to biomass and other low GHG solutions and promotes a programme to end the use of oil in heating applications (Bioenergy International, 2021).

Large biogas plant in Europe. ©abadoniant@www.gettyimages.ae

7. SUSTAINABLE BIOMASS FOR CLEAN COOKING

7.1. BACKGROUND

Around one-third of the global population (approximately 2.4 billion people) rely on inefficient stoves and traditional biomass for heating and cooking. These practices usually involve very low-efficiency stoves or open fires fuelled by traditional forms of biomass (*e.g.* charcoal, firewood, dung, wood), kerosene or coal, especially in rural areas. The majority of the affected population lives in the developing world, such as sub-Saharan Africa, Central Asia, South Asia and Southeast Asia. Sub-Saharan Africa is the region that faces the greatest challenge, with the population without access to clean cooking significantly increasing the last 20 years (see Box 7.1).

The primary energy demand linked to the traditional use of biomass for cooking and heating accounted for around half of total global biomass consumption in 2018 (IRENA, 2021b). This practice leads to significant indoor and outdoor air pollution with severe negative health consequences, directly linking to 3.8 million premature deaths annually (WHO, 2021). It also causes negative environmental and socio-economic impacts. For example, the low efficiency of cooking stoves or charcoal production means that fuel demands are high and may exceed local supply, leading to deforestation and impacts related to this, such as disruption of local water cycles (Hosonuma *et al.*, 2012).

Box 7.1. Bioenergy and clean cooking in sub-Saharan Africa

More than one-third of the world's population without access to clean cooking solutions are living in sub-Saharan Africa. In 2019, around 84% of the whole population in this region (some 906 million) lacked access to clean cooking solutions and relied on inefficient cookstoves using traditional biomass as fuels. The situation is more challenging when development trends over the last two decades are taken into consideration: the number of people without access to clean cooking increased by 50%, driven by higher population growth without an accompanying gain in access to clean cooking solutions.

Bioenergy and waste are the most widely used energy sources in Africa, accounting for 40% of the whole continent's energy supply. Most biomass is consumed for residential heating and cooking, in the form of charcoal or firewood. For example, as the largest economy in Africa, Nigeria consumed more than 66 million tonnes of firewood and 4 million tonnes of charcoal for cooking in 2019.

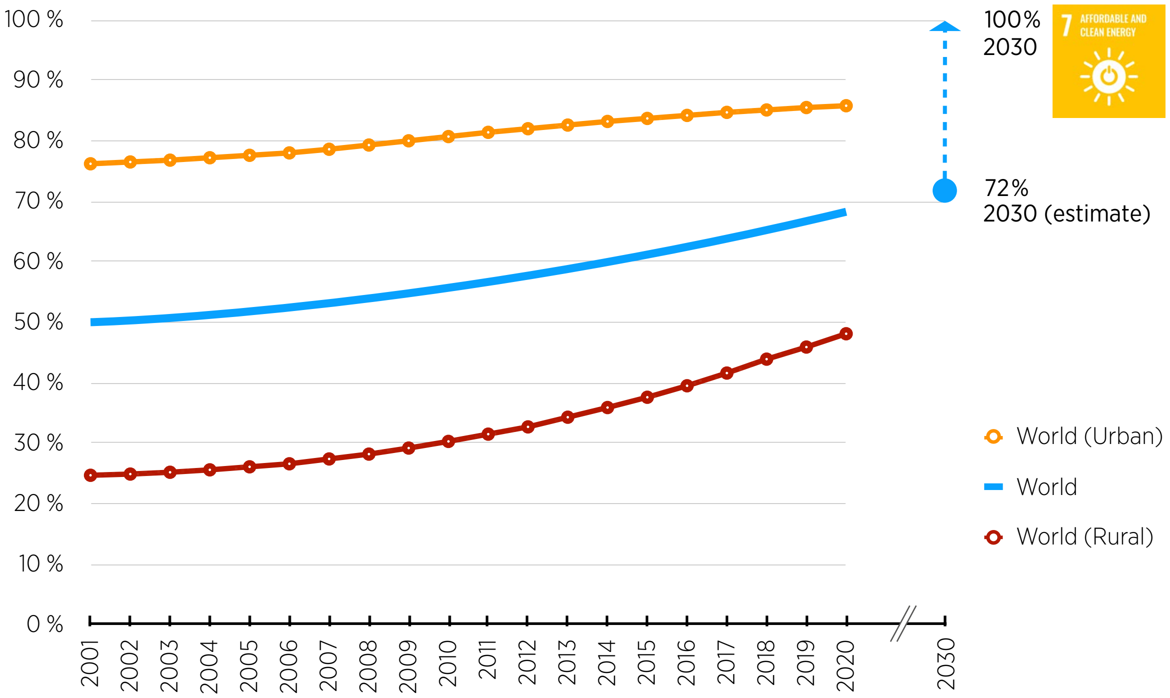
If current policies remain, the number of people in sub-Saharan Africa without access to clean cooking may further increase to more than 1 billion, indicating a failure of the world to deliver the SDG target of achieving universal access to clean cooking by 2030. Potential solutions exist, such as improved biomass cookstoves and modern forms of solid biomass, biogas and renewable electricity-powered electric cooking. For example, biogas digesters have the potential to serve 18.5 million households in this region. But the potential is unlikely to be realised without the necessary policy measures to fill the cost gap and address various barriers.

Source: IRENA (2022b), IEA, IRENA, UNSD, World Bank and WHO (2021), REN21 (2021).

Another major socio-economic impact is inequity related to women and children, who are more affected because they are usually responsible for firewood collection and cooking. While cooking with traditional biomass fuel and inefficient cookstoves, women disproportionately suffer the health consequences associated with household air pollution. Potential impacts on health include respiratory diseases, cancers, tuberculosis, perinatal outcomes (*e.g.* low birth weight), and eye disease. According to the data from two surveys in Bangladesh, respiratory problems are both prevalent and correlated with time spent cooking (World Bank, 2004). Disproportionate responsibilities for women regarding cooking also take away opportunities for education and other income-generating activities due to the time taken for wood fuel collection. Meanwhile, they also risk being exposed to sexual and other forms of violence during the collection trips (WFO, 2017).

Given these negative consequences of inefficient use of biomass, SDG 7.1 aims to ensure universal access to clean cooking solutions by 2030. Replacing traditional biomass use and ensuring universal access to clean cooking solutions have formed parts of the global effort. However, the progress is slow and needs to be accelerated (see Figure 7.1) (IEA, IRENA, UNSD, World Bank and WHO, 2021).

FIGURE 7.1. Global clean cooking access rates from 2001 to 2020 and forecasted for 2030



Source: IRENA (2022a), WHO (2022).

7.2. OPPORTUNITIES

Transforming the inefficient use of bioenergy for cooking and heating with efficient cookstoves and modern fuels is an essential pillar of the energy transition. This will involve using renewables such as renewable-based electricity, biogas, sustainable biomass (*e.g.* pellets and charcoal briquettes produced from agricultural and forestry residues) and improved cookstoves that could mitigate the negative environmental and health impacts. Available approaches depend on local factors.

Current clean cooking solutions in many national and regional strategies mainly focus on fossil fuel-based solutions, such as the use of liquified petroleum gas (LPG) and natural gas, which have been deployed in regions such as South Asia, Southeast Asia, Latin America and the Caribbean, but less so in sub-Saharan Africa. However, these fossil fuel-based solutions bring additional GHG emissions and other negative consequences.

Considering the large reliance on solid biomass and the lack of other renewable alternatives, solid biomass is likely to continue to play an important role in many areas without access to clean cooking fuels. Changes to the fuel and improvement of cookstoves can help to make it more sustainable. Improved cookstoves can reduce negative impacts due to their higher efficiencies, although the gains are often lower than expected as they are tested in laboratories rather than field settings (Abdelnour and Pemberton-Pigott, 2018).

Improved biomass cookstoves and modern bioenergy have been used in many countries to expand access to clean cooking solutions, particularly in rural areas where sustainable feedstock (such as residues and wastes) are the most affordable option. For example, in partnership with international donors, Bangladesh and Kenya have implemented national programmes to support the deployment of improved biomass cookstoves. The Bangladesh Improved Cookstove Programme has been operating since 2013 and has delivered over 2.5 million cookstoves, with a target of 5 million by 2023 (IDCOL, 2021). In Kenya, improved cookstoves are reported to have a fuel-saving potential of 40% compared to firewood and 30% compared to charcoal stoves. The project demonstrates that increasing access to modern cooking technologies is a cost-effective way of reducing fuel poverty and boosting livelihood opportunities (Energy for Impact, 2021).

Improved biomass fuels are also being widely used to expand access to clean cooking. These include briquettes made from agricultural residues, sawmill residue and pellet. For example, Emerging Cooking Solutions, a social enterprise in Zambia, produces pellets from sawdust from pine and eucalyptus plantations. It has sold pellets and cookstoves to 20 000 households, with cost savings of 30-40% compared to charcoal.

Biogas digesters have played a significant role in helping people transition from inefficient biomass to clean cooking solutions, with successful examples in China, India, Nepal and Viet Nam (see Box 7.2 and Box 7.3). As biogas can be produced from locally available agricultural residues, organic waste and manure, biogas technologies are more attractive in places with wood scarcity, reducing the pressure on forests while improving the soil by using the organic fertiliser as a by-product (REN21, 2021).

Box 7.2. Development of small-scale biogas digesters in India, Viet Nam and Africa

India has huge potential for biogas based on around 512 million livestock. The Indian national government implemented two schemes to support small-scale digesters (capacity at 1-25 cubic metres) and medium- to large-scale plants for heating and power generation. By 2018-2019, India's National Biogas and Organic Manure Programme had supported the installation of over 5 million small-scale digesters, providing clean cooking fuels, lighting and heating for millions of Indian households.

The Biogas Programme for the Animal Husbandry Sector in Viet Nam started in 2003 to promote biogas for heating, lighting and cooking. This programme has facilitated the installation of around 250 000 domestic biogas digesters, improving living conditions for over 1.2 million people. It has created about 16 800 full-time jobs since the beginning of the programme. It also significantly reduced indoor air pollution and GHG emissions.

In Africa, biogas is being utilised by over 400 000 people for residential cooking. Biogas production has been increased more than 50% annually (average) in the last decade. A significant share of the deployment comes from Rwanda, Senegal and countries covered by the Africa Biogas Partnership Programme. During 2014-2019, more than 38 000 biogas digesters were installed under this programme with funding from EnDev and the Dutch government.

Source: MNRE (2022), IRENA (2022b).

Box 7.3. Biogas to provide clean cooking and heating for 160 rural households in Feidong County, China

China has been one of the leading countries utilising biogas. It has built more than 7 700 medium and large biogas and biomethane projects, producing 1.3 billion cubic metres of biogas every year for half a million households. China also targets the production of 20 billion cubic metres of biogas and biomethane yearly by 2030, contributing to 5% of total gas consumption.

Most of the biogas and biomethane can be directly injected into the gas grid to provide fuel for cooking and heating. In Feidong County (China), a large-scale agricultural residue-based biogas project has been constructed. With a 1 000-cubic metre fermentation tank, this project can process around 1 000 tonnes of agricultural residue collected from local farmers every year and produce biogas for the cooking needs of 160 households in the rural area. The biomethane share in produced biogas is more than 60%. With the help of improved air supply of the stove, biogas cooking provides better heat efficiency than LPG (which these rural households used before changing to biogas). Furthermore, the project also provides 1 500 tonnes of organic fertiliser. The cost of the project was around USD 1 million.

Source: MARA (2019), BEIPA *et al.* (2021).

7.3. BARRIERS TO DEPLOYMENT

A lack of **co-ordinated policy making on clean cooking** has been a significant impediment to progress in many countries, especially in sub-Saharan Africa. Policy making on clean cooking to drive the transition from traditional and inefficient biomass to sustainable options needs to involve many government departments, including rural development, energy, agriculture, health, social, financial, environmental and forestry. Co-ordination can be difficult and time-consuming (FAO, 2017).

The investment gap hinders progress. Although the inclusion of clean cooking within the SDGs has stimulated more international efforts to address the issue, investments from public and private sectors are still not in line with that required to meet the SDG goals (IEA, IRENA, UNSD, World Bank and WHO, 2021). The goals of universal access to electricity and to clean cooking can be achieved with an additional investment of USD 65 billion to USD 86 billion a year until 2030, if that investment is combined with dedicated policies that lower the costs of modern cooking fuels and stoves (SE4ALL, 2017a). Although finance commitments for clean cooking tripled from USD 48 million in 2017 to USD 131 million in 2018, they remain substantially below the required investments (REN21, 2021).

Gender inequality is a fundamental and dominant barrier to the deployment of clean cooking. Energy needs remain a disproportionate burden for women, especially in the traditional use of biomass for cooking (FAO, 2018a). Women are most occupied with cooking activities and suffer from indoor air pollution and fuel collection activities. However, they often do not have the right to invest in clean cooking solutions within a family. For example, in some cases, women may have control over cash for food purchases but do not have the financial independence to make a decision about purchasing cooking fuels (ESMAP, 2021).

Some basic improved biomass stoves can be built with readily available local materials but tend to provide relatively limited benefits in terms of efficiency and reduced pollution. More advanced stoves can deliver greater benefits but face a **higher cost of appliances and fuels** (FAO, 2018b). Given that the clean cooking deficit is highest where there are high levels of poverty (*e.g.* rural areas in sub-Saharan Africa, South Asia and Central Asia), many potential users do not have the means to continue paying for fuels; they have to resort to living in a more informal economy. Biogas systems can be capital intensive, and the upfront investment is beyond the reach of many rural households. Unsubsidised capital costs of biogas digesters range from USD 500 to USD 1 500, while biomass gasifier stoves can cost between USD 75 and USD 100. These costs are usually unaffordable for low-income consumers, and financing options are rarely available (IRENA, 2022b). This cost barrier is reinforced by **the lack of access to affordable capital** for financing the purchase of efficient cookstoves, clean fuels, or providing for investment and working capital for fuel or equipment production systems. When affordable loans are available, they are generally only for small amounts, which disincentivises potential lenders from undergoing the administrative costs to offer the financial products in the first place (Winrock International, 2017).

Technical deficiencies in improved cookstove or biogas digesters may influence the scaling up of clean cooking solutions if the product standard and quality assurance framework are not in position. This issue is linked to the challenge of **lacking skills and trained workers**. Operational failures may damage market growth. Biogas digesters, for instance, require basic periodic maintenance, including cleaning, and can fail as a result if end users are not adequately trained. Such failures can give technology solutions a bad reputation for unreliability. For example, in China, some of the deployed biogas digesters had a low use rate due to lack of labour and inadequate maintenance (Xia, 2013). Lack of maintenance has also been a major barrier to biogas development in Africa.

Clean cooking fuels, such as biomass briquettes or improved cooking stoves, usually have immature supply chains, leading to concerns about the security of supply of clean cooking fuels or resulting in volatile prices. For example, distributing clean cooking fuels to remote rural areas is challenging. **Lacking reliable information** or low public awareness on the potential benefits of clean cooking solutions to health and the environment remains another barrier to adopting clean cooking technologies.

Concerns about the sustainability of biomass feedstock and the supply chain could be another barrier to the uptake of bioenergy for clean cooking (see Chapter 2). Other barriers also exist, such as tax burden, technology and fuel performance, after-sale support, public perception and information, and even factors linking to population characteristics (ESMAP, 2021). Completely transitioning away from traditional use of biomass might take a longer time than expected because households may still use biomass even when provided with electricity and other fuels.

Box 7.4. Clean cooking framework to empower women

The International Center for Research on Women (ICRW) partnered with the Clean Cooking Alliance to design a framework for measuring the social impact of clean cooking solutions, including on women's social and economic empowerment. Their initial research demonstrates that clean cooking solutions can create a social impact for women in two ways.

Women can be empowered through their involvement in the clean cooking value chain. As primary users of energy in the household, women have a comparative advantage in reaching out to other end users of clean cookstoves. According to the Clean Cooking Alliance study, women outsold male cookstoves sellers by nearly 3 to 1. Furthermore, if women sold cookstoves to other women, those consumers were more likely to report consistent and correct cookstove use and were more likely to report the benefits of cookstoves compared to male counterparts. Women's direct engagement in renewable energy projects plays a significant role in their positive impact on and wide adoption by their intended beneficiaries.

Clean cooking solutions can improve a household's social and economic situation with saved time and money on fuel collecting and cooking (ICRW, 2015). According to Eco-Fuel Africa, a Ugandan-owned, for-profit social enterprise, households can save USD 200 per year using biomass briquettes on average, equating to 40% of their average annual income. Women potters producing cookstoves in Cambodia under the Cambodian Fuelwood Saving Project experienced a 61% increase in average daily income. Income earning opportunities for women can have wide positive impacts beyond the clean cooking sector. Studies show that women reinvest 90% of their income to their families and communities, while men reinvest 30-40%. Women's empowerment through clean cooking initiatives has economic implications far beyond the individual alone.

Source: Clean Cooking Alliance (2021).

7.4. POLICIES AND MEASURES

While the UN SDG targets have provoked higher levels of attention and stimulated greater international efforts in clean cooking, progress remains limited, especially in sub-Saharan Africa. Clear targets, greater ambition and more investments are urgently needed to accelerate the clean cooking access gains.

National plans need to set clear time-bound targets and designate responsible and co-ordinated implementation mechanisms. Including **clean cooking targets in NDCs** can be a helpful measure. For example, the Nepalese government included clean cooking targets in its 2020 NDC. The targets included installing 500 000 additional improved cookstoves and 200 000 household biogas systems (REN21, 2021). International and national programmes and strategies can substantially catalyse efforts to deploy clean cooking solutions. In 2018, eight countries in West and Central Africa built an alliance to strengthen the policy support for the adoption of biogas digesters (Hivos, 2018). Bangladesh aims to achieve 100% improved cookstoves by 2030. Under this target, the country has installed 1.6 million improved cookstoves and helped families spend less on fuel. The project also had a gender mainstreaming component involving women in the supply chain (see Box 7.4) (World Bank, 2018a).

National cookstove programmes supported by development finance can provide financial support for clean bioenergy cooking systems (see Box 7.5). These have been launched or scaled up in many sub-Saharan countries, including Ethiopia, Ghana, Malawi, Nigeria, Rwanda, Senegal and Uganda (Hosier *et al.*, 2017). Results-based financing (RBF) has been commonly used to support the scale-up of proven business models and behaviour change campaigns of clean cooking solutions. The RBF approach aims at providing incentives to foster private sector investments in target markets and to overcome market failures constraining delivery of services to end users. For example, from 2016 to 2019, the Pico PV and Cookstove RBF programme in Kenya facilitated sales of 272 128 improved cookstoves and EUR 3.8 million (euros) by households and the private sector, providing around half a million people with access to clean cooking (SNV, 2020). The Indonesia Clean Stove Initiative, an RBF programme, also launched a focus on cookstove delivery and included innovative stove testing methods that incorporated local cooking practices and preferences (SE4ALL, 2017b). China, India, Nigeria and South Africa have implemented a variety of financial and fiscal measures, including subsidies, tax benefits and duty exemption for suppliers of clean cooking solutions (IEA, IRENA, UNSD, World Bank and WHO, 2021).

Box 7.5. International donor and development funding for clean cooking

International donors from international aid agencies, development organisations and multilateral development banks have played a major role in providing clean cooking programmes in Africa and Asia. The Green Climate Fund has provided USD 27.6 million funding for improved cookstove programmes in Kenya and Senegal. It has also provided around USD 20 million to support the clean cooking programme in Bangladesh since 2018.

The African Development Bank, Sustainable Energy Fund for Africa and European Commission are providing co-funding of USD 50 million to an impact investment fund called SPARK+ Africa launched by Enabling Qapital and Clean Cooking Alliance. The funding aims to invest 70% in debt instruments and 30% for equity and quasi-equity instruments for clean cooking in the sub-Saharan African region, addressing the growth capital gap of cooking energy-focused small and medium-sized enterprises.

The Dutch government has provided funding for the African Biodigester Component for 2021-2025, a follow-up programme of the African Biogas Partnership Programme. This funding aims to deliver 50 000 small digesters by 2025, based on a partnership between the Netherlands Enterprise Agency and EnDev in Burkina Faso, Kenya, Mali, Niger and Uganda. There is also support for the Biodigester Alliance of West and Central Africa to accelerate the use of biogas in the region. The Dutch government has also partnered with the Vietnamese Ministry of Agricultural and Rural Development to support a biogas programme in Viet Nam. This programme has resulted in the installation of 250 000 domestic biogas digesters.

Launched in 2017, the Biogas Dissemination Scale-Up Programme is funded by the European Union in partnership with the Ethiopian government. This five-year programme aims to provide 180 000 people with biogas for cooking by building 36 000 biogas digesters. In 2021, the Swiss government announced its support for a clean cooking programme in Africa and aimed to develop 60 000 biodigesters from cattle dung and fecal sludge in Senegal.

Source: IRENA (2022b), IRENA, IEA and REN21 (2020), FAO (2020), SNV (n.d.), GCF (2018).

Mandatory standards and labelling backed up by monitoring and testing can ensure the high quality of clean cooking solutions and, therefore, long-term market development. For example, Ghana planned a national energy performance standard and labelling regulation for improved biomass cookstoves (WTO, 2019). The Ethiopian government also endorsed the standard on clean cooking stoves and solutions (Ethiopian Standards Agency, 2017). Training for workers is critical for qualified installation and maintenance of cookstoves and biogas digesters. In Viet Nam, the National Biogas Programme, supported by the Dutch government, provides training for manufacturers and government technicians. Manufacturers must be certified before they are able to build digesters, and trained officials provide quality assurance and training for users (IRENA, 2018).

Programmes to raise public awareness have proven important to deploy clean cooking solutions. For example, the Clean Cooking Alliance with support from the UK government supported behaviour change communication activities in Bangladesh, Kenya and Nigeria from 2016 to 2019, reaching over 13 million people through radio, print advertising, TV programming, social media and interpersonal communications (Clean Cooking Alliance, 2020).

Barriers, policies and examples for bioenergy for clean cooking are summarised in Table 7.1.

TABLE 7.1. Barriers and policies for bioenergy in clean cooking

Barriers	Policies	Examples of countries with policies and programmes
Lack of co-ordinated policy making Gender inequity	International and national programmes and strategies Clean cooking targets in NDCs Streamlining women's empowerment	Bangladesh, Nepal Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Togo
High cost of appliances and fuels Lack of access to affordable capital	RBF Subsidies, tax reduction, duty exemption	China, India, Indonesia, Kenya, Nigeria, South Africa Ethiopia, Ghana, Malawi, Nigeria, Rwanda, Senegal, Uganda
Technical deficiencies	Mandatory standard and labelling	Ethiopia, Ghana
Weak supply chain Lack of skills and trained workers	Training (*e.g*, technical, business and marketing skills)	Kenya, Nepal, Viet Nam
Low public awareness	Awareness-raising programmes	Bangladesh, Kenya, Nigeria

Preparing food in Ethiopia. ©Canyalcin@Shutterstock.com

Food preparation in Uganda. ©Anjo Kan@Shutterstock.com

8. MODERN BIOENERGY FOR HEAT IN BUILDINGS

8.1. BACKGROUND

In 2020, the building sector accounted for around 31% of total final energy consumption. A majority of energy in buildings is used to provide heating services, including water heating, space heating and cooking. Most of current heating is based on fossil fuels, such as coal and natural gas, causing air pollution and GHG emissions. Modern bioenergy for heat in buildings includes modern forms of biomass (*e.g.* pellets), biogas, biomethane and others. Bioenergy-based heating systems can integrate with existing district heating networks and provide renewable heat for multiple buildings or even a whole district. Efficient biomass boilers for single houses are also common technologies.

In 2020, modern forms of bioenergy contributed to half of the total renewable heat in buildings (excluding traditional use), around some 4% (5 EJ) of total heat demand in buildings (IEA, 2021a). This accounts for around 11% of total bioenergy consumption across all sectors (IRENA, 2021d). European countries remain at the centre of modern biomass for heating. Europe accounts for more than 75% of global pellet demand, more than half of which is used for residential and commercial heating (IFI, 2021). A significant share of pellets consumed in European countries is imported from Canada and the United States because domestic production cannot meet demand (see Chapter 3). Austria, France, Germany, Italy and Sweden are major consumers (Schipfer *et al.*, 2020). China is also a growing market for bioenergy for heating. In 2020, biomethane production capacity in China reached 150 million cubic metres. Most biomethane is injected into the gas grid for heating purposes. Bioenergy provides heating for 300 million square metres of building area, accounting for 1.5% of the total building area that needs heating in northern China (CREEI, 2021).

8.2. OPPORTUNITIES

Modern and sustainably sourced bioenergy for heating buildings has an essential role in the energy transition (see Figure 8.1). According to IRENA's 1.5°C Scenario, the consumption of modern biomass for heating buildings would need to increase to 18.2 EJ by 2050, tripling the current level (IRENA, 2021b). From 2021-2026, China, India and the European Union will contribute to a large share of the increased bioenergy demand for heat in buildings (IEA, 2021a).

FIGURE 8.1. Major pathways for modern bioenergy use in buildings

Feedstocks

- Agricultural residues
- Forestry residues
- Processing waste
- Municipal solid waste
- Food waste
- Manures
- Sewage and other waste water

Technologies

- Modern biomass boilers
- Small-scale biogas digesters
- Medium and large-scale biogas projects
- Biomethane injected into gas networks

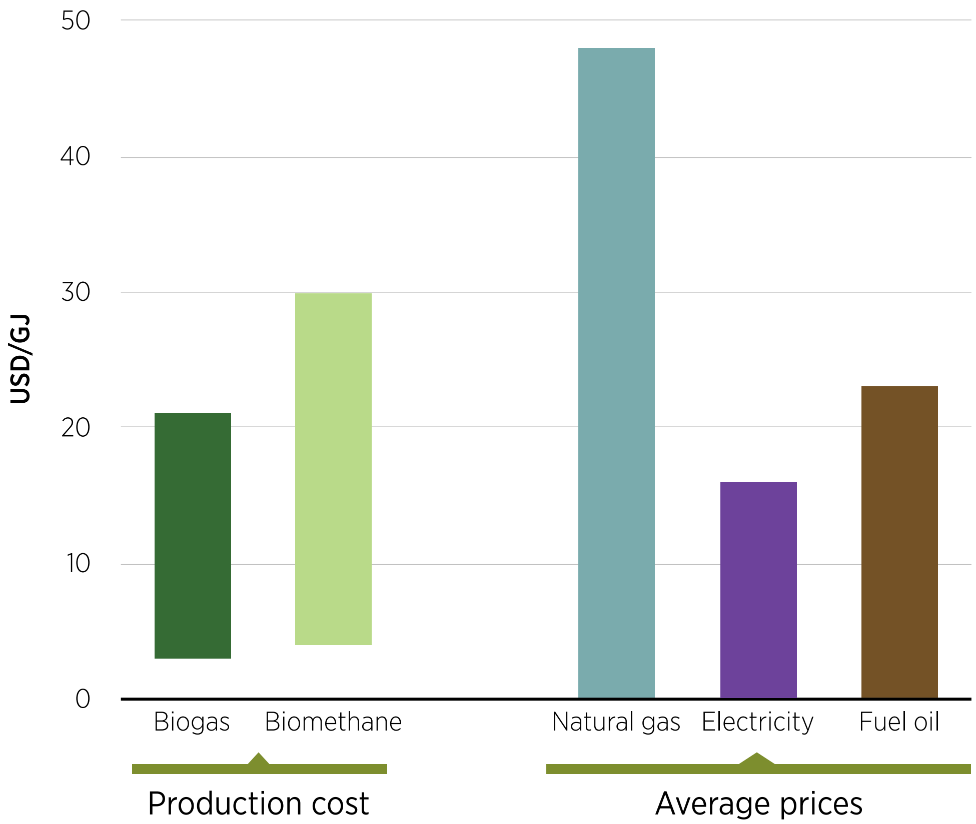
Infrastructure

- District heating networks
- Gas grids
- Other transportation and distribution infrastructures

Biomass-based heating. ©Dizfoto@Shutterstock.com

Biogas and biomethane have huge potential to meet the demand because their costs are more likely to be competitive with fossil fuel options if low-cost feedstocks are available and tax burden is low (see Figure 8.2). Two-thirds of current biogas production is used for power generation and CHP plants. Biogas and biomethane can utilise existing infrastructures and appliances (*e.g.* natural gas networks, boilers and stoves) and harness industry knowledge. Developing regions, such as Asia and Central and South America, have half of the global biogas potential. The largest sources of feedstock to meet the transition requirements are crop residues and animal manures (IEA, 2020c). These sources could also synergise with sustainable management of solid urban waste and livestock manure, which remain untapped and have huge potential (see Box 8.1).

FIGURE 8.2. Biogas and biomethane production cost (left) and average prices of natural gas, electricity and fuel oil for residential consumers in OECD countries (right)



Source: IRENA, IEA and REN21 (2020).

Wood pellets have been used for residential heating and may play an important role in transitioning heating away from fossil fuels when feedstocks can be sustainably sourced (*e.g.* from forestry and agricultural residues). Wood pellets can be used in both decentralised applications and combined with a district heating system, with possible competitive costs compared to natural gas. For example, the delivered cost of wood pellets for domestic use in Europe was around USD 16/gigajoule (GJ) in 2018, showing competitiveness over residential fossil gas, the price of which was between USD 14/GJ and USD 35/GJ, depending on the levels of VAT and other taxes (Bioenergy Europe, 2019; UK BEIS, 2020). The production and use of wood pellets for heating have been growing, with 9 million tonnes produced for heating applications in 2019 (Bioenergy Europe, 2021). The European Union and North America are major producers, accounting for more than half of the world total pellet production in 2020. China is another main producing country. It produced around 20 million tonnes of pellet in 2020, accounting for around 30% of the world total (Bioenergy Europe, 2021; Wang, 2021).

District heating systems can be an enabling infrastructure for supplying bioenergy heat for buildings. District heating networks can provide cost-effective solutions compared to decentralised heating appliances using fossil fuels or electricity, depending on many factors such as gas price and discount rates, etc. The deployment of district heating becomes more likely in highly populated areas with high heating demand. District heating networks can be deployed to service a group of buildings or a whole district and it is easy to integrate biomass boilers or bioenergy-based CHP plants (IRENA, IEA and REN21, 2020). Currently, district heating networks only contribute to 3% of total final energy consumption, with 9% from renewables (mainly biomass). To achieve the 1.5°C target, they would need to provide 5% of total final energy consumption by 2050, with 90% from renewables (IRENA, 2021b).

Box 8.1. Waste to energy: Utilising solid urban waste and manure to produce biogas

Waste management is becoming an increasingly difficult problem in the world as rising populations and higher living standards increase waste volumes. The World Bank estimates that globally waste quantities are set to rise from some 2.0 billion tonnes in 2016 to 3.4 billion tonnes in 2050. Properly treating the waste and minimising potential impacts could be challenging and costly.

Municipal solid waste (MSW) contains a portion of biomass-based materials – food and vegetable wastes, used wood and textiles – plus some organic materials and inorganic wastes. The organic composition can be around 50% to 80% of total MSW, depending on the location of production and on the prosperity of the city. For example, food organic components accounted for 63% of waste in Beijing and 22% of the waste in Amsterdam. The organic portion of MSW can produce biogas through the anaerobic digestion process. While measures have been taken to reduce waste production and reclaim and re-use or recycle, the remaining parts, including the organic portion, are disposed of in landfills. Landfill gas is the lowest-cost biogas source. It can be captured and used for power generation or be purified to methane used as a transport fuel or injected into the gas grid.

Manure from farms can also provide sustainable feedstock for biogas production. Utilising manure to produce biogas can reduce fugitive methane emissions from open slurry holding tanks, reduce smells, and minimise pollution effects on rivers and wells. While crops provide feedstock for more than 90% of biogas produced in Europe, manure contributed to more than two-thirds of biogas feedstock in China. Studies estimate that the potential of manure-based biogas could be upgraded to produce 250-370 billion cubic metres of biomethane. This could replace all the natural gas consumption of China and India.

Waste-to-energy can play an essential role in accelerating the energy transition and addressing the issues related to waste treatment. Policies should consider waste reduction, re-use and recycling and help countries move towards a circular economy that optimises material use and minimises associated GHG emissions.

Source: World Bank (2018b), IRENA (2021d), IEA Bioenergy (2021c), World Biogas Association (2019).

8.3. BARRIERS TO DEPLOYMENT

A number of barriers are impeding further uptake of modern bioenergy systems for heating buildings. **Weak policy attention given to renewable heating in buildings** remains a significant barrier, affecting all renewable heat, including bioenergy, the largest renewable heat source. In 2020, only 19 countries set renewable heat targets, compared to 137 countries with renewable energy power targets (REN21, 2021).

Higher up-front costs of biomass boilers compared to gas or oil systems is another major barrier. For example, the average initial costs of a residential-scale biomass (wood-pellet) boiler can be three to seven times the cost of oil or gas-fired boilers in the United Kingdom. In China, biomass boilers used for district heating and industrial heat cost almost twice as much as gas boilers. In most cases, the production cost of biomethane is higher than natural gas, depending on the region. If using the least expensive biomethane to meet 10% of gas demand, the cost of biomethane could be 4 times higher than natural gas in North America and 1.2 times higher in developing Asia (IEA, 2020c).

Lacking skilled workers for operation may reduce the performance of biomass heat technologies. Developing successful bioenergy projects requires qualified and experienced people to plan, design, execute and provide continuous operation and maintenance. Although technologies for producing low-temperature heat from biomass for use in buildings are well developed, systems must be designed and operated professionally to ensure that the system works properly, such as fuels to match the appliance and a cost-effective operation. An unskilled operation may reduce the system efficiency and cause worse air pollution. For the same reason, poor quality appliances or biomass fuels can also halt deployment.

Lack of district heating infrastructure can also be a barrier to scaling up bioenergy heat for buildings in dense urban areas. This is linked to other barriers related to district heating networks, such as high capital investment and uncertainty of heat demand. When solid biomass such as pellets, woodchips and other agricultural and forestry residues are used for a district heating system, heat demand may require considerable space for fuel storage and handling, which may not be convenient in urban situations and could limit deployment. Biomass heating using agricultural and forestry residues that are seasonally available would require sufficiently large spaces for feedstock storage.

Sustainability concerns are among the main barriers. Solid biomass combustion can also emit various **air pollutants** that negatively affect human health. In Europe, biomass burning has been identified as one of the major air pollution sources. In the best cases, these emissions can be maintained within acceptable limits, but emissions levels vary significantly according to the type of heating system, how the system is operated and the characteristics of the fuel used. Detailed discussion and examples can be found in Chapter 2. Other sustainability concerns related to feedstock supply as well as international trade are discussed in chapters 2 and 3.

8.4. POLICIES AND MEASURES

A ban on fossil fuel heating fuels and boilers can create a market opportunity for low-carbon fuels, including bioenergy. A number of national and subnational governments have either announced or implemented progressive restrictions and eventual phaseout of fossil fuel heat and related appliances. For example, Denmark, Norway and Sweden have banned new oil-fired boilers in residential properties. In the United Kingdom, new homes will have to be built with low-carbon heating sources starting in 2025 (Committee on Climate Change, 2019). Seattle (United States) announced a ban on fossil fuel for heating on new construction in 2020 (Derrick, 2020). However, a ban on fossil fuel heating may not be feasible for some contexts and should avoid increasing the energy poverty of poor households without providing affordable clean heating options.

Obligations and targets can also increase bioenergy heat by regulating the percentage of biomethane to be included in the natural gas grid. For example, Denmark aims to achieve 100% green gas (*e.g.* biomethane, green hydrogen) in the gas grid (Scarlat, Dallemand and Fahl, 2018). **Financial support such as grants** can support the deployment of bioenergy for buildings. In 2019, the New Zealand government released a subsidy scheme, "Warmer Wiki Homes", providing grants for building insulation improvement and renewable heating, including covering 80% of an efficient biomass burner for heating (EECA, 2019). France's *Fond Chaleur* (Heat Fund), in place since 2009, offers subsidies for residential, commercial and industrial renewable heat, including small-scale biomass applications. The subsidy aims to increase the uptake of renewable heat by pushing the price of renewable heat 5% below fossil-fuel alternatives (IRENA, IEA and REN21, 2020).

Regulation and standards on appliances help to ensure product quality, low emissions and high levels of energy efficiency on the market. The Ecodesign Directive and Energy Labelling Directive set requirements on energy-related products in the European Union, including solid fuel boilers. All biomass boilers with a rated heat output of 70 kilowatts should be labelled on an energy efficiency range from A (most efficient) to G (least efficient). All biomass boiler manufacturers and suppliers must meet emission limits such as carbon monoxide, nitrogen oxide and organic gaseous compounds (European Commission, 2018a). Strict energy regulations within **building codes** are also widely used to improve the energy performance of both new and refurbished buildings. Building codes can be used to incentivise the use of renewable heat, including bioenergy, by setting requirements on building performance in terms of reduced GHG emissions.

Various policies can help deployment of district energy networks. **Connection mandates** for new developments and public buildings can support the expansion of district energy networks and ensure heat demand. For example, all new developments in Amsterdam (the Netherlands) are required to connect to district heating networks. All municipal buildings in Oslo (Norway) are also required to have a district heating connection unless they prove to have lower emission options. **Subsidies, grants and other financial incentives** can also mitigate the high upfront cost of district heating networks. For example, the German government launched a subsidies scheme called District Heating Network 4.0 in 2017. Utilities and co-operatives could apply for grants from this scheme to cover up to 60% of the costs of feasibility studies and 50% of investment in new networks (Epp, 2017).

Barriers, policies and examples on bioenergy use for heat in buildings are summarised in Table 8.1.

TABLE 8.1. Barriers and policies for bioenergy heat in buildings

Barriers	Policies	Examples of policies and programmes
Weak policy attention	Obligations, targets, ban on fossil fuel heating	Denmark, Norway, Sweden, United Kingdom Seattle (United States)
High upfront cost and fuel cost	Financial and fiscal support	France's *Fond Chaleur* (Heat Fund), New Zealand's "Warmer Wiki Homes"
Poor quality Lacking skilled workers for operation	Regulation and standards on appliances Quality standards on fuels Training	European Union's Ecodesign Directive and Energy Labelling Directive
Lack of district heating infrastructure	Connection mandates Subsidies, grants and other financial incentives	Amsterdam (Netherlands), Oslo (Norway) German's District Heating Network 4.0

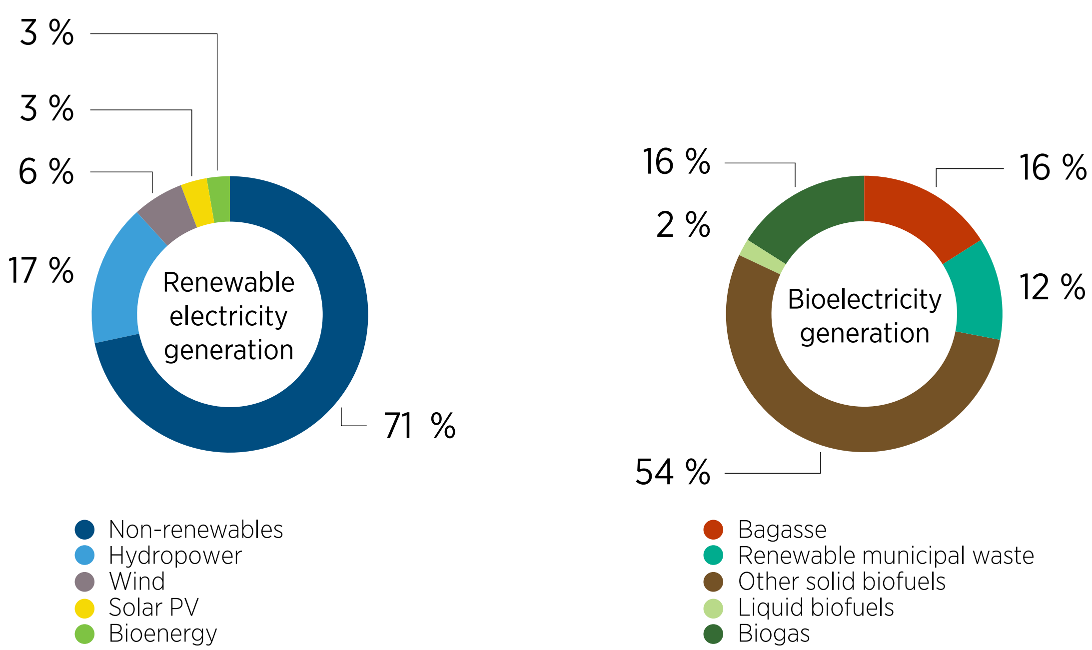
9. SUSTAINABLE BIOENERGY FOR ELECTRICITY PRODUCTION

9.1. BACKGROUND

In 2020, electricity generation contributed almost 40% of global total energy-related emissions. Renewables accounted for 29% of global total electricity generation, most of which comes from hydropower, wind and solar PV (see Figure 9.1). Bioenergy only contributed to around 2% of total power capacity and 3% of electricity generation (around 718 terawatt hours). Bioenergy electricity doubled from 2009 to 2019. China, Brazil, India, the United Kingdom, the United States and the European Union have the largest installed capacity, accounting for more than three-quarters of the global total. Within Europe, Finland, Germany, Italy, Sweden and the United Kingdom have the largest installed capacity.

Solid biofuels, such as renewable municipal waste, bagasse, pellets and woodchips, contributed almost 90% of the total installed capacity (see Figure 9.1). This can be translated to one-third of the global total solid biomass supply. China accounted for 44% of the total installed capacity of renewable municipal waste generation. For other solid biofuels such as agricultural and forestry residues, pellets, and woodchips, China, Europe, India and the United States accounted for three-quarters of global capacity or two-thirds of electricity generation in 2019. Within Europe, Denmark, Finland, Germany, Sweden and the United Kingdom have the largest pellet and woodchip-based installed capacity, accounting for two-thirds of Europe's total.

FIGURE 9.1. Share of bioenergy in electricity generation by feedstock, 2020



Based on: IEA (2021b), IRENA (2021a).

Biogas generation accounted for a smaller share, with global installed capacity reaching 20 gigawatts (GW), doubling the level in 2010. Brazil, China, the European Union, the United Kingdom and the United States accounted for more than 86% of total biogas installed capacity in 2020. Germany alone contributed 37% of the global total, followed by the United States (11%), the United Kingdom (9%), Italy (7%) and China (4%). Two-thirds of global biogas production is used for power generation: half for electricity generation only and another half for CHP (IRENA, IEA and REN21, 2020).

Liquid biofuels have also been used for power generation. Almost all of these plants are located in EU member countries and the United States. Italy and Sweden contributed 80% of the global total, followed by Germany (10%), the United States (5%) and Belgium (2%).

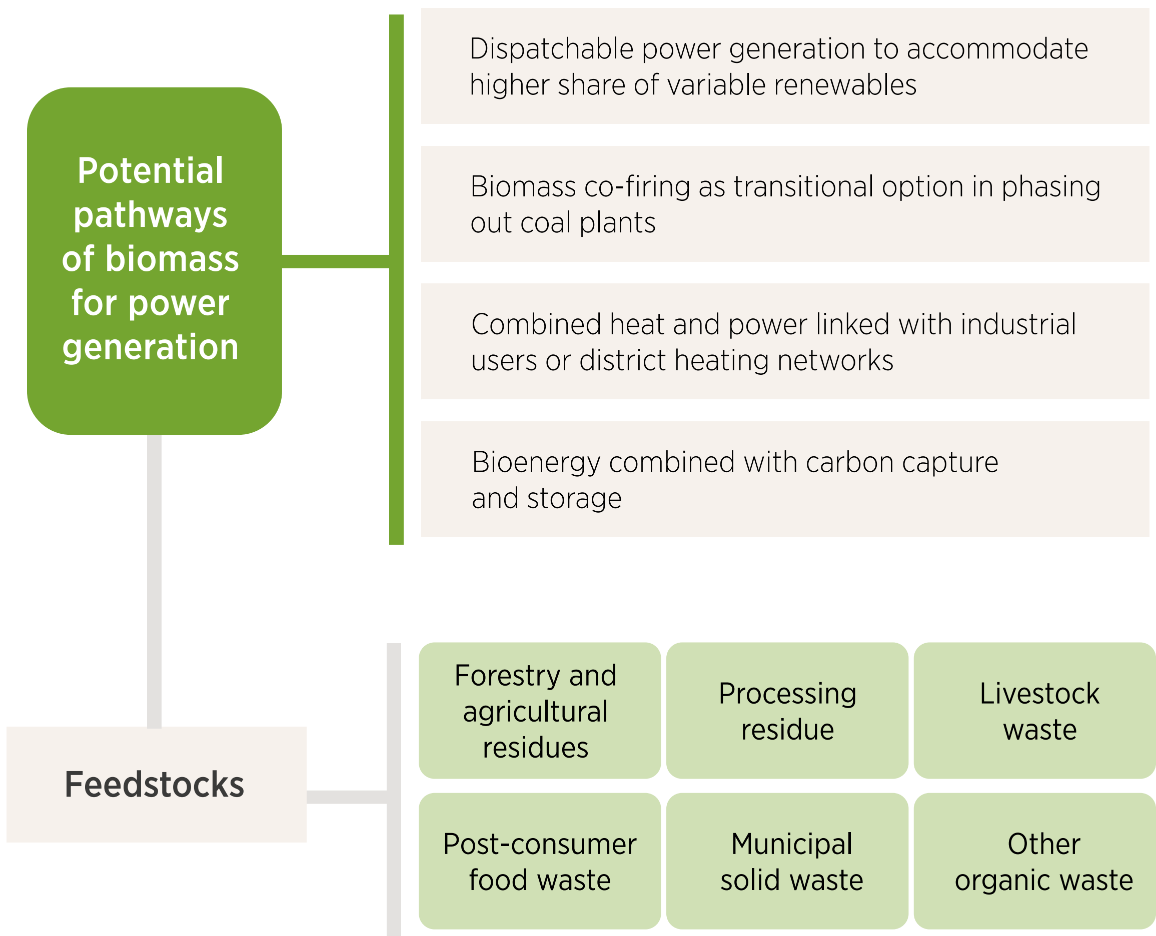
In 2020, bioenergy electricity increased by 6.7% compared to the previous year. China and Europe contributed to over half of bioenergy-based electricity. In 2020, cumulative biomass generation capacity reached around 30 GW, including 5 GW of new installations. Forestry and agricultural residues-based plants accounted for more than half of total bioenergy electricity generation, followed by MSW.

The use of internationally traded pellets and other solid biomass for electricity generation has been growing recently. Countries such as Denmark, Japan, Republic of Korea, Netherlands and the United Kingdom are the major importers, while Russian Federation, Viet Nam and the United States are the major exporters. However, international trading on pellets for power generation could raise concerns about sustainability (see Chapter 3).

9.2. OPPORTUNITIES

Bioenergy for power generation may have a role in achieving the net zero target. However, bioenergy electricity generation should be limited to projects that use low-cost and sustainably-sourced residues and waste, provide dispatchable electricity, are combined with heat or BECCS, or that act as a transitional fuel by co-firing in existing power facilities (see Figure 9.2). In the context of the energy transition, fossil fuel electricity will need to be phased out. The power grid will have a higher share of variable renewable electricity produced from solar and wind. According to IRENA's 1.5°C Scenario, renewables will account for 90% of electricity generation by 2050, including 63% from variable renewable electricity (compared to 10% in 2018). This will require flexible renewable options to ensure system stability, for which bioenergy electricity could provide multiple benefits and services. For example, one study suggests that biogas-based flexible bioenergy generation could reduce 10% to 18% of the carbon footprint of electricity in Germany (Dotzauer *et al.*, 2022)

FIGURE 9.2. Conditions that bioenergy power generation projects need to meet to ensure prioritised use of limited biomass feedstock



Box 9.1. Major co-firing technologies

Biomass co-firing includes three major technologies:

- Direct co-firing is the simplest, cheapest and most common option. Biomass can either be milled jointly with coal *(i.e.* typically less than 5% in terms of energy content) or pre-milled and then fed separately into the same boiler. Common or separate burners can be used, with the second option enabling more flexibility with regard to biomass type and quantity.
- Indirect co-firing is a less common process in which a gasifier converts the solid biomass into a fuel gas that is then burned with coal in the same boiler. Though more expensive because of the additional technical equipment *(i.e.* the gasifier), this option allows for a greater variety and higher percentages of biomass to be used. Gas cleaning and filtering are needed to remove gas impurities before burning, and the ashes of the two fuels remain separate.
- Parallel co-firing requires a separate biomass boiler that supplies steam to the same steam cycle. This method allows for high biomass percentages and is frequently used in pulp and paper industrial facilities to make use of by-products from paper production, such as bark and waste wood.

Source: IEA-ETSAP and IRENA (2013).

Biomass co-firing offers potential as a transitional option to reduce the CO_2 emissions of coal power plants and avoid stranded assets. Coal power plants can usually last for three to four decades before they are decommissioned or phased out. When abundant low-cost residues or waste can be sourced locally and sustainably and existing coal power plants can be utilised without major capital investment, co-firing may provide low-cost options and contribute to other benefits, such as additional income and clean air.

CHP can increase the efficiency and economics of biomass power generation or biomass cofiring plants. The efficiency of steam turbines in biomass power generation-only plants can range between 10-15% to 30%, which is lower than fossil fuel options that can be over 50% for modern combined cycle gas turbines plants and 40% for modern coal plants (IRENA, 2019d). The overall efficiency of biomass CHP can reach around 70% to 90%, more than doubling the efficiency of biomass power generation-only plants or co-firing plants (IEA-ETSAP and IRENA, 2015). Biomass CHP can be based on all kinds of biomass feedstock and commonly uses biomass and biogas. The European Union and the United Kingdom have deployed more than 1 000 such CHP plants. In the European Union, biomass accounted for 18% of fuel used for CHP in 2014, half of which was from solid biofuels, followed by biogas and renewable waste and around 1% from biofuels (Padinger, Aigenbauer and Schmidl, 2019).

Moreover, BECCS in power generation and industry would need to deliver negative emissions needed in achieving the 1.5°C target. BECCS has a number of different technology pathways (see Box 9.2). According to IRENA's 1.5°C Scenario, BECCS would need to contribute 14% (4.5 $GtCO_2$) of the total needed carbon emission abatement by 2050 (see Figure 9.3). From 2021 to 2050, BECCS for power and heat plants would need to remove 36 $GtCO_2$ (cumulative) (IRENA, 2021b).

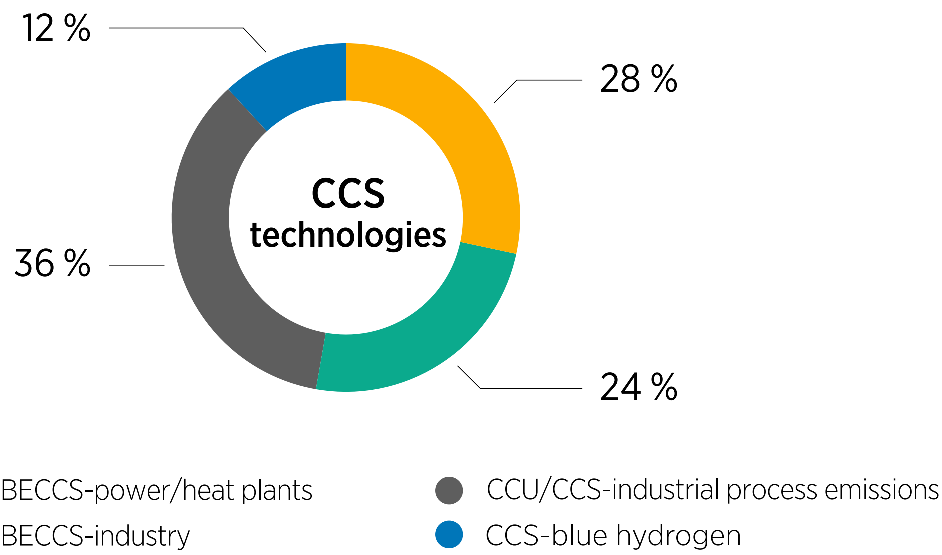
Box 9.2. BECCS technology options

Some BECCS technology options may include:

- Post-combustion capture uses solvents (typically amines) to strip CO_2 from the flue gases. The CO_2 is separated by heating and then compressed for transportation.
- Oxy-fuel combustion supplies pure oxygen for the combustion process, producing a concentrated CO_2 stream, which can be captured and then purified via condensing.
- Pre-combustion capture requires the conversion of the fuel into gaseous form, producing a mixture of hydrogen and CO_2.

Source: Donnison *et al.* (2020).

FIGURE 9.3. Share of different CCS options in total carbon removal needs in the 1.5°C Scenario



Note: CCS = carbon capture and storage; CCU = carbon capture and utilisation.
Source: *IRENA (2021b).*

While there are a few BECCS projects based on ethanol production and dozens planned and in development, mainly in the United States, bioenergy power plants based BECCS still remain at the demonstration stage with few projects in the pipeline. In Sweden, the Stockholm Exergi BECCS project plans to be in operation by 2025. This project is based on biomass CHP and designed to capture a maximum of 0.8 $MtCO_2$ per year. In the United Kingdom, the largest biomass power plant, Drax Power Station in Yorkshire, announced its plan to build a BECCS facility by 2027, capturing more than 4 $MtCO_2$ per year. In the United States, Clean Energy Systems' BECCS project is located in California's Central Valley. It aims to capture 0.32 $MtCO_2$ per year and to be in operation in 2025 (Global CCS Institute, 2021).

9.3. BARRIERS TO DEPLOYMENT

Supply chain and infrastructure are major barriers for biomass power generation, especially those that rely on bulk biomass such as residues and waste. Agricultural and forestry residue-based feedstock are seasonal and, therefore, the feedstock market price may fluctuate in a wide range. In many contexts, smallholders are the majority of potential suppliers for agricultural and forestry residues and animal manure. To secure a large and stable feedstock for biomass power plants or CHP projects will require the management of a large number of suppliers from different sectors, increasing the complexity and challenges. Pre-treatment through washing, drying, thermal treatment and others may be used to improve the energy density of bulk biomass and mitigate the transport cost. It could also improve the efficiency of biomass combustion. However, this would require relevant infrastructure and additional costs.

The cost of biomass generation can be high and less competitive than fossil fuel and other renewables such as wind and solar PV. Co-firing costs can be high due to the need for additional transport and pre-treatment. For example, in China, the cost of agricultural residue-based electricity generation is 80% higher than coal-based electricity. Co-firing of biomass in existing power plants at 25% could increase an additional 5% to 20% of the cost per kilowatt hour (KWh) compared to coal electricity, depending on the condition of coal plants and biomass feedstocks (Li *et al.*, 2021). The co-firing retrofitting also needs to be carefully designed to avoid technical issues, such as plant outage or additional operational requirements.

Financing bioenergy generation or CHP projects can be challenging due to potential technology and contractual risks coupled with market uncertainties. Investors may be concerned about the long-term economic supply of sustainable biomass feedstock, making financing difficult for biomass generation and CHP projects. The complex contracting of biomass CHP is another reason for the financing issue. Receiving financing for CHP usually requires not only a secured electricity off-take agreement and fuel supply contract but also a contract for the supply of heat. Preparing and submitting these contracts within a given period for competing financing opportunities could be complex and discourage developers.

For BECCS there are significant **technical, logistical and economic** challenges to be overcome simultaneously for both bioenergy supply and use and in the CCS elements, so this is doubly challenging. BECCS projects require additional investments in the infrastructures and operation costs for capturing, transporting and storage of CO_2. The investment can be very high, but the profitability of projects is not clear, making BECCS unlikely to be economically viable in the absence of incentive measures (Yang *et al.*, 2021). Including negative emissions in ETS schemes may have difficulty in implementation under current conditions (Olle *et al.*, 2020).

Most importantly, large-scale bioenergy power generation CHP or BECCS projects may cause sustainability risks, including GHG emissions, biodiversity loss, and increased water consumption, among others. These potential sustainability risks are discussed in Chapter 2. Other barriers include the issues of feedstock quality and skills of workers. If feedstock is not of high enough quality, co-firing biomass with coal may greatly increase the PM emissions compared to single combustion of coal (Jiang *et al.*, 2022). A high share of biomass for co-firing may also reduce power plant efficiency or electricity output.

9.4. POLICIES AND MEASURES

Bioenergy power production is often included within renewable generation support schemes and could benefit from widespread supporting policies, including FITs, renewable portfolio standards and power purchase agreements. FITs can tackle the high cost of bioenergy generation and possibly provide an assured electricity income. They offer a long-term agreement that guarantees a price per unit of output and feed-in-premiums, which offer a premium tariff and wholesale electricity prices. Such mechanisms have been widely used to promote bioenergy generation in Germany, Japan and the United Kingdom. In Germany, the FIT scheme provides a higher rate for bioenergy CHP plants.

A number of emerging and developing economies have FITs for biomass generation. For example, China has provided FITs for bioenergy (*e.g.* forestry and agricultural residue, MSW, landfill captured biomethane, biogas) generation projects since 2006, with complimentary financial and fiscal support such as subsidies to grid infrastructure for project connection and favourable taxes (NDRC, 2006; NEA, 2021). In Viet Nam, the government announced a FIT policy for biomass generation in 2014 and further revised it in 2020 to raise the biomass CHP from USD 0.058 per KWh to USD 0.070 per KWh (New Climate Institute, 2020). In support of this country's target of biomass energy accounting for 2.1% of total energy demand by 2030, the Kenyan government released the Feed-in-Tariff Policy on Renewable Energy Resource Generated Electricity in 2021. According to this policy, both biomass and biogas power generation plants can receive USD 0.095 per KWh for 20 years (Ministry of Energy, Kenya, 2021).

Subsidies and grants can also be used to encourage sustainable use based on the local context. For example, China provided USD 387 million (CNY 2.5 billion [Chinese yuan renminbi]) for biomass power generation. Biomass CHP and small-scale plants will be prioritised to receive the subsidies. The policy also encourages local government to support and improve the needed infrastructure for agricultural and forestry residues and MSW, including collection, storage, transportation and pre-treatment, to improve the cost competitiveness (NEA, 2021). In 2021, a BECCS project in Sweden developed by Stockholm's energy company Stockholm Exergi received funding from the EU Innovation Fund (Smart City Sweden, 2021).

Renewable obligations such as renewable portfolio standards (common in the United States) and other renewable obligations can help plants owners to earn additional income from the value of traded certificates. Biomass projects were included in Republic of Korea's renewable obligation and certificate trading scheme.

The use of auctions to award long-term PPAs has become a very common and effective tool for promoting renewable generation and helping drive renewable generation costs down (especially for wind and solar) (IRENA, 2019e). Separate auction schemes for variable renewables (*e.g.* solar and wind) and dispatchable renewables (*e.g.* biomass generation) can help to recognise the benefits of bioenergy-based electricity to provide flexibility to power systems.

A blending mandate for biomass co-firing in coal power plants may bring multiple benefits. For example, the government of India announced a policy to mandate a 5% blending of biomass pellets with coal for three categories of thermal power plants, starting from October 2022. Within two years, the blending rate will rise to 7% for two categories of plants (Varadhan, 2021). This policy comes with a background that burning crop residues by farmers has caused significant air pollution in the country. Studies estimated that around 516 million tonnes of crop residues were generated during 2017-2018, and 22% of it was burnt by farmers (Venkatramanan *et al.*, 2021). For example, crop residue burning in Punjab and Haryana states accounted for around one-third of the air pollution of Delhi in October and November 2021. Over USD 300 million was invested in stopping farmers from burning crop residue but failed to have a measurable impact (Bhardwaj and Arora, 2021). In this context, mandatory blending of biomass for coal power plants may build synergies between decarbonisation of coal power plants by biomass co-firing and mitigating the air pollution issue. Similarly, Indonesia also plans to mandate biomass co-firing for coal power plants as an intermediate solution for the phaseout of coal power plants (Reuters, 2021a). However, biomass co-firing policies should also not be contradictory with the phaseout of fossil fuels that are required for the energy transition.

Some business models are also discussed for promoting BECCS, such as tradable certificates for negative emissions or BECCS projects to bid for a certain volume of negative emissions based on government commitment and procurement. However, policy measures to incentivise BECCS should consider the potential impacts on the ecosystem depending on the scale and site (Olle *et al.*, 2020).

However, a policy framework to support the deployment of bioenergy generation should be carefully designed to avoid unwanted results, such as a policy that contradicts climate change targets or takes sustainability risks. For example, policies should not encourage biomass for power generation-only projects due to the limited feedstock. Instead, the policies should maximise synergies and co-benefits of bioenergy generation, such as synergies with waste management and intermediate solutions to decarbonise existing coal power plants before they are decommissioned.

TABLE 9.1. **Barriers and policies for bioenergy in power generation**

Barriers	Policies	Examples of countries and regions with policies and programmes
Weak supply chain Lack of infrastructure	Subsidies and grants	China
High cost Lack of finance access	FITs, subsidies and grants, renewable obligations, auctions Mandatory biomass co-firing	China, European Union, Germany, India, Indonesia Japan, Kenya, Republic of Korea, United Kingdom, United States, Viet Nam India, Indonesia
Technical, logistical and economic challenges related to BECCS	Funding to demonstration projects, innovative business models	European Union
Sustainability risks	Sustainability governance and regulations	European Union

10. BIOMASS FOR INDUSTRY

10.1. BACKGROUND

Industry is the largest energy-consuming sector, accounting for around 38% of global total final energy consumption in 2020. Three main energy-intense industries – iron and steel, chemicals, and cement – contributed to around 44% of the industrial sector's total energy demand and 70% of its total CO_2 emissions (IEA, 2021b). In 2020, biomass contributed to around 7% of the total final energy consumption of industries. Biomass has three main uses in industry: as biomass-based CHP to provide heating and electricity, for industrial process heating, and as feedstock to replace fossil fuels – for example, in the chemical sector.

Most of the current bioenergy use in industry is concentrated in heat for cement and biomass-based industries. In 2020, bioenergy and renewable MSW provided 3% of the cement industry's heat consumption globally. The pulp and paper, sugar, and food and wood industries have reached a higher share of biomass heat. For example, bioenergy provided the largest share of energy for the global pulp and paper industry, accounting for 42% of total final energy consumption in 2019.

Bagasse cogeneration has been widely established in main sugarcane-producing countries, including Brazil and India, the largest producers (To, Seebaluck and Leach, 2018). Brazil is the most prominent current user of industrial bioenergy (1.6 EJ) through the use of heat produced in the cogeneration of electricity from sugarcane bagasse in sugar production, as from wood residues in pulp and paper plants. Bagasse-based cogeneration has been widely deployed in the developing world. In sub-Saharan Africa, Ethiopia, South Africa, Sudan and Zimbabwe have installed more than 100 MW of bagasse capacity. In Asia, Indonesia, Pakistan, the Philippines and Viet Nam and have installed more than 200 MW of capacity. In Latin America, Guatemala installed more than 1 GW of capacity, and Mexico installed around 0.8 GW (IRENA, 2021a).

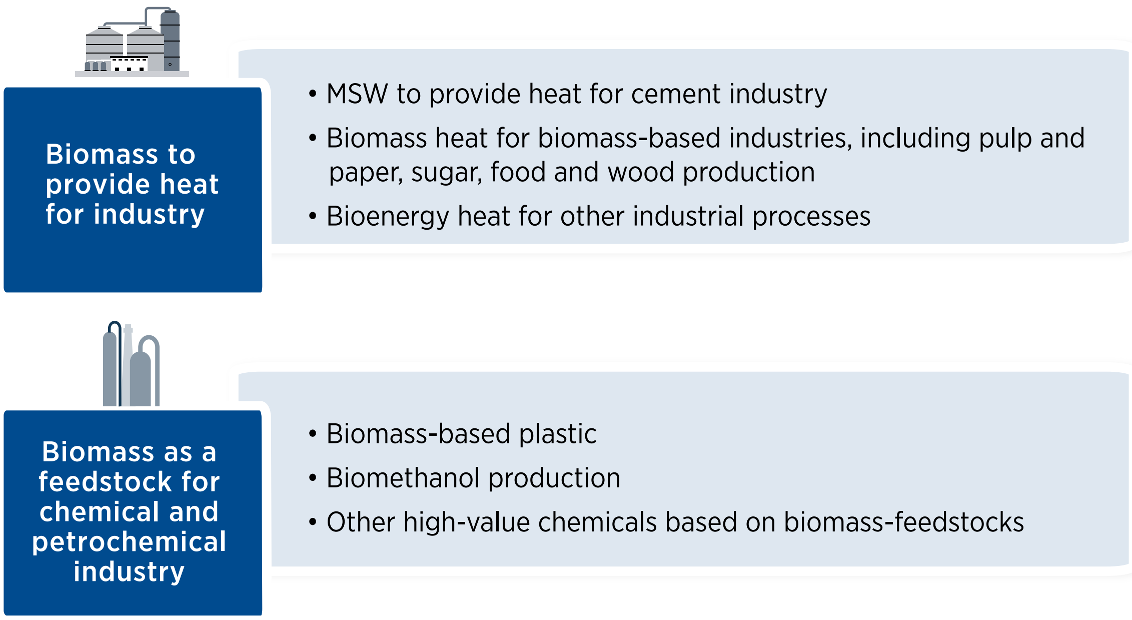
Biomass as industry feedstock is currently used on a very limited scale. In 2021, global production of biomass-based plastic (bioplastic) was around 2.42 million tonnes, contributing to less than 1% of global plastic production. Biodegradable plastic accounted for 64% of total production capacity and bio-based non-biodegradable plastic made up the rest, 36%, of global production in 2021. Almost half of the bioplastic is used for packaging purposes. Other market segments include catering products, consumer electronics, automotive, agriculture, horticulture, toys, and textiles. Asia and Europe contributed around three-quarters of global production capacity in 2021, and the remaining share was mainly from North and South America (European Bioplastics, 2021).

Methanol is another key chemical product, contributing to 10% of total chemical emissions. Currently, almost all methanol is produced by fossil fuels. Methanol can be produced by biomass feedstocks, including forestry and agricultural waste and by-products, biogas from landfills, sewage, MSW, and black liquor from the pulp and paper industry. Currently, biomass-based methanol production is less than 0.2 million tonnes (Mt), accounting for a negative share of global total methanol production (98 Mt per year) (IRENA and Methanol Institute, 2021).

10.2. OPPORTUNITIES

Bioenergy for industrial process heat and industrial feedstock will need to increase significantly in the coming decades to achieve the energy transition. These biomass uses for the decarbonisation of industry would need billions in investment every year in the next three decades (IRENA, 2021b). The main opportunities include bioenergy-based CHP to provide heat and power for industries, biomass-based feedstock for the chemicals sector (such as bioplastics and biomethanol production), biomass to provide high-temperature heat for cement, as well as feedstock to replace coke and coal in iron and steel in the short term (see Figure 10.1).

FIGURE 10.1. Potential opportunities of bioenergy for industrial decarbonisation



Bioenergy-based CHP will need to continue expanding to provide sustainable low-cost renewable heat for biomass-based industries, especially in developing countries, where production of these industries is likely to keep increasing. In rural and developing areas, efficient and sustainable biomass and biogas can be an essential facilitator of economic activities providing heat for drying, distillation, dairy and cottage industries. For example, Sri Lanka's Elpitiya Plantations PLC, a leading tea producing company, uses estate-grown biomass for the thermal energy required for tea and rubber production processes and operates with 100% renewable electricity (IRENA Coalition for Action, 2021). In Lugazi (Uganda), the largest industry, Sugar Corporation of Uganda, installed bagasse-fired cogeneration plants with a capacity of 9.5 MW (IRENA, 2022d). In Colombia, biomass combined with solar energy has enormous potential as a renewable source for drying coffee (Manrique *et al.*, 2020).

The chemical and petrochemical sectors are some of the most energy-intensive, contributing to around 13% of total industrial energy consumption and 15% of total industrial emissions in 2020. These sectors use significant amounts of fossil fuels as feedstock and for non-energy use, consuming 10% of global natural gas and 12% of global oil (IEA, 2021b). Renewable options to decarbonise the chemical and petrochemical sectors are limited, but biomass may have the potential to replace fossil fuel feedstocks and provide renewable industrial heat for this sector.

For example, bioplastic contributes a negligible share of global production now but will need to increase to around 20% (or 73 Mt per year) of global plastic production by 2050 under the 1.5°C Scenario. In the 1.5°C Scenario, almost half of the biomass-based feedstock and fuels for the chemical and petrochemical sector is used to produce high-value chemicals, such as ethylene, propylene, benzene, toluene and mixed xylenes (Saygin and Gielen, 2021). Moreover, biomass-based methanol could also play a larger role in decarbonising the chemical industry. The production of biomethanol from the waste streams, including MSW and black liquor from paper mills, in particular offers opportunities to simplify the feedstock logistics and improve overall plant economics (IRENA and Methanol Institute, 2021).

Biomass has the opportunity to expand its industrial use by providing heat for industrial processes to replace coal and other fossil fuels for high-temperature industrial processes such as those in iron and steel and mineral processing industries. Biomass use in the cement sector can also be scaled up to replace fossil fuel for heating and may combine with CCS technologies. The cement sector is the third-largest energy-consuming industry globally (after iron and steel and chemicals), but it contributes to almost the same level of emissions as the largest emitter in the industry sector (iron and steel). Waste, including a share of renewable MSW, has been used for heating of cement plants and could almost replace all fossil fuel heat for cement production through MSW or other types of biomass.

Biomass has the potential to replace coal and coke in metal industries, such as aluminium and iron and steel. Biomass may play a role in the short term by replacing fossil fuels in decarbonising the metal industries before other renewable options, such as green hydrogen, become economical and commercially available. For example, in Brazil, charcoal (from forestry plantations) has been used as one of the main energy sources for crude iron production in the steel industry (Profor, 2017).

10.3. BARRIERS TO DEPLOYMENT

Low policy attention to biomass as fuel and feedstock for the industry is a major barrier. There are very few existing policies for biomass use in industry, especially for the chemicals sector. The high upfront cost is another major barrier for biomass use in industries, which has a capital-intensive nature, even if it brings substantial economic and environmental co-benefits over the project lifecycle. Industry can be wary of prioritising capital expenditure in such projects rather than on fossil fuel options.

Fuel cost is high as biofuels must be collected, stored and transported, raising the costs to further exceed those of fossil fuels and discouraging their use outside bio-based industries. For example, costs rise substantially for large-scale operations such as high-temperature industrial processes, most of which currently use low-cost coal or coke as an energy source.

The high cost of biomass feedstock is also the major barrier to bioplastic and biomethanol production. For example, the cost of biomethanol is estimated to be in the range from USD 320-770 per tonne with a low-cost biomass feedstock. This cost is 1.2 to 7.7 times the cost of fossil fuel-based methanol (IRENA and Methanol Institute, 2021). Bio-based plastics also have higher production costs than fossil-based plastic products, especially in the segment of novel polymers (Wellenreuther, Wolf and Zander, 2021).

Financing bio-based solutions for the industry can be challenging given the uncertainties around returns on investment. These financing-related uncertainties are relevant to the volatility of fossil fuel prices and the risks related to supply chain and associated policy uncertainty.

Technical constraints are also a barrier to using high levels of biomass for industries requiring high-temperature heat. Although technologies, such as gasification, that can produce high-temperature heat for the industrial process exist, most bioenergy technologies in high-temperature processes have not yet been widely demonstrated. In some cases, without proper investment and infrastructure for pre-treatment, biomass fuels may have lower calorific value, high moisture content, trace elements and chlorine content when compared to conventional coal. This may disrupt the manufacturing process and even impact product quality (MPA, Cinar and VDZ, 2019).

Meeting the energy and feedstock requirements of large-scale industrial projects will call for extensive **supply chains**, which face the same issues as those for power generation and heating: dealing with suppliers from multiple sectors; unstable supply, transport, storage and pre-treatment infrastructures; worker qualifications and skills; and others. For example, a typical large-scale steel plant producing 5 million tonnes of steel a year would use some 2.5 million tonnes of coal. Replacing significant proportions of the fuel for such a plant with biomass would entail up to 4 million tonnes of biomass and, therefore, a very extensive supply chain, for which transport costs may also rise.

Sustainability risks are another major barrier for further scaling up biomass as fuels and feedstock for industry. Meeting future feedstock and fuel needs through biomass and bioenergy may negatively impact environmental and social aspects, including increased GHG emissions, threatening food security, biodiversity loss, reduced soil quality, increased water consumption, and others. These sustainability risks are discussed in Chapter 2.

10.4. POLICIES AND MEASURES

Specific targets for biomass heat for industry could secure policy certainty. Policy makers can integrate bioenergy targets with a larger industrial strategy, considering all decarbonisation solutions available, such as renewable-based electrification, energy efficiency and green hydrogen. For example, as part of the EU-RED II, the European Union required member countries to develop integrated energy and climate plans that show how they will reduce emissions from these sectors and the potential role of each technology, including for heat in industry (European Commission, 2019b). In China, the largest industrial energy consumption country, the 13th national five-year plan (2015-2020) set targets of using 30 million tonnes of modern biomass on the national level to provide residential and industrial heat (NEA, 2016).

India has provided **capital subsidies** for promoting bagasse-based cogeneration in the sugar industry. India has around 55 sugar mills and had installed around 7.5 GW of bagasse-based cogeneration as of June 2021. Under a financial scheme called Central Financial Assistance, the Indian government provides a capital subsidy (around USD 33 814 per MW) for bagasse-based cogeneration based on the surplus capacity that can be fed into the grid (MNRE, 2022).

Government **funding and grants for RD&D** of novel biomass-based technologies for industry are vital. For example, in Japan, the New Energy and Industrial Technology Development Organization (NEDO) has supported demonstration projects of biomass for industrial heat use. In Kurashiki City (Japan), waste wood is used to supply steam for an industrial complex (Renewable Energy Institute, 2018). In the European Union, Horizon 2020, a funding programme to support research and innovation projects from 2014 to 2020, provided EUR 305 million for a plastic programme, for which bioplastic is a key component (European Commission, 2018b). The Canadian government launched a "Plastic Challenge" in 2018 to provide grants (CAD 150 000 [Canadian dollars]/USD 117 840 for Phase 1 and CAD 1 million/USD 785 630 for Phase 2) for projects related to bioplastics (Government of Canada, 2021). In the United Kingdom, the national innovation agency, Innovate UK, awarded almost GBP 2 million (United Kingdom pounds; around USD 2.72 million) to support 14 projects focused on sustainable solutions for plastic packages, including research and development projects on bioplastic (UKRI, 2021). Other financial and fiscal supports (*e.g.* tax exemption) could help mitigate the high cost of bioenergy and biomass for industry. These cross-cutting measures are discussed in Chapter 6.

Regulations to guarantee the CO_2 emission reduction of industrial products could be another driver to help establish an increasing share of low-carbon products. **Mandates** for biomass-based industrial products in specific markets, such as public procurement, could also incentivise deployment. For example, in the United States, the BioPreferred Program was created in 2002 and expanded in 2018. This programme set mandatory requirements for federal agencies and their contractors to purchase specific bio-based products identified by the US Department of Agriculture (USDA). Currently, there are 139 product categories and approximately 14 000 bio-based products under the programme. This programme also includes a voluntary labelling initiative, in which the "USDA Certified Biobased Product" label on a product meets USDA criteria (USDA, 2021b).

Measures on sustainability are needed to minimise negative environmental and social impacts. These measures should be designed based on local context and may include regulation frameworks, certificate schemes, cross-sectoral co-ordination and integration, as well as clear sustainability targets. These measures are discussed in Chapter 4.

TABLE 10.1. Barriers and policies for biomass use in industry

Barriers	Policies	Examples of countries and regions with policies and programmes
Low policy attention	Targets, regulations Public procurement mandates	China, European Union, United States
High cost	Grants, subsidies	India
Low technical readiness	Funding, grants for RD&D	Canada, European Union, Japan, United Kingdom

Modern biomass co-generation power plant. ©Konstantin Romanov@Shutterstock.com

11. BIOENERGY FOR TRANSPORT

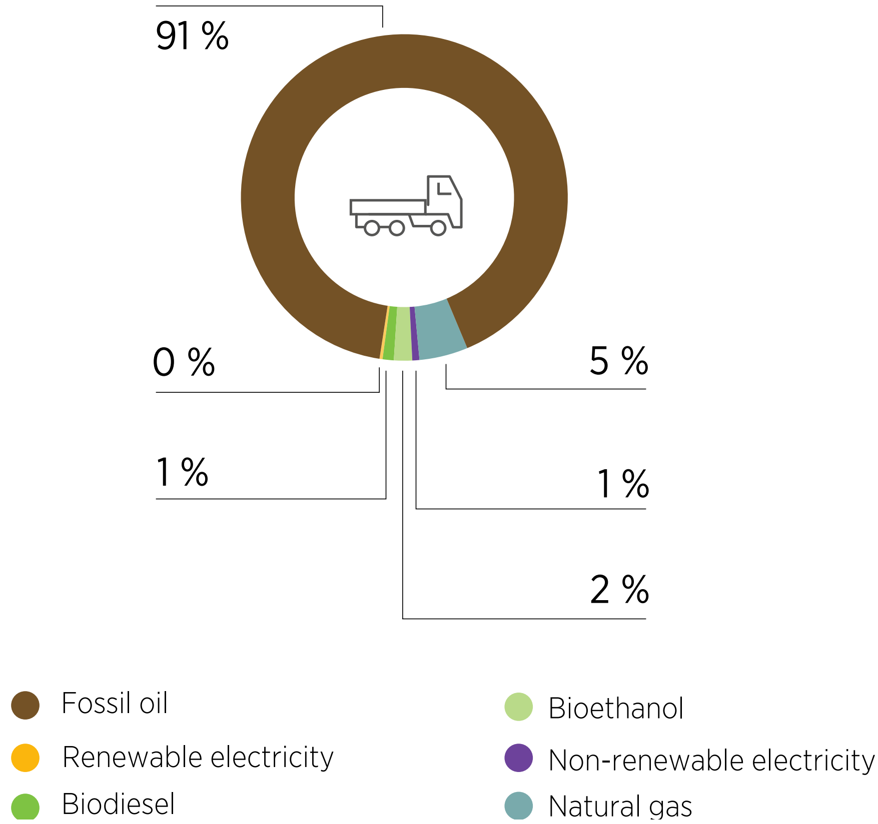
11.1. BACKGROUND

In 2020, the transport sector accounted for a quarter of global final energy consumption and around 21% of global CO_2 emissions. Road transport consumed around 80% of total energy demand, followed by shipping (11%) and aviation (8%). Fossil oil dominated the transport fuels in all subsectors. Bioenergy accounted for around 3% of global transport fuel demand, mainly in road transport (see Figure 11.1) (IEA, 2021b).

Bioenergy use for transport includes bioethanol, biodiesel and other diesel substitute fuels (HEFA or hydrogenated vegetable oil [HVO]), biomethane, and other biofuels. Because they can be used for combustion vehicles with limited technical changes, liquid biofuels are more available to decarbonise the current vehicle stock compared to other solutions (*e.g.* electric, hydrogen fuel cell). The consumption of liquid biofuels for road transport grew at around 5% per year from 2014 to 2019 and was concentrated in Europe and North and South America. However, due to the COVID pandemic, biofuels consumption experienced a 5% decline in 2020 (IEA, 2021d; REN21, 2021).

Bioethanol provided around 61% of the liquid biofuel consumption for transport. It can be produced from corn, sugarcane and other starch crops as well as from lignocellulosic biomass, and can be used as a replacement for gasoline in vehicles. The United States and Brazil produce a majority of global bioethanol and are also the major users. Bioethanol accounted for 4% of transport energy consumption in the United States in 2020 (EIA, 2021). Global trade in ethanol also exists, mainly from the United States to Brazil, Canada, India and the European Union (see Chapter 3).

FIGURE 11.1. Total energy demand in transport, by fuel, 2020



Based on: IEA (2021b), REN21 (2021).

Biodiesel provided around 33% of total biofuel consumption in transport in 2020, in the form of FAME. Biodiesel is produced from vegetable oils and fats, including waste products such as used cooking oil. In 2020, Indonesia (17%), the United States (14.4%) and Brazil (13.7%) were major biodiesel producers (REN21, 2021). The European Union is the largest importer of biodiesel for blending in transport. It imported millions of litres of biodiesel from Argentina, Indonesia and China (see Chapter 3).

Biomethane has also been used for transport but contributed a smaller share, around 0.25% of total transport fuel demand, in 2020 (IEA, 2021b). Biomethane is mainly used in the United States and Europe for road transport. The United States is the largest producer and user of biomethane transport fuel.

Some advanced technologies to promote liquid biofuel use for shipping and aviation are under development, but most are not in commercialisation yet (IRENA, 2021c). Due to limited renewable options for the decarbonisation of the aviation and maritime sectors, these biofuel technologies may have an important role in achieving the net zero targets of the transport sector.

11.2. OPPORTUNITIES

Bioenergy has an important role to play in decarbonising the transport sector for achieving the 1.5°C Scenario. Biomass-based transport fuels include bioethanol, biodiesel, biomethane and biomethanol. Liquid biofuels with sustainably sourced waste and residue feedstocks can be used for shipping, aviation and road transport. Biomethane produced from the anaerobic digestion of wastes and residues, including sewage, animal manures and liquid organic effluents, can also decarbonise road transport and the shipping sector.

Bioenergy's role in the decarbonisation of road transport and the shipping sector will need to be co-ordinated with other options such as electric vehicles and other potential renewable-sourced fuels, such as green hydrogen or green ammonia, due to the limited biomass feedstock and potential sustainability risks. In road transport, electric vehicles will likely dominate and, therefore, be prioritised in relevant policies. In the short- and medium-term, liquid biofuels produced from waste and residues will still be an option to replace fossil fuels in existing internal combustion vehicles before they are fully phased out from the market. For example, the European Commission estimated that by 2030 at least 80% of total vehicles in road transport will still have internal combustion engines (European Commission, 2020b).

However, bioenergy has a more significant role to play in aviation for achieving the 1.5°C targets. Biojet fuel is a sustainable aviation fuel that can be produced through the hydrotreatment pathways based on fats, oils and greases, and other potential biogenic feedstocks such as forest and agricultural residues, sludge, algae and waste gases (IRENA, 2021c). Biojet fuels have started development and demonstration in EU member countries, the United States and Africa. In 2016, South African Airways became the first airline on the continent to power commercial flights with biofuel produced locally and certified by the RSB (Biofuels International, 2019). BECCS may also be a relevant technology to reduce the emission of the transport sector. BECCS is discussed in chapters 2 and 9.

11.3. BARRIERS TO DEPLOYMENT

Policy uncertainty is a cross-cutting barrier to the deployment of biofuels for transport and impeded investment in advanced biofuels given the long timescale associated with projects (IRENA, 2019b). This barrier is discussed in Chapter 6. In a few countries, such as Brazil, ethanol can be economically competitive with gasoline with no subsidies. In many other countries, the higher cost of biofuels (*e.g.* bioethanol, biodiesel, biomethane and other biofuels) compared to fossil options (*e.g.* gasoline or diesel) is the main barrier limiting the deployment, considering existing fossil fuel subsidies. For example, wholesale prices, without taking taxes on drivers and users into account, are in the range of USD 14-32/GJ for bioethanol and USD 22-28/GJ for biodiesel compared to USD 9-16/GJ for fossil-based gasoline or diesel fuels (IEA, 2020b). The cost of biojet fuels produced from HEFA can be three to six times more than fossil jet fuels, depending on the oil prices and cost of lipid feedstock used for production (IRENA, 2021c).

The low technical readiness level of novel biofuel technologies is another barrier to commercialisation and scaling up deployment. For example, most advanced biojet fuels are in pilot or demonstration stages. The low technology readiness of novel biofuel technologies is related to the complexity of technical processes such as gasification, pyrolysis, hydrothermal liquefaction and others, and the availability of sustainable feedstock.

Difficulty in securing financing for large-scale demonstrations for new technologies such as novel biofuel technologies for transport is another barrier. Novel bioenergy technologies are more difficult to access and finance due to potential technology risks, coupled with market uncertainties. The demonstration of liquid biofuel production projects usually needs to be on a large scale to test their maturity and therefore requires a large investment. This makes financing for liquid biofuel projects more challenging than other projects that do not need demonstration at a large scale.

Depending on the vehicle fleet and other factors, higher biofuel blend levels can technically be accommodated in some regions, but blending regulations can inhibit this. Much higher levels (including bioethanol blends of up to 95% ethanol [E95] and pure bioethanol, or even 100% bioethanol or biodiesel with the support of flex-fuel vehicles [FFV]) can be accommodated, but this may require separate distribution channels and pumps at fuel stations, along with vehicle modifications.

Lacking necessary infrastructure is also a crucial barrier. Scaling up biofuels deployment for transport requires additional investment for necessary infrastructure for storage, transport and distribution. For example, "drop-ins" such as HVO can replace fossil fuels but still require some infrastructure. This issue becomes critical for biojet fuels because a limited number of airports have established biojet fuelling infrastructure. Infrastructure also constrains the use of blending biofuels in the United States because the number of E85 fuelling stations is limited.

A weak supply chain slows down the commercialisation of advanced biofuels, especially those based on cellulosic feedstocks. For example, HEFA is technically mature, but the production capacity of HEFA-derived biojet fuels is limited due to the finite availability of lipid or oleochemical feedstocks.

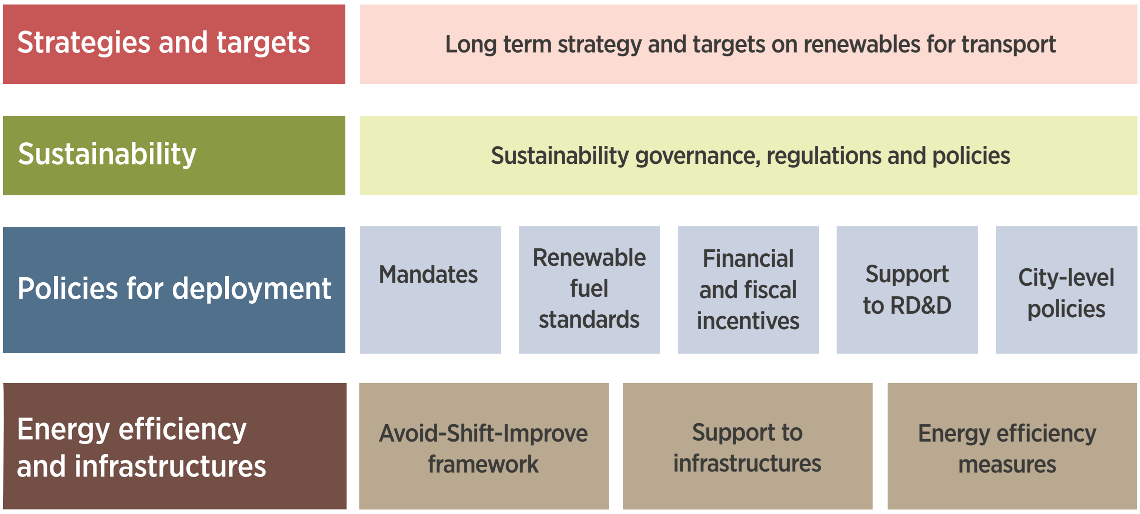
Potential sustainability risks of liquid biofuels (like all other biomass-based fuels) have been a challenge for a long time. Most of the first-generation bioethanol is produced from corn and sugar crops. Depending on different contexts, changing pasture land and forest to energy crops may increase GHG emissions and negatively impact biodiversity, water quality, soil quality, and smallholders' land rights, which are discussed in Chapter 2.

A biodiesel production plant in China. ©chinahbzyg@Shutterstock.com

11.4. POLICIES AND MEASURES

Policies for the deployment of bioenergy in the transport sector should be put in the overall policy framework for the decarbonisation of transport. The overall framework includes policies for the deployment of biofuels and other renewable options, such as mandates, financial and fiscal incentives, renewable fuel standards, support to RD&D, as well as city level policies. It also includes the long-term strategy and targets and measures to ensure sustainability. Most importantly, policy makers should put biofuels in the bigger picture that considers the "Avoid-Shift-Improve" approach, supporting infrastructure and energy efficiency measures (see Figure 11.2). This section highlights some policies that are most relevant to bioenergy deployment in transport.

FIGURE 11.2. Overall policy framework for deployment of renewables in transport



A long-term strategy integrating transport with biofuels can ensure the confidence of investors, producers and users. The integrated strategy needs to incorporate road transport and biofuel use for aviation (both domestic and international) and shipping (*e.g.* inland shipping, fishing, and ocean-going vessels). The long-term strategy should also co-ordinate the deployment of biofuel produced from sustainable feedstock with the electrification of road transport in the medium and long term. For example, biofuels may have more roles in aviation in the long term, and electric vehicles might dominate urban transport and light vehicles in many contexts.

Targets on low-carbon fuels indicate that GHG reduction can incentivise biofuels with a higher potential of avoided GHG emissions. By 2019, at least 16 EU member countries, Thailand and the United States had set targets for using advanced biofuels in the future (REN21 and FIA Foundation, 2020). The EU-RED II makes explicit provision for increasing the volume of advanced biofuels with a target of 3.5% by 2030. Seven European countries (Denmark, Finland, France, Germany, Italy, Norway and the United Kingdom) have set specific obligations for such fuels (IEA, 2020d). In 2021, the European Commission further revised RED II and released the "Fit for 55" package, including specific targets on renewables for shipping and aviation (see Box 11.1).

Blending mandates are key measures to deploy liquid biofuels for transport. They place requirements on transport fuel suppliers to use a certain share of biofuels blended with fossil fuels and can be effective if mandates are enforced and penalties are handed out for non-compliance. More than 70 countries have national or subnational-level blending mandates, most for bioethanol and biodiesel. In countries where blending regulations are in place, bioethanol and biodiesel can be blended into fossil gasoline and diesel fuel up to certain blend limits, commonly 7% for biodiesel and more than 20% for bioethanol. Blending mandates can utilise existing fuel distribution and related infrastructure and are compatible with nearly all road vehicle engines (REN21 and FIA Foundation, 2020). Brazil provides an example of biofuel blending mandates in the transport sector (see Box 11.2). In Africa, some seven countries, including Angola, Ethiopia, Kenya, Malawi, South Africa and Zimbabwe, have announced blending mandates for biofuels in the transport sector (IRENA, 2022d).

Box 11.1. Targets on biofuels for shipping and aviation in the European Union's "Fit for 55" package

In July 2021, the European Commission proposed some revisions to the current RED II and proposed new initiatives to further raise the ambition. The new revision of the RED II aims to achieve carbon neutrality in the European Union by 2050 with an intermediate target of at least 55% net reduction in GHG by 2030. It also released a "Fit for 55" package, which is part of the EU Green Deal and a plan aiming to transform the European Union into a modern, resource-efficient and competitive economy. Except for the updated targets on liquid biofuels for road transport, it includes some specific targets for shipping and aviation, including:

Sustainable aviation fuels, including advanced biofuels and synthetic aviation fuels, must meet at least 5% of aviation fuels by 2030 and 63% by 2050.

Renewable and low-carbon fuels, including electrification, advanced biofuels, and other renewable and low-carbon fuels, should represent between 6% and 9% of the international maritime transport fuel mix in 2030 and between 86% and 88% by 2050.

Source: European Commission (2021b-c).

Box 11.2. Biofuel blending mandates in Brazil

Brazil has a long history of bioethanol blending mandates. A 5% blend was first put in place in 1931. The blending mandate was later relaxed but reinstated in 1975 as part of the ProAlcohol Program. The blend level has progressively been increased and, since 2015, has been set at 27% (volume/volume) (c. 18% by energy). All standard gasoline contains this level of ethanol.

In addition, neat (hydrous) ethanol is also widely available at the pump. Since most passenger vehicles are flexible-fuel and able to use blends of bioethanol or gasoline in any proportion, consumers can also choose to buy neat (hydrous) ethanol when this is more economical.

A blending mandate for biodiesel was instituted under the National Biodiesel Production Programme in 2005. The initial level of 2% has been progressively increased and is now 12% (volume/volume) (c. 11% by energy), with the intention that this will rise to 15% by 2023. Diesel vehicles, such as fleets of buses and trucks, can go beyond this mandated level (15%) if they wish.

The National Biofuels Policy (RenovaBio) is another important policy scheme for biofuel development in Brazil. It was launched in 2017 to reduce GHG emissions and help Brazil fulfil its commitment under the Paris Climate Agreement. RenovaBio is a market-driven incentive mechanism, which transfers the social/environmental costs of using fossil fuels as an income to the production of biofuels. It gives "carbon credits" per unit of energy, increasing efficiency in the production of biofuels, certified to the individual producer based on audit and product lifecycle.

Source: ICCT and DieselNet (2019), Morandi (2020), UNICA and Apex-Brasil (2020).

Expanding the scope of blending regulation to cover aviation would help to decarbonise this subsector. For example, Norway has established obligations to use 0.5% sustainable bio-based fuel for aviation (McKinsey & Company, 2020). Sweden also recently introduced a GHG reduction mandate for aviation fuel, increasing GHG reduction targets of aviation from 0.8% in 2021 to 27% by 2030 (Biofuels International, 2021).

Programmes of FFV can have a higher blending ratio. Based on modification (*e.g.* fuel pump and injection system, control module), FFV can use both gasoline or any blend of ethanol, which could be a high level such as 85% (E85 in the United States) or even 100% (E100 in Brazil). For example, Brazil started introducing FFV in 2003 to promote bioethanol use for transport (Engler Pinto, Algate and Carbonara, 2017). The United States has more than 21 million FFV running on the road (AFDC, n.d). However, the promotion of FFV should be based on co-ordination between the availability of vehicles and fuel.

Renewable fuel standards are another policy option. In some countries where blending mandates have been put in place, fuel distributors must meet compliance with a required share of the obligation by supplying biofuels or buying certificates for each volume of biofuel acquired from other suppliers or else face a penalty. Examples include the US Renewable Fuel Standard and Californian Low Carbon Fuel Standard, as well as similar schemes in the United Kingdom (UK DoT, 2021) (see boxes 11.3 and 11.4). Moreover, low carbon fuel standards could be more effective in scaling up biojet fuel production than other policies, given that the production level of advanced biofuels for aviation remains too low (IRENA, 2021c).

Box 11.3. The US Renewable Fuel Standard

The Renewable Fuel Standard (RFS) is the most significant policy measure used to drive the use of biofuels in the United States. It led to a ten-fold increase in fuel bioethanol consumption, significant increases in biodiesel and, more recently, HVO in the US market since its introduction in 2005. Now, biofuels provide 5% of US transport fuel needs.

The RFS establishes a quota for biofuels and provides financial support to biofuel producers. An overall target of the quota was set at 36 billion gallons of biofuels/year (136 billion litres) by 2022, with separate indicative tranches for different biofuels, including cellulosic biofuels, bioethanol, biodiesel and advanced biofuels. It capped the level of corn-based bioethanol at 14 billion gallons to stimulate the production and use of other biofuels.

The scheme includes tradeable certificates. Fuel distributors must achieve a mandated level of biofuels each year (the Renewable Volume Obligation) based on their market share. To demonstrate compliance, they must obtain the requisite number of certificates, called Renewable Identification Numbers, generated when a biofuel producer makes a gallon of fuel through an approved pathway. These certificates can be obtained by selling biofuels or buying from other suppliers.

The Environmental Protection Agency can revise the required volumes annually. The overall level for 2020 was much lower than originally intended, at 20.9 billion gallons compared to the initially indicated 30 billion gallons, mainly because production capacity for cellulosic ethanol and other advanced biofuels has lagged behind expectations. The authority can also award “waivers” to some small-scale fuel suppliers regarding the share of the RFS obligation.

The value of certificates (Renewable Identification Numbers) depends on the fuel category and market supply and demand situation. The certificate values vary significantly between the fuel categories, with an average of USD 5.6/GJ for corn-based ethanol for 2015-2019 and USD 2.0/GJ in 2019. For FAME fuels, the equivalent numbers are USD 5.4/GJ and USD 3/GJ. These rise to USD 21.7/GJ and USD 17.7/GL for D3 fuels (principally biomethane). A biodiesel blending credit adds USD 1/gallon to the policy support for these fuels.

Source: EPA (2020)(DoE, n.d.a).

Box 11.4. The Low Carbon Fuel Standard of California

The National RFS of the United States is complemented by a number of state-level specific programmes, notably the Low Carbon Fuel Standard (LCFS) in California, which is also being adopted in several other US states, including Oregon and Washington.

The LFCS was initiated in 2007 with an initial objective to reduce emissions from transport by at least 10% by 2020 from the 2010 baseline through the use of low carbon fuels, including biofuels and LPG, compressed natural gas, and electricity. The objective has recently been extended to a 20% reduction by 2030. Under the LCFS, life-cycle analysis is used to establish a target carbon intensity for each year, which declines in line with the longer-term targets. Fuels that have a carbon intensity above this figure generate deficits, while those with lower carbon intensities generate credits. Regulated parties must balance deficits and credits to comply with the regulation.

In the early years, credits came mostly from the use of bioethanol and fossil natural gas. In 2019 renewable diesel (HVO) was the most significant source of credits (32%), while electricity (19%), biodiesel (13%) and biomethane (6%) also played important roles.

Source: California Air Resources Board (2021).

Financial and fiscal incentives can be used to offset the high cost of biofuels and encourage local biofuels production. For example, Sweden exempts energy taxes on biofuels to encourage biofuels production and consumption (Biofuels international, 2020). The Philippines also exempts materials for biofuels production from VAT (DoE, n.d.b). Specific financial incentives such as funds and grants for biofuel projects can also address the high cost of biofuels. For example, Brazil, Thailand and the United States provide financial incentives to biofuels projects. In the context of COVID-19, the US government announced it would provide USD 700 million for biofuel producers to assist the industries recovering, with the background of reduced biofuel (*e.g.* bioethanol) consumption in the transport sector (Reuters, 2021b). Financial incentives for infrastructure for higher blending levels can accelerate the deployment. In the United States, the Higher Blends Infrastructure Incentive Program initiated by the USDA provides funds to assist transportation fuelling and biodiesel distribution facilities with converting to higher ethanol and biodiesel blends and offering sales incentives for installing fuel pumps, related equipment and infrastructure (USDA, 2021c).

Government-funded RD&D programmes are being used to help with the development of novel biofuel technologies. For example, the United States has an extensive research effort co-ordinated by the Biotechnologies Office to support the research related to advanced biofuel (CRS, 2022). Loan guarantees are also provided to offset the risk of biofuel projects. In the United States, the Biorefinery Assistance Program provides up to USD 250 million loan guarantees to develop, construct and retrofit projects (USDA, 2021c).

Sustainability governance supported by regulations, certification schemes, sustainability targets and co-ordinated planning is necessary to improve the biofuels supply chain and minimise the negative impacts on environmental, social and economic aspects. These measures are discussed in Chapter 2.

TABLE 11.1. Barriers and policies for bioenergy in transport

Barriers	Policies	Examples of countries and regions with policies and programmes
Policy uncertainty	Long-term strategy and targets	European Union, Thailand, United States
High cost	Blending mandates	Angola, Brazil, Canada, Ethiopia, Kenya, Malawi, South Africa, United States, Zimbabwe
	Renewable fuel standards	United Kingdom, United States, California (United States)
	Financial and fiscal incentives	Brazil, Philippines, Sweden, Thailand, United States
Low technical readiness level	Loan guarantees to RD&D	United States
Sustainability concerns	Sustainability governance	European Union

A ethanol fuel station in Sweden. ©Jeppe Gustafsson@Shutterstock.com

CONCLUSION

The growth in the use of biomass materials is an essential component of the energy transition aligning with the 1.5°C Scenario, with biomass reducing GHG emissions by replacing fossil fuels and also by opening up the possibility for linking bioenergy with CCS. The contribution from modern bioenergy to the demand for energy in all end uses and for chemical feedstocks will need to increase in the following decades.

The main required developments are reductions in the traditional use of biomass by 2030, increases in modern bioenergy used to heat buildings, more bioenergy use in industry and biofuels for transport (road, aviation and shipping). In addition, strong growth in the use of biomass for non-energy purposes, especially to replace fossil fuel feedstocks for chemical production, is needed. Although there is more direct use of solid biomass as a fuel to produce heat, there is also stronger growth in bioenergy heat produced and distributed via district heating systems and biogas and biomethane.

To support this enhanced role for bioenergy, biomass supply will need to increase, posing an urgent need for sustainability governance and practices. Improving the sustainability of the bioenergy supply chain and minimising the negative impacts are priorities for all bioenergy policy making. Achieving them requires the full engagement of stakeholders from all sectors and the careful examination of operations along the whole supply chain. To avoid negative impacts, the production and use of bioenergy must be managed with care. Again, issues requiring particular attention include land for energy versus land for food and other purposes and heightened emissions caused by land-use change and the impacts on forestry, biodiversity, air pollution and smallholders. Sustainability-based bioenergy targets and co-ordinated policy making from different departments are essential to ensure sustainability. Certificate schemes and regional, national and subnational regulations are key pillars for sustainability governance. Moreover, integrating with the SDGs can also help bioenergy policy making.

In the shorter term, the contribution of modern bioenergy needs to increase in all end uses by 2030. Unless policy measures are taken, bioenergy deployment will not attain the levels aligning with the 1.5°C Scenario. Cost presents the most significant barrier. Bio-based fuels and chemicals cost more than fossil fuels. Market access is more difficult, along with investment in infrastructure and the development of supply chains compatible with sustainability requirements. In addition, many market sectors need to demonstrate and rapidly deploy new technologies (for example, to produce bio-based aviation fuels).

To combat these barriers to deployment, policy packages need to address the barriers associated with costs, supply chains and others; provide a science-based sustainability governance regime; and develop and promote innovative processes and products, along with other measures. To avoid investment uncertainties, policies need to show a long-term strategy for bioenergy deployment, with clear targets, as an integral part of a country's climate and energy plan. Policy makers need to demonstrate certainty around the levels of support available to bioenergy producers and users over the longer term. There are already many good examples of sector-specific policies in practice, and these need to be deployed with greater urgency in many more markets if the ambitious deployment objectives are to be achieved.

GLOSSARY

Selected technical terms used in this report are defined here.

Anaerobic digestion	The biological process that occurs when wet biomass materials are held in the absence of oxygen at ambient temperatures. Bacteria and other organisms break down the feedstocks' yield biogas (methane, carbon dioxide and other gases), which can be used directly as a fuel for heating or power generation or be refined to biomethane. The process also produces a solid and liquid product (digestate) that can, in many cases, be used as a fertiliser.
Biodiesel	A bio-based substitute for fossil diesel produced through the FAME or HVO process. Biodiesel is produced using two different technologies (transesterification and hydrotreatment) that often use the same raw feedstocks (crop or organic wastes).
Bioenergy	Energy (such as electricity, heat and fuel) generated from the conversion of solid, liquid and gaseous biomass or from products derived from biomass.
Bioethanol and cellulosic ethanol	Most bioethanol is produced by the fermentation of materials containing sugars and starches, such as sugarcane, corn and cereals such as wheat. However, bioethanol can also be produced by pre-treating cellulosic materials (such as straw, bagasse and other agricultural residues, or woody biomass) to produce sugars in solution, which can subsequently be fermented to second-generation ethanol (or other fuels).
Biogas	A mixture of methane, CO_2 and a small share of other gases produced through anaerobic digestion or fermentation of a variety of organic materials, such as manure, sewage, crop or forest residue and other organic waste. The main technologies include biodigesters, landfill gas capture and wastewater treatment plants. Biogas typically consists of 50-75% methane and can be used directly (*e.g.* for cooking) or upgraded (or purified) to biomethane.
Biogasoline	A fuel with properties similar to fossil gasoline is produced from biomass materials, mostly by gasification and subsequent treatment of the synthesis gas produced.
Biojet	Biofuels based on biomass feedstocks can be used as jet engine fuels.
Biomass	Biological materials derived from animals, plants or algae, such as wood and agricultural crops, and organic waste from municipal and industrial sources. Biomass can be used to feed livestock or produce food for people. It can also be used as feedstock to produce bioenergy, such as solid biofuel, liquid biofuels and biogas, or feedstock for industries, such as the chemicals industry, to produce plastic.
Biomethane	Biomethane is near 100% of methane derived from biomass. It could be produced through upgrading biogas from anaerobic digestion or through the biomass gasification process followed by methanation. Biomethane can be injected into existing gas pipelines for heating or used for transport purposes.

Biomethanol	Biomethanol is a kind of methanol produced from biomass materials, mostly by gasification and subsequent treatment of the synthesis gas produced.
FAME	FAME (fatty acid methyl ester) is produced by treating oil from fats, vegetable oils and greases with methanol or ethanol (transesterification) to produce a diesel-like fuel that can be used as a transport fuel.
Gasification	The treatment of biomass materials at high temperature with limited oxygen levels to produce a synthesis gas that may contain hydrogen, carbon monoxide and carbon dioxide, methane, water and nitrogen. The relative proportions of the products depend on the reactor design and process conditions. The synthesis gas can be used directly (for example, as a fuel for power generation or heating) or be further processed using hydrogen to produce fuels such as methanol, methane, biogasoline, biojet and *other* fuels.
HEFA	HEFA (hydroprocessed esters of fatty acids) is another term for HVO, recognising that a wider range of feedstocks than vegetable oils can be processed.
HVO	HVO (hydrogenated vegetable oil) is produced by treating biomass-based fats, oils and greases, including vegetable oils such as palm, soy and canola, either as virgin oils or as used products (such as used cooking oil [UCO] and animal fats such as tallow) with hydrogen to reduce the oxygen content. The resulting hydrocarbon can be refined to produce a range of fuels with properties very similar to fossil-based diesel, gasoline, jet fuel and propane.
Liquid biofuels	Liquid fuels are derived from biomass. Liquid biofuels include 1) bioethanol, a liquid produced from fermenting any biomass type high in carbohydrates, such as sugar crops (*e.g.* sugarcane, corn); 2) biodiesel, a diesel equivalent fuel made from both vegetable oil and animal fats; and 3) other advanced biofuels. They can be used for transport, heating, cooking and electricity generation.
Pyrolysis	The treatment of biomass materials at high temperature with very restricted oxygen levels to produce a fuel gas, a liquid fraction (pyrolysis oil) and a char. The relative proportions of the products depend on the reactor design and process conditions. The pyrolysis oil can be used directly (for example, as a heating fuel) or else further processed using hydrogen to produce fuels such as HVO.
RNG	RNG (renewable natural gas) is an alternative term for biomethane.
Solid biofuels	Include wood chips, wood pellets, agricultural and forestry residue and other solid form of bioenergy that are directly and indirectly obtained from biomass. They can be used for cooking, heating, power generation or as feedstock for industries.

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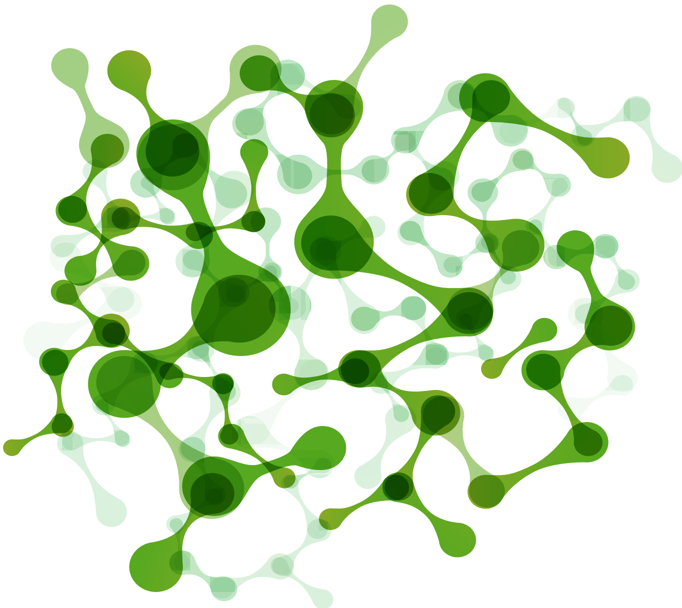

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