Bioenergy sustainability in the global South

Constraints and opportunities

Michael Brady
Sunil Sharma
Himlal Baral
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Michael Brady
CIFOR-ICRAF

Sunil Sharma
CIFOR-ICRAF

Himlal Baral
CIFOR-ICRAF

Robert Nasi
CIFOR-ICRAF

CIFOR-ICRAF

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Photo by Himlal Baral/CIFOR
Degraded peatland in Perigi, South Sumatra being restored for food, energy and raw materials

CIFOR
Jl. CIFOR, Situ Gede
Bogor Barat 16115
Indonesia
T +62 (251) 8622-622
F +62 (251) 8622-100
E cifor@cifor-icraf.org

ICRAF
United Nations Avenue, Gigiri
PO Box 30677, Nairobi, 00100
Kenya
T +254 20 7224000
F +254-20- 7224001
E worldagroforestry@cifor-icraf.org

cifor-icraf.org

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Abbreviations

Bha	Billion hectares
BLy-1	Billion litres per year
BP	British Petroleum
BR&DI	Biomass Research and Development Initiative
BRDTAC	Biomass Research and Development Technical Advisory Committee
CEPS	Centre for European Policy Studies
CIFOR	Centre for International Forestry Research
CO2e	carbon-dioxide equivalent
EJ	Exajoule
EJy-1	Exajoule per year
EPA	Environment Protection Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GAIN	Global Agricultural Information Network
GBEP	Global Bioenergy Partnership
GDP	Gross Domestic Product
GHG	Greenhouse gas
GW	Gigawatt
ICRAF	World Agroforestry
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
Mha	Million hectares
MPE	Ministry of Petroleum and Energy
MtO-e	Million tonnes oil equivalent
NDC	Nationally Determined Contribution to the United Nations Framework Convention on Climate Change
PES	Planned Energy Scenario
RSB	Roundtable on Sustainable Biomaterial
SDGs	Sustainable Development Goals
SRES	Special Report on Emissions
tCO2e	Tonnes of carbon-dioxide equivalent
TES	Transforming Energy Scenario
UNCTAD	United Nations Conference on Trade and Development
USCA	United States Climate Alliance

Executive summary

This study aimed to provide a better understanding of bioenergy issues, potential and sustainability to inform countries in the global South and provide guidance on integrating bioenergy into their national energy plans by proposing a simplified sustainability framework for wood-based bioenergy.

Many countries have recently adopted bioenergy as a critical strategy to reduce greenhouse gas (GHG) emissions to meet targets under the Paris Climate Agreement. In addition, several studies have forecast bioenergy to become a primary energy source. Because of increased efficiency and lower production costs, along with legislative support and investment incentives, bioenergy use is swiftly becoming a renewable energy substitute for fossil fuels.

There are several arguments against bioenergy expansion. Food security is the most prominent because existing or new agricultural land may be required to produce bioenergy crops or feedstock. Food insecurity restricts availability and accessibility, leading to price rises. In addition, clearing forestland may occur if demand for bioenergy feedstock increases, resulting in biodiversity loss, increased soil erosion, hotter microclimates and GHG emissions. Pro-bioenergy groups argue that bioenergy has co-benefits if biomass is produced on degraded and underused land and provides energy security and emission reductions, supports rural livelihoods and enhances biodiversity and ecosystem services. For example, the EU Renewable Energy Directive (RED) II contains sustainability criteria, including biodiversity for forest bioenergy (Camia et al 2021).

Some countries, for example, the USA, Brazil and European nations, are including bioenergy for achieving their emission-reduction targets, optimizing the national energy mix and reducing fossil-fuel dependency. In these countries, bioenergy is an integral part of a bioeconomy, focusing on sustainability and promoting bioresources and bioproducts. This includes developing a circular economy, which aims to minimize waste from biological processes.

In this context, the global review of this study shows an increasing trend of inclusion of bioenergy in the total global energy-supply share from 1.4% in 2001 to 5.1% in 2018. The trend has been projected to grow by 3.7% and double use from 53 Exajoules (EJ) to 108 EJ between 2010 and 2030. Various studies using different assumptions estimate potential global bioenergy production to be between 273 EJy-1 (per year) and 1471 EJy-1.

The main drivers of growth of bioenergy are energy security, climate change and green economy, financial investment and access to technology, land availability and productivity, production costs and market guarantees.

The review of sustainable wood-based bioenergy in this study identified several benefits applicable to the global South, including sustainable forest management, high energy efficiency and low production costs of advanced biofuels, a reduction in GHG emissions, value addition to woody biomass, supporting biodiversity, socio-economic benefits to local people through new employment, income generation and support to rural economies, and new and diversified energy supplies.

With 1.4 billion hectares (Bha) of land globally potentially available for bioenergy production, integrating bioenergy with landscape-scale production systems can directly contribute to five of the 17 UN Sustainable Development Goals (SDGs) and indirectly influence another four.

Therefore, bioenergy can allow developing countries to better support rural communities, create more equitable economic opportunities and enhance energy access. However, some countries may need to refine their natural resource, climate, energy and land-use policies and strategies to adapt to production of wood-based bioenergy based on their social, economic and environmental circumstances.

To help countries in the global South design wood-based bioenergy systems, we present a sustainability framework herein that explains how to better use low-value land resources, produce bioenergy, restore ecosystem services, and mitigate and adapt to climate change.

The study offers the following points as guidance to establish sustainable, wood-based bioenergy supply in developing countries in the global South: (1) **Landscape-level planning and management** by establishing a strategic vision for an integrated land-use approach that identifies the resource base, land tenure and appropriate land use across whole landscapes, typically mixed use; (2) **Use of marginal and degraded land** should be considered for biomass production for power generation. Importantly, biomass supply must not be sourced from existing natural forest or high conservation value areas; (3) **Mixed-species plantations** must consider species suitability to the land and people. A mix of high-yielding and drought-resistant species suitable for the area are ideal for a sustainable supply of biomass; (4) **Seamless monitoring systems** based on 'smart' technologies, such as smartphone-based monitoring applications, can provide evidence regarding the biomass supply chain and bioenergy production in real time; (5) **Local initiatives** will ensure a focus on local needs and provide energy access for market certainty. Strong partnerships and collaboration are needed among stakeholders, including smallholders, communities, larger private sector, research and academic institutions, and government and nongovernmental bodies; (6) **Conflict management** is necessary and should include all stakeholders involved in a bioenergy initiative and be based upon conflict management protocols; (7) **Governance of the biomass supply system** should include local government authorities and integrate the biomass supply system governance into public systems to ensure sustainable biomass production; and (8) **Documentation and record-keeping** are essential to demonstrate that the biomass supply chain and bioenergy production adhere to the principles and criteria of bioenergy sustainability. Documentation, monitoring, and reporting are key to verify that biomass production and bioenergy generation comply with the bioenergy sustainability framework.

In addition, the study concludes that a global South bioenergy forum is needed to support dialogue, learning and cooperation and help ensure that the positive, transformative aspects of bioenergy are realised and deleterious ones avoided. An example of such a forum is the CIFOR-ICRAF Circular Bioeconomy Transformative Partnership Platform (https://www.cifor.org/cbe).

Acknowledgement

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1 Introduction

The adverse impacts of climate change threaten the existence of life on our planet. Global actions addressing this have become paramount. Anthropogenic emissions — that is, human-induced emissions of greenhouse gases (GHG) — are broadly accepted as the cause of climate change. Twenty years after the first climate summit in Berlin in 1995, at the Twenty-first Conference of Parties (CoP) to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, 196 countries agreed to seek to limit global temperature rise to below 2 0C — preferably 1.5 0C — by 2050 (IPCC 2019). The Paris Climate Agreement is a legally binding and ambitious target for all countries to become carbon neutral by mid-century. To achieve net-zero carbon emissions, bioenergy is increasingly seen as part of land-based mitigation measures to limit climate change.

Carbon-intensive and non-renewable fossil fuel is the major source of global energy supply for transport and electricity; accounting for 64% of total emissions in 2019 (38 gigatonnes of carbon-dioxide (Gt CO2)) (UNEP 2020). Reducing and replacing fossil fuel has been a major focus to achieve the global target of net-zero carbon emission through diversifying energy source for ensuring energy security (Field et al. 2020). In this context, bioenergy derived from sustainable biomass sources[1] can significantly contribute to climate-change mitigation by enhancing and replacing carbon-intensive and non-renewable fossil fuel and diversifying energy sources to ensure energy security (Souza et al. 2017). IPCC's modelled pathways estimated up to 700 million hectares will be needed for bioenergy production to limit global temperature rise to below 1.5 0C by 2050 (IPCC 2019).

Bioenergy produced from sustainably sourced biomass — forestry or agricultural feedstock — is considered a renewable energy source that promotes decarbonization through industrial-scale power generation, heating and transport energy (IPCC 2019; Nakada et al. 2014). The International Renewable Energy Agency (IRENA) claims that transition from fossil fuels to bioenergy not only avoid emissions from direct combustion of fuels but also provides other benefits by reducing the dependency on imported energy sources and enhancing energy security by diversifying sources (IRENA 2017). Use of bioenergy as an energy source is increasing because of several factors.

Development and use of bioenergy is a key strategy proposed by many countries to help meet their Nationally Determined Contribution (NDC) to targets to reduce GHG emissions under the Paris Climate Agreement.

1. Bioenergy development is an opportunity to integrate with land- and biodiversity-restoration programmes, with biomass from restoration used for production of bioenergy.
2. Bioenergy is renewable and can replace fossil fuels and reduce dependency on imported fossil fuels for many countries.
3. Technological advances continue to increase the efficiency and affordability of bioenergy.
4. Many countries already feature policies encouraging use of bioenergy in transport, power generation and heating.
5. Bioenergy offers new investment opportunities.
6. A well-functioning bioenergy sector stimulates the economy of rural areas, creating local jobs.

A few countries, for example, the USA, Brazil and nations of the European Union (EU), are pursuing commercial bioenergy to help achieve

1 'Sustainable' defined in a broad sense as including consideration of, among other factors, ecosystem health, climate-change mitigation, electricity grid stabilization, energy security, rural development, income and employment, other environmental impacts such as air pollution and other non-GHG climate forcers (Camia et al. 2020).

their emission-reduction targets, optimize their national energy mix and reduce dependency on fossil fuels. In these countries, bioenergy is seen as an integral part of a bioeconomy, with a focus on both a sustainable economy — by promoting the use of bioresources and bioproducts — and a circular economy, which aims to minimize waste from biological processes (Johnson 2017; Asveld et al. 2011).

Bioenergy, however, is not free from controversy (Johnson 2017). There are concerns regarding food insecurity (Rosillo-Calle and Johnson 2010), land-use change (Berndes et al. 2013), replacing natural forest with energy crops or plantations, water crises, and no measurable GHG benefits. The IPCC (2019) acknowledged, with 'high confidence', these negative impacts of bioenergy. However, IPCC qualified that such impacts depend on many factors, including the scale of operation, previous land use and land type, carbon stock and management regime.

It is widely agreed that bioenergy produced from sustainable biomass with comprehensive social and environmental safeguards can avoid negative impact and generate a wide range of benefits. Consequently, bioenergy sustainability is considered a prerequisite for future expansion. In many developed countries, bioenergy-sustainability frameworks and certification systems have been developed to ensure social, economic and environmental safeguards that avoid detrimental impact at all stages of the bioenergy lifecycle, from production of feedstock to energy end-use.

The Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF) is an international research institution with the strategic goal of sustaining people's livelihoods in the global South by transforming landscapes. Our research agenda includes restoration of degraded landscapes using commercial bioenergy crops sustainably (for example, Sharma 2016; Borchard et al. 2018; Jaung et al. 2018; Artati et al. 2019).

Yet while bioenergy can mitigate climate change and be an alternative, sustainable energy source, adoption remains limited to a few countries.

In this context, a better understanding of bioenergy issues, potential and sustainability is necessary to inform developing countries on how to assess their energy needs and integrate bioenergy into their national energy plans.

CIFOR-ICRAF has undertaken this study to address these needs, focusing on several major areas.

1. Review of the bioenergy literature to understand bioenergy as an emerging alternative energy source and document global trends, drivers and factors favouring its expansion.
2. Summary of the arguments for and against bioenergy production and use, which emerge mainly from the global North.
3. Synthesis and refinement of the arguments in the context of environmental and socioeconomic conditions of the global South to identify bioenergy sustainability frameworks for wood-based bioenergy.
4. Discussion of the ways forward to promote the use of wood-based energy in the global South.

1.1 Scope of the study

While bioenergy can be successfully produced from various types of biomass feedstock, technological innovations and development continue to make bioenergy an even more efficient and cost-effective alternative energy source compared with fossil fuels.

Of the various bioenergy sources, relative efficiencies depend on type of feedstock and the technology used in production. Agricultural (for example, sugar cane (*Saccharum officinarum*) and maize (*Zea mays*)) and oil crops (for example, oil palm (*Elaeis guineensis*) and rapeseed (*Brassica napus*)) have been the principal feedstocks supplying 'first generation' bioenergy production: ethanol and diesel (IRENA 2016).

Crop and wood residues, grasses and trees are high-yielding biomass feedstocks used to produce 'second generation' bioenergy (IRENA 2016). They have the potential to generate a large portion of global bioenergy production.

'Third generation' bioenergy from microalgae is still in the research-and-development phase, therefore, current bioenergy production is derived from first- and second-generation feedstock. Much of the bioenergy literature refers to first-generation bioenergy because of its degree of technological advancement and its important contribution to global bioenergy supply.

For second-generation biofuel, woody biomass can be sustainably sourced by growing suitable tree species on degraded land that is unsuitable for agriculture, creating no competition with food crops. If bioenergy species are grown in mixed agroforestry systems, food security and biodiversity will be enhanced (Sharma et al. 2016). The wide availability of degraded and under-used land in the global South offers an opportunity for restoration through growing woody biomass for bioenergy production without impacting natural forests and habitats. Further, the restoration of degraded land engages local communities and provides employment opportunities and ecosystem goods and services from restored landscapes, including increased food supply and enhanced biodiversity if under agroforestry.

However, it is important to contrast the bioenergy potential of woody biomass in the global South against with global bioenergy potential using a sustainability framework. Although charcoal and fuelwood are dominantly used for cooking in Africa and Asia (Mirzabaev et al. 2014), these sources' low energy efficiency, lack of regulation and unsustainable sources are well noted in the literature (IEA 2021). This study excludes traditional uses of fuelwood for cooking, focusing rather on other types of wood-based bioenergy.

2 Methods

This study was based on a desktop review of literature collated through an extensive Internet search using databases and search engines Scopus, Science Direct and Google Scholar. Primary keywords were used — 'bioenergy', 'bio-energy', 'bioeconomy', 'biofuel' and 'wood-based bioenergy' — in combination with 'supply', 'demand', 'policy', 'renewable', 'sustainability' and 'framework' (Figure 1).

The literature was sorted based on global or international scope, regional or country scale and whether they were 'supportive', 'qualitatively supportive' or 'non-supportive' toward bioenergy production and use.

An annotated bibliography was prepared after a detailed review of these references to assist in the study. References were prioritised that were evidence-based and peer-reviewed to offer the latest information on bioenergy within the scope of this study.

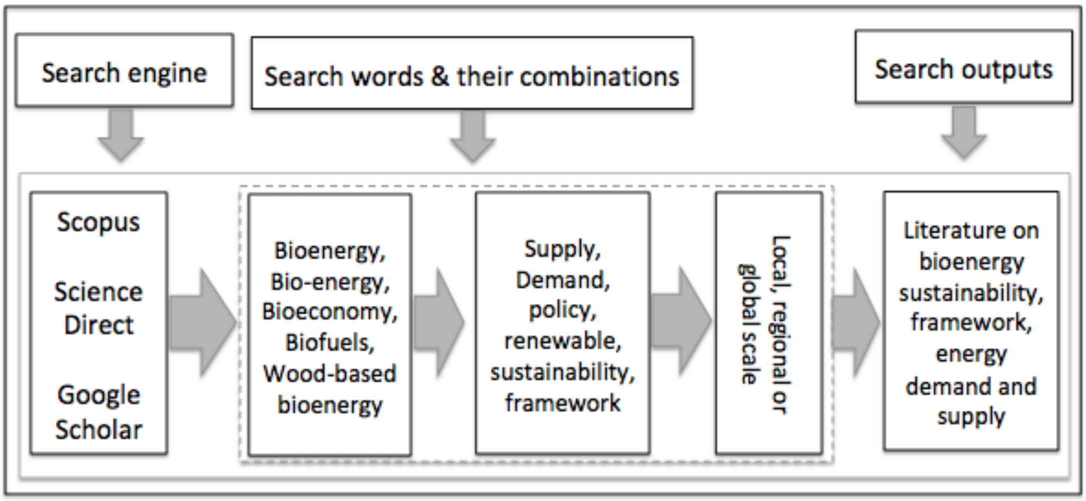

Figure 1. Flow diagram of the literature search for this study

3 Findings

3.1 Understanding wood-based bioenergy pathways

Woody biomass constitutes that biomass accumulated on a tree[2], including the trunk, branches and twigs, roots and foliage. The increasing use of woody biomass for bioenergy production is attributed to a number of factors, including the versatile nature of woody biomass to generate various bioenergy types, year-round availability, relative price stability, ease of transport and no food-security risks (Ranta 2014).

Whether it is a whole tree or a part, woody biomass by-products can serve as raw material in bioenergy pathways to produce, for example, biofuels, synthesis gas (syngas) and power generation and heating, based on biochemical, thermochemical and direct combustion processes (Figure 2).

Debates have occurred over whether the source of the woody biomass is natural or plantation forests, the amount of emissions produced during long-distance transport of biomass and the carbon debt from production.

The EU's Renewable Energy Directive II (RED II) (EP&CPU 2018), in particular, has raised serious concerns regarding use of forest biomass derived from tree harvesting and the potential for indirect land-use change, despite sustainability criteria in place. Nasi (2018) highlighted the need for better understanding of the science through lifecycle analysis; the 'time debt' was the most concerning issue, which can undermine climate-change mitigation efforts. At the stand level, tree harvesting and burning for bioenergy emits GHGs immediately and stand regrowth takes many years to sequester the same amount of carbon dioxide from the atmosphere. Therefore, Nasi opposed harvesting natural forests and the long-distance transport of wood pellets or chips for bioenergy production and use. Instead, he proposed that dedicated plantations of fast-growing species in local areas on degraded or unused land could supply a sustainable source of woody biomass without jeopardising natural ecosystems, promoting land-use change or weakening mitigation efforts. Consistent with this view, Cowie et al. (2021) emphasized the need for a 'systems approach' when assessing options and developing policy for forest bioenergy in which the whole lifecycle of bioenergy systems is considered, including the effect of associated forest management and harvesting on carbon balances at landscape level.

The woody biomass bioenergy pathway outlined in Figure 2 provides a framework for lifecycle analysis of production of different bioenergy types and accounting for climate benefits. This pathway assumes the woody biomass is produced through new plantings on degraded land and the biomass does not come from natural or remnant forests. Net carbon benefits occur when the sum of carbon sequestered, and the emissions avoided, exceeds GHG emissions from harvesting, processing and transportation of material and bioenergy products.

The total carbon footprint of converting woody biomass to bioenergy is the sum of GHG emissions from the woody biomass production and harvesting, pre-processing and bioenergy production processes and transport of the raw materials and bioenergy products. The net climate benefit of the woody biomass bioenergy pathway is estimated by subtracting total GHG emissions from the processing and transportation of the biomass from total GHG removal by the biomass through carbon sequestration and total GHG avoided by the transition of fossil

2 A tree is generally defined as a woody perennial plant with single or multiple stems with a more or less definite crown.

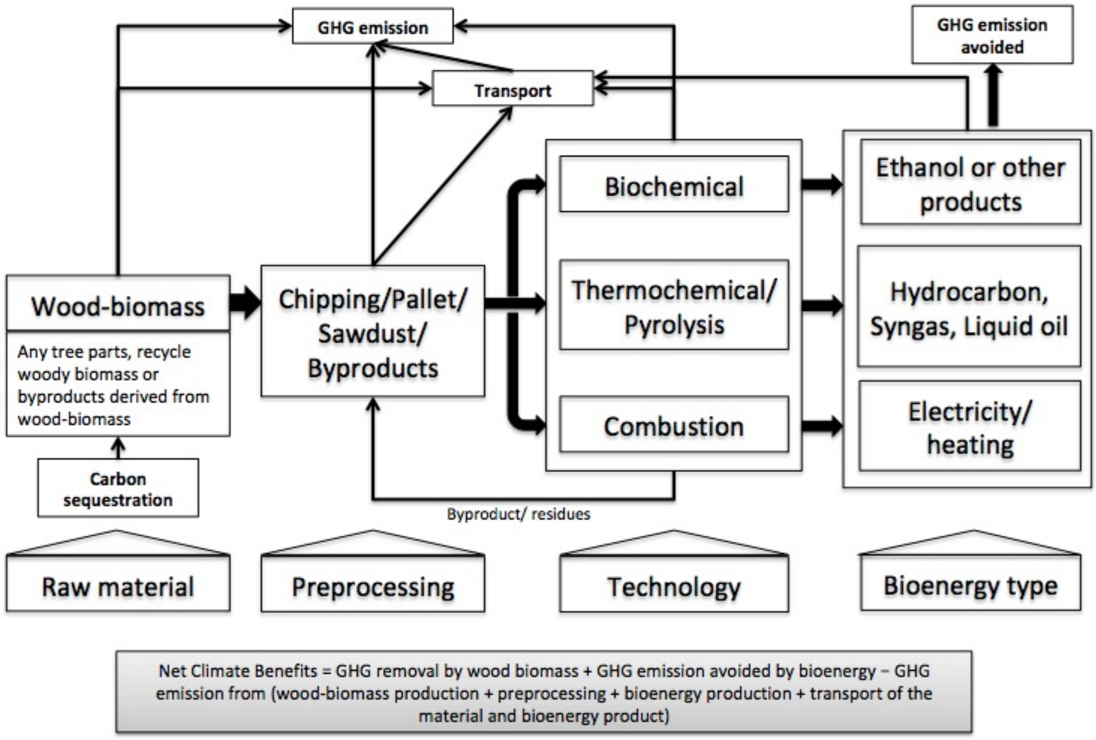

Figure 2. Woody biomass bioenergy pathways, including steps from production through pre-processing to the technology converting woody biomass to various bioenergy types

Source: The authors

fuel to bioenergy or emissions avoided from burning coal to generate equivalent energy.

Suppose the biomass is sourced from an existing forest, in which case, the calculation must consider the baseline situation of direct or indirect land-use change, the management regime (thinning, harvesting), harvested product types and uses, geographical location and spatial extent of the biomass production.

3.2 Review of global trends of bioenergy use: past, present and future

In 2001, bioenergy nominally contributed 5.7 EJ or 1.4% of the total global energy use of 418 EJ, excluding use of traditional biomass — that is, fuelwood — that accounted for 39 EJ or 9.3% of total global energy use (Goldenberg and Johansson 2004). Traditional biomass is used in developing countries by about 40% of the world's population, who depend on mostly unsustainably sourced biomass for cooking and heating (Mirzabaev et al. 2014). However, a recent report estimated that bioenergy (without traditional biomass) supply increased from 2001 about three-fold to 4.1% in 2015, rising to 5.1% in 2018, along with an increase in total primary energy supply, by providing an alternative to all end-use energy sectors (IRENA 2020).

In 2018, biofuel production grew by about 10%. The USA and Brazil lead production, with 38 and 21 MtO-e respectively, and together accounted for about two-thirds of global production in 2018. The EU produced about 14 MtO-e or 14.6% of global production (Figure 3).

Bioenergy is considered one of the renewable energy sources in many international frameworks and policies that can support the transition from fossil fuels to renewable energy as part of decarbonisation and in support of sustainable development (IRENA 2014). The Global Renewable Energy Roadmap 2030 (Remap) of the International Renewable Energy Agency (IRENA) forecasts bioenergy to grow annually by about 3.7% and double from 53 EJ to 108 EJ between 2010 and 2030 (IRENA 2014). Nakada et al.

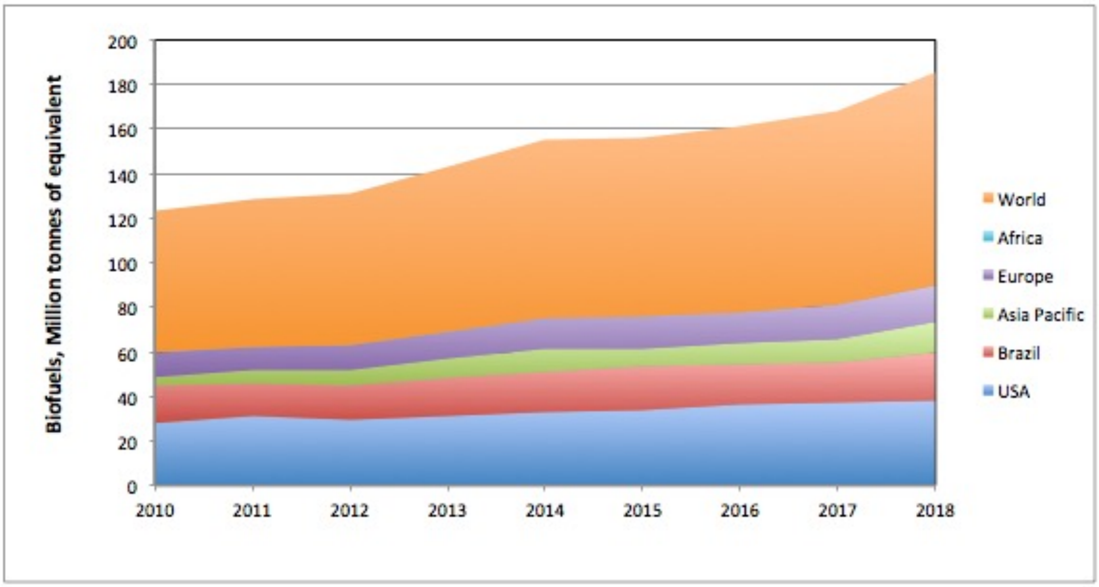

Figure 3. Production of biofuels in 2018 by country and region

Source: Adapted from BP 2019

(2014) estimated the annual global biomass supply would vary from 97 EJ to 147 EJ and account for about 60% of total renewable energy, with a collective contribution of agricultural residues and waste (37–66 EJ), energy crops (33–39 EJ) and forest products and residues (24–43 EJ) by 2030.

IRENA (2020) provided a comprehensive analysis of the global energy outlook for 2050 and projected total energy supply and consumption under the Planned Energy Scenario[3] (PES) and Transforming Energy Scenario[4] (TES) for 10 global regions. The total global bioenergy installed capacity was estimated to be 106 GW; equivalent to 3.3 EJ[5] with 134 billion litres of biofuels produced worldwide.

Under the PES — and considering current energy policies, plans and targets — bioenergy production increases by three-fold to 336 GW or 10.6 EJ. The TES is more ambitious and sees a six-fold bioenergy increase to 690 GW or 21.8 EJ in 2050 compared with the 2017 reference level[6]. Global biofuel production will increase by almost three times to 373 BLy-1 and five times to 641 BLy-1 under these scenarios, respectively. Thus, bioenergy rises significantly to 10% and 23% of the projected primary energy need in 2050 under the PES and TES, respectively (IRENA 2020)

Some studies estimate global bioenergy potential in 2050 under various scenarios using different assumptions. For example, Smeets et al. (2004) estimated that total global bioenergy production potential would range 273–1471 EJy-1 by 2050 under four different consumption scenarios. These scenarios assumed increasing efficiencies of agricultural and livestock production systems, growing energy crops on additional land and the use of forest residues and growth enhancement in natural forests. A comparable estimate of global bioenergy potential in 2050 ranged 311–706 EJ y-1 under four IPCC Special Report on Emissions scenarios based on future economic structure, population growth and approaches to address

3 A reference case based on current energy policies, plans and targets.

4 A realistic energy transformation pathway based on renewable energy sources and energy efficiency.

5 Using a conversion rate of 1 GWh = 0.000036 EJ

6 Forest Reference Level is a country-determined projected level of emissions and removals against which future emissions and removals will be compared. Few countries in the global South have calculated FRLs. Moreover, age-related forest dynamics are difficult to determine in tropical vegetation owing to limited seasonality and lack of a robust forest inventory and monitoring information.

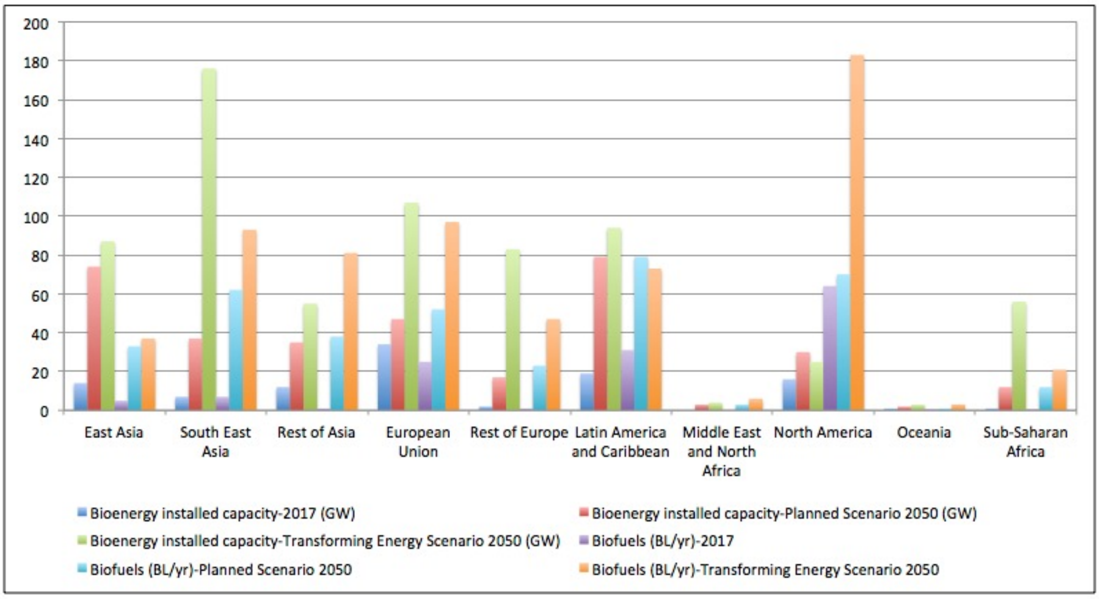

Figure 4. Bioenergy and biofuel production in 2017 and projected production under the Planned Energy Scenario and Transforming Energy Scenario in 2050

Source: IRENA 2020

sustainability issues at various scales (Hoogwijk et al. 2003).

These estimates suggest the substantial global potential of biomass to provide low-carbon energy for all energy end-uses, including biofuels for the heavy transport and aviation sectors. Despite the potential and demonstrated application of bioenergy, its development and uses vary between, and are influenced by, development priorities, energy policies, investment markets and social, economic and environmental sustainability concerns.

Figure 4 illustrates the bioenergy (GW) and biofuels (BLy-1) production as of 2017 and compares with projected estimates under planned and transforming energy scenarios by 2050. Among 10 regions, the EU had the highest installed bioenergy capacity of 34 GW in 2017 followed by Latin America and the Caribbean with 19 GW and North America with 16 GW.

Under the PES, the fastest growth of bioenergy will occur in East Asia, with a bioenergy capacity of 74 GW, increasing from 14 GW in 2017, while Latin America and the Caribbean will lead bioenergy production with 79 GW by 2050. Bioenergy production will almost double in North America to 30 GW in this scenario. Under the TES, bioenergy production must increase six-fold from 2017 levels and there will be significant growth in Sub-Saharan Africa from 1 GW in 2017 to 56 GW in 2050. Southeast Asia is predicted to increase bioenergy production capacity by 25 times from 7 GW to 176 GW between 2017 and 2050.

North America dominated biofuel production by delivering 64 BLy-1 equivalent to almost half of global biofuel production in 2017. About a quarter of worldwide biofuel production occurred in Latin America and the Caribbean with 31 BLy-1 biofuels followed by the EU with 25 BLy-1 (about 19%). Biofuel production grows by about nine-fold to 62 BLy-1 in Southeast Asia and by about seven times to 33 BLy-1 in East Asia under the PES. The rest of the Asia region will experience a drastic increase in biofuel production from 1 BLy-1 to 81 BLy-1. In North America, biofuel production will rise by about three times to 183 BLy-1 by 2050 under the TES.

3.3 Major drivers of bioenergy development

Bioenergy has experienced enormous growth in the last decade and become a dominant renewable energy source. Switching to bioenergy from conventional energy sources is influenced by many factors. It varies between countries depending on their specific circumstances, development strategies and adaptation of energy policies and action plans.

The literature suggests several drivers responsible for this expansion, which are often complex and interconnected. Mirzabaev et al (2014) compiled a non-exhaustive list of about 20 drivers across six categories. Discussing each of these drivers is beyond the scope of this review. However, by reviewing bioenergy growth in several leading countries, we can identify the following key factors influencing bioenergy development in general.

3.3.1 Energy security

Energy is a significant indicator of economic development and national prosperity and energy use has demonstrated a strong, positive correlation with higher Gross Domestic Product (GDP) per capita (Stern 2018). Fossil fuels (coal, gas and oil) have dominated primary energy supply since the industrial revolution (Ritchie et al. 2020). In the transition from fossil fuels to bioenergy, energy security is as vital as the provision of affordable and reliable energy . Moreover, it is a prerequisite for sustainable development as signified in nine out of the 17 SDGs.

Energy security has become a significant concern owing to the growing dependency on fossil fuels, their increasing cost, and the real and perceived risks of supply, availability and affordability (Anderson et al. 2004). The data show that between 1971 and 2018, energy consumption increased by 2.3 times from 6098 to 14,282 MtO-e, with fossil-fuel consumption rising from 5287 to 11,611 MtO-e, to sustain economic development and population growth (IEA 2020). In 2019, fossil fuels supplied 84% of total global energy (Ritchie et al. 2020).

Concern about energy security is deepening because 1) fossil fuels are non-renewable resources with finite reserves (Ritchie et al. 2020); 2) a limited number of countries own the reserves and control the production and supply of fossil fuels (Anderson et al. 2004); 3) industrialized and developing countries depend on imported fossil fuels for their primary energy needs and economic development; 4) production and supply of fossil fuels may be disrupted owing to wars, politics or market and trade conflicts between countries (Anderson et al. 2004); and 5) fossil fuels may become unaffordable as costs rise (FAO 2008).

These factors and their interactions add complexity to energy security. Heavy dependence on fossil fuels has caused more significant concerns and stimulated the search for sustainable and renewable energy sources. In this regard, besides hydropower and solar energy, bioenergy is being promoted for power generation and is considered a worthy substitute for the fossil fuels used in many sectors (Gustavsson et al. 2021). Industrialized countries have acted quickly to adopt, and promote, renewable energy sources for their primary energy supplies, with goals specifying the share of bioenergy in energy supply. For example, Brazil is a leader in the use of bioethanol to curb fossil-fuel imports and reduce foreign debt (FAO 2008)). Further, as a part of energy security, the trade of biofuels between producer and consumer countries has also supported the growth of biofuels over fossil fuels (Anderson et al. 2004).

Finally, a renewed focus on renewable energy sources, including biomass, took place at the COP26 of UNFCCC in Glasgow. The final statement from CoP26 included, for the first time, a reference to rapidly scaling up the deployment of clean power generation and energy efficiency measures, including accelerating efforts towards the phase-down of unabated coal power (ENB 2021).

3.3.2 Climate change and green economy

Climate change is the greatest threat to the planet and is caused by anthropogenic emissions (IPCC 2019), primarily attributed to increasing energy demand, accounting for about two-thirds of total GHG emissions, derived mainly from fossil fuel use (IPCC 2011a). Mitigation efforts to reduce emissions from conventional energy sources without jeopardizing energy supply has been one of the primary drivers for bioenergy development.

Bioenergy is recognized as a potential alternative energy source for heat and power generation and as a replacement for fossil fuels in the transport sector (IPCC 2019; IPCC 2011a). With the potential to replace fossil fuels using second-generation bioenergy, the need to mitigate climate change has supported the use of biodiesel in mainly replacing fossil fuels used in heavy vehicles, ships and aeroplanes. The global North, such as the

EU and the USA, has adopted bioenergy as a key mitigation action. Hence, the share of bioenergy has increased in simultaneously meeting growing energy demand and reducing emissions. Brazil is the only country in the global South that has pioneered bioethanol production for domestic energy markets and sale on international markets.

The Paris Climate Agreement in 2015 was instrumental in bringing together the global community to commit to mitigation and adaptation and take urgent action to reduce GHG emissions to limit global temperature rise to 1.5–2 °C relative to pre-industrial levels during this century (IPCC 2019). One hundred ninety-four entities — 193 countries and the EU — signed the Agreement and submitted NDCs outlining the strategies and pathways to reducing emissions.

Many countries in the global North have adapted renewable energy as a mitigation strategy to achieve emission reduction targets by 2030 from 1990 or 2005 levels (Table 1). Among the countries of the global South, China and Brazil have included renewable energy in their mitigation plans.

In addition to the adaptation of bioenergy as an integral mitigation strategy, climate-modelling scenarios have considered the significant role bioenergy (IPCC 2019) plays through providing clean, green and renewable energy substitutes for fossil fuel and reducing GHG emissions.

3.3.3 Energy policies

Energy policy is the foundation of the energy transition by providing a clear vision, strategies and action plans. Policy underpins bioenergy development by providing legal and financial support to secure investment for adopting bioenergy in different sectors (IRENA 2015). However, a comprehensive policy framework is needed to facilitate the uptake of the energy transition. IRENA 2020 identifies three broad energy transition policy areas: deployment, integrating and enabling.

1. Deployment policies offer domestic or international investors a new opportunity by ensuring financial incentives, support and investment security. Economic incentives and tax relief are essential to secure investment and participation in the energy transition to bioenergy. Removing fuel subsidies is a critical measure to increase the competitiveness of bioenergy against fossil fuels. Similarly, providing tax credits to bioenergy enhances competitiveness and encourages production. For example, biodiesel production in North America reduced by around 39% to 2009 levels in 2010 owing to the removal of biodiesel tax credits. In contrast, biodiesel production substantially increased in 2013 with the restatement of the tax credit (Nakada et al. 2014).

2. Integrating policies provide a framework to integrate electrical power from various sources into the energy network by ensuring market or buy-back guarantees. However, for a small-scale bioenergy plant, for example, financial-support policies to generate and distribute energy are more valuable. These policies help to integrate bioenergy into the energy system. In addition, mandatory energy mix policies successfully enforce guidelines on energy transition from fossil to biofuels.

3. Enabling policies and supporting programmes have encouraged energy transition in the USA, Brazil and European countries. For instance, Brazil's enabling policies supported the use of bioethanol by ensuring a competitive and stable bioethanol price, providing incentives to car manufacturing industries and loan access to farmers (Morgera et al. 2009).

The section below outlines the energy policies supporting bioenergy development in selected countries.

1. In the USA, the vision for bioenergy and bio-based products began in 2002. It was the primary driver of bioenergy production and use by stipulating goals for biofuels and biopower for 2010, 2020 and 2030 (BRDTAC 2007). The Energy Policy Act 2005 endorsed the 2002 bioenergy vision and required updating of the vision after assessing bioenergy use. The 2006-updated vision enhanced economic opportunity, energy security and environmental sustainability and increased the biofuels and biopower targets to 20% and 7% of market share by 2030, respectively (BR&DI 2006). The Energy Independence and Security Act (2007) emphasized an increase in clean

Table 1. Emission reduction targets for selected countries by 2030, renewable energy targets and nations with net-zero targets

Country	Emission reduction target	Net zero Target by	Renewable energy target	Global region
Brazil	43% below 2005 levels in 2030	2050	28–33% renewables in energy sector by 2030: 23% to power supply; 18% sustainable biofuels energy mix	South
USA	26–28% below 2005 by 2025 (-35 to -39% of 2005 levels in 2030	2050	-	North
UK	50% below 1990 levels by 2023–2027	2050	15% of energy consumption from renewable sources by 2020 (sufficient biomass resources to meet heat and power demand in 2020 and additional woodfuel to meet 2% of renewable energy target by 2020)	North
China	60–65% reduction in carbon intensity by 2030 from 2005 level	2060	20% non-fossil fuel to primary energy consumption by 2030; increase forest stock by around 4.5 billion m3 from 2005 level	South
Germany	40% below 1990 by 2030	2050	National target of 18% renewable energy by 2020	North
Indonesia	29% (unconditional) or 41% (conditional) reduction from business-as-usual emissions by 2030	-	Mixed energy-use policy with renewable energy targets at least 23% in 2025 and at least 31% in 2050	South
Australia	43% below 2005 levels by 2030	2050	AUD 20 billion investment in the electricity sector for decarbonisation of the grid and promoting renewable energy	North
India	Energy intensity of GDP by 33–35% below 2005 by 2030		Electricity from renewable energy from wind and solar (National Electricity Policy and Integrated Energy Policy)	South
Viet Nam	8% (unconditional) or 25% (conditional) reduction from BAU emissions by 2030	-	National Energy Development Strategy to 2030 with vision to 2050	South
Japan	26% below 2013 levels by 2030	2050	22–24% of electricity from renewable energy including 3.7–4.6% from biomass energy	North
Ethiopia	64% reduction from BAU emissions by 2030	-	Power generation from renewable energy, remove subsidies of fossil fuel to encourage renewable energy	South
Finland	40% below 1990 by 2030	2035	-	North
Argentina	37% reduction from BAU emissions by 2030, if all conditional measures implemented	-	-	South

Source: https://www.visualcapitalist.com/race-to-net-zero-carbon-neutral-goals-by-country.

and renewable energy, energy efficiency and security (EPA 2020). The federal-level policy initiatives supported a renewable energy goal of 80% clean electricity by 2035 (IRENA 2015). Several states adopted policies, laws and regulations to enhance use of bioenergy (Anderson et al. 2004).

2. China's Renewable Energy Law 2006 and the Revised State Renewable Energy Law 2010 provided a legal framework for an extensive expansion of bioenergy use through biomass power generation, biogas and biofuels (Xu and Yuan 2015). In addition, China has been integrating the renewable energy initiative into its national five-year development planning since 1995 and has strengthened and supported the initiative (Xu and Yuan 2015) to become the top country in the world in renewable energy generation in 2018 (BP 2019).

3. European countries attributed approximately 80% of GHG emissions to the energy sector and heavily depended on imported fossil fuels for their energy source. Hence, the EU actively pursued climate and energy policies to address climate change and energy security issues (CEPS 2008). The Climate and Energy Policy 2007 and the Renewable Energy Directive (RED I) were instrumental in driving bioenergy development and use in Europe and beyond by setting out an explicit, binding target of a minimum of 20% renewable energy of total energy consumption and at least 10% biofuel use in all transport sectors by 2020 (EP&CPU 2009). In addition, member countries developed national renewable energy actions outlining their strategies, programmes and plans to meet the intended targets by aligning with the EU climate and energy policy. By achieving the 2020 targets for GHG emission reduction and renewable energy, EU countries adopted RED II. They agreed on a new minimum threshold of 32% renewable energy in total energy consumption and a minimum of 14% bioenergy in the transport sector to meet the binding target of emissions reduction by 40% below the 1990 level by 2030 (EP&CPU 2018). In addition, RED II introduced new risk-based sustainability criteria for forest biomass with the aim of ensuring compliance with sustainable forest management laws and principles (for example, legality, regeneration, protection of sensitive areas, minimization of biodiversity impacts and maintenance of long-term forest productivity) and that the carbon impacts of bioenergy were properly accounted for in the land use and land-use-change sector (Camia et al 2021). Further, the EU regulation on deforestation free products was agreed in 2022 to minimize consumption of products, including wood, coming from supply chains around the globe associated with deforestation or forest degradation (EUDR 2022).

4. Brazil is the world leader in biofuel production, accounting for over 20% of global production in 2018 (BP 2019). The National Alcohol Programme supported bioethanol production from sugarcane as a substitute for fossil-fuel use in the transport sector in the mid-1970s (Morgera et al. 2009). The programme ensured bioethanol availability at a low price, consistent national pricing, tax incentives to vehicles using ethanol and financial assistance to farmers (Morgera et al. 2009). In addition, the demand for biofuel increased owing to a policy on a mandatory 11% biodiesel blend and 27% bioethanol mixed with petrol in the transport sector (GAIN 2019).

3.3.4 Financial investments and access to technology

Transitioning from fossil fuels to bioenergy and other renewable energy requires a substantial financial investment. IRENA (2020) estimated a minimum investment of USD 20 billion per year to supply biofuels under the low-carbon transport scenario and projected a redirection of investment from fossil fuels to the renewable energy sector. Over USD 3 trillion per year is required for a total transformation of the global energy system to climate-friendly, efficient and cost-effective renewable energy by 2050 (IRENA 2020). The level of investment in the energy sector depends on individual countries' policies and strategies for clean, green and renewable energy pathways. However, the vast investment required to integrate bioenergy into developing countries' energy systems is a formidable barrier to implementation.

While research and development into second-generation biofuel technologies have improved the cost-effectiveness of production, this still needs to be made available to developing countries that cannot use their potential biomass production to generate bioenergy. Using bioenergy for power is an opportunity for developing countries to facilitate universal energy access and support achievement of the SDGs. Programmes that provide financial support to replace fossil fuels by co-funding farmers' co-operatives, community groups or industry will enable power generation from sustainable biomass sources. Developing countries can learn from the experience of countries in which programmes provide financial support that encourages bioenergy.

For example, Norway offers financial support to farmers or industries to establish or convert fossil-fuel heating plants (MPE 2012). In addition, the USA states involved in the Climate Alliance have various schemes to provide financial support to encourage renewable energy, including bioenergy use and technology development. For example, New Mexico established a Biodiesel Blending Facility Tax Credit of a maximum of USD 50,000 to produce at least 2% biodiesel blends. New York State established the NY Green Bank and provided loans to clean-energy projects across the state. In Puerto Rico, a Green Energy Fund from motor-vehicle sales tax and government co-funding supported renewable energy projects (USCA 2019).

3.3.5 Land availability and productivity

Net land availability should exclude land required for socio-cultural, economic and environmental purposes. Several studies assessed land availability for bioenergy using different methodologies, assumptions and datasets (Baridzirai et al. 2012). Collectively, they estimated land availability for bioenergy ranging from 240 million hectares (Mha) to over 1 billion hectares (Bha) (Woods et al. 2015). The lower value of the potential bioenergy area resulted from applying strict rules excluding regions of food production, high conservation value, wetlands, land competing with water, agricultural land, unmanaged land and protected areas (van Vuuren et al. 2009).

A global analysis of land use and availability estimated 1.4 Bha available for bioenergy in 2010. However, they projected it would reduce to 905 Mha by 2050 owing to competition with other land uses (Alexandratos and Bruinsma 2012). Another study based on the Food and Agriculture Organization of the United Nations' (FAO) high-level assessment of land suitability estimated about 2.7 Bha of total area (of about 13 Bha) was suitable for crop production and about 1.3 Bha of this was already under agriculture. The remaining 1.4 Bha that was suitable, but unused, for crop production could be potentially available for bioenergy production (Nakada et al. 2014).

According to this analysis, Africa had the highest area suitable for crop production, with over 800 Mha, about 29% of the total area suitable (2.7 Bha) for crop production and 239 Mha (30%) under agricultural use in 2010. South America had the second-highest area, of 540 Mha, suitable for crop production with 173 Mha (32%) under agriculture. Asia had the third highest suitable for crop production (529 Mha) and the most extensively used, with about 391 Mha (74%) under agriculture. Oceania had the lowest area suitable for crop production (113 Mha), with 41 Mha (36%) under agriculture in 2010.

Table 2. Cropland suitability under different land uses based on a high-level analysis of FAO data

Region	Suitable land, Mha	Currently under crop production, Mha			Surplus land for bioenergy, Mha		
		2010	2020	2030	2010	2020	2030
Africa	806	239	265	290	567	541	516
Asia	529	391	392	392	137	137	137
Europe	448	254	255	255	195	194	193
South America	540	173	197	221	367	343	319
North America	352	187	188	188	165	165	164
Oceania	113	41	40	40	72	73	74

Source: Nakada et al. 2014

Table 3. Land and bioenergy demand in 2010 and 2050

Bioenergy	2010			2050		
	Bioenergy Demand, EJ	Land Demand, Mha	Land intensity, Mha/EJ	Bioenergy Demand, EJ	Land Demand, Mha	Land intensity, Mha/EJ
Biofuels demand (EJ)	1.5	30	20	32	100	5
Bioelectricity (EJ)	4.1	11.4	2.8	28.9	44.2	1.5
Bio-Heat (EJ)	13	13	1	67	44	0.8
Total or **Average**	18.6	54.4	**2.9**	127.9	188.2	**1.5**

Source: IEA 2011

In 2020, by excluding land under agriculture, the potential area for bioenergy production was highest in Africa with 541 Mha (70%) followed by South America with 343 Mha or 68% and Asia with 137 Mha (26%) (Table 2). Table 2 presents the projected area for bioenergy production by 2030.

Biomass production depends on site suitability. The bioenergy potential of degraded or marginal land is estimated to be as low as 1 tonne of dry matter per hectare per year (tdm ha-1yr-1) for abandoned agricultural land or degraded grassland (Hoogwijk et al. 2003) and about 4 tdm ha-1yr-1 for abandoned pastoral land (Campbell 2008).

With an increasing demand for biomass to supply biofuels, bio-electricity and bio-heat, the International Energy Agency (IEA) (2011) estimated land demand in 2010 and the projected land requirement for 2050, with increased energy efficiency (Table 3). A significant increase in land productivity was projected by 2050 — approximately 3.5 times that of 2010 — to supply energy demand of about 130 EJ in 2050, that is, about seven times more than in 2010l. The highest gain in efficiency is predicted to be a four-fold increase by 2050 from 2010 levels owing to technological enhancements.

The above theoretical projection of the global potential of bioenergy is based on assumptions of land availability and suitability and the efficiency of production per land unit. These estimates may be far from the actual figures. Therefore, a comprehensive analysis of bioenergy potential that integrates the various socio-economic and environmental factors with high-resolution spatial data is needed to determine more accurate potential that could practically be achieved. Such an investigation is more feasible at country or local levels. In this context, Batidzirai et al. (2012) reviewed studies of bioenergy potential at national scale, estimating the potential from agricultural and forestry biomass of five countries — China, India, Indonesia, Mozambique and the USA — ranging from as low as 1.1 EJ in India to a maximum of 27.3 EJ in China by 2030.

3.3.6 Cost of bioenergy production and market guarantee

The cost of bioenergy production and the markets determine bioenergy deployment and operational continuity. The cost of bioenergy production depends on the initial and maintenance costs of machinery, the cost of bioenergy feedstock, the yield of bioenergy crops, operating costs, harvesting and transport costs of the feedstock, insurance, labour/staff costs and supply costs. Therefore, increasing the yield of bioenergy crops using suitable land, diversifying feedstock for sustained supply, and the low price and use of by-products in a circular economy will help lower production costs.

A lower production cost will make bioenergy more competitive with fossil fuels in the energy market. The high price of the latter often supports demand for biofuels as a cheaper alternative to increasing fossil-fuel production. A rise in the price of fossil fuels between 2000 and 2007 was linked to a tripling in ethanol production and a ten-times increase in biodiesel production (FAO 2008). Government policy favouring biofuels provides market guarantees, encouraging users to switch to biofuels from fossil fuels. Brazil guaranteed the market for ethanol by enforcing fossil-fuel prices (de Andrade and Miccolis 2011).

3.4 Advancing bioenergy

Bioenergy is not without its challenges, which occur in a range of social, economic and environmental contexts. This section highlights those challenges and describes the arguments for and against bioenergy.

3.4.1 Arguments against bioenergy

Over the past two decades the development of bioenergy, particularly use of biomass fuels in the global north has been strongly criticised. The key issues and arguments against biomass energy development are reviewed here.

Environmental implications

Accelerating deforestation and loss of biodiversity: One of the severe environmental impacts of the growing use of bioenergy is deforestation to expand the area of cropland needed for producing feedstock (EPA 2018). The increasing demand for feedstock requires more cropland, clearing of forest areas (Aberman and Cohen 2012) and expansion into less productive areas. For example, in the USA, food demand is predicted to double by 2050, forcing the production of energy crops into less productive and conservation areas, resulting in their loss and associated losses in biodiversity, and increases in soil erosion (Avery 2006) and other negative environmental impacts, which will affect achieving true sustainability. In addition, increased demand for biofuels has pressured exporting countries to expand bioenergy crop areas into other land uses, including forest areas in Brazil and Indonesia (EPA 2018). A study commissioned by Rainforest Foundation Norway suggested a sharp increase in demand for biofuel using, in particular, palm and soy oil, which would likely cause extensive deforestation, estimated at 7 Mha. Peatland would make up more than half of that deforested area. The resulting GHG emissions were estimated at 11.5 billion tCO2-e, greater than China's annual fossil-fuel emissions (Malins 2020). Further, land-use change from forest to agricultural land destroys unique habitat for flora and fauna, that is, loss of biodiversity, with concomitant increases in soil erosion and sedimentation, which has a negative impact on water quality, in addition to impact from increased fertilizer application (FAO 2008; Rosillo-Calle 2012).

No climate benefits: Biofuel's climate benefits are also questionable, particularly concerning whether there is a tangible reduction of GHGs when switching from fossil fuels to bioenergy (see Norton et al. 2019). Aberman and Cohen (2012) argued that converting forests into cropland for biofuel feedstock results in more GHG emissions, despite reducing emissions by replacing fossil fuel. It takes several years to reach net GHG reduction, depending on carbon-stock lost from land clearing and feedstock energy efficiency. Even biofuels produced from high energy-efficient feedstocks, such as sugarcane, could take at least 17 years to achieve a net GHG benefit (Fargione et al. 2008). More than 650 scientists heavily criticized (see the letter) RED II for allowing EU countries to use woody biomass from tree harvesting for bioenergy production as a contribution to meeting the binding target of a minimum of 32% renewable energy by 2030. The scientists contended that this provision encouraged forest harvesting for bioenergy production and immediately released GHG emissions, which otherwise would have been sequestered in the trees. Even burning of woody biomass derived from sustainable forest management exceeds GHG emissions from fossil fuels. The scientists argued that regrowth of forest would take a considerable period before recovering the carbon debt and urged restriction of eligible forest biomass to woody residues and wastes.

Increasing water scarcity: The impact of biofuel's water us is another negative environmental implication (Aberman and Cohen 2012; IEA 2010). The additional requirements of high water-demand biofuel crops (sugarcane, maize, oil palm) worsen water scarcity by competing with agriculture. In the USA, the water needed for maize ethanol production — 100 million gallons per year — is estimated to be the equivalent amount needed for 5000 people (Service 2009). Water scarcity results in less water available for human use, negatively affecting health and sanitation. Further, fertilizers and pesticides used in bioethanol crops can contaminate water systems and negatively affect water quality. For example, the high-intensity use of nitrogen fertilizer and low uptake by maize crops resulted in nitrate pollution in the USA's groundwater (Garcia et al. 2017). At worst, such water can be unsuitable for human use, other animals or plants (FAO 2008).

Food security (prices, nutrition, availability, access)

A simple fact is that the world's population is growing and food demand is increasing. The agricultural system must produce more food, feed and fibre to sustain population growth by expanding the agricultural area and enhancing productivity through technology. However, using food crops for bioenergy puts pressure on food supplies. Using food crops as bioenergy is a concerning issue from food security and environmental perspectives (FAO 2008). In the USA, the use of first-generation feedstock, maize, in particular, was the centre of this debate on the rapid expansion of maize for biofuels and the subsidies provided (Rosillo-Calle 2012). The use of land for biofuel crops has resulted in direct competition with agricultural use for food, reducing the area for food production. Thus, the large-scale use of grain crops for bioenergy production is understood to compete directly with food, increasing food prices and negatively impacting food availability and affordability (Valentine et al. 2012), especially for economically disadvantaged people in developing countries (Rosillo-Calle 2012). Many factors interact to determine food prices and the role of bioenergy in food price rises is often disputed. However, food price increases in 2007–2008 concurred with considerable growth in bioenergy production (FAO 2008; Aberman and Cohen 2012; Rosillo-Calle 2012).

Aberman and Cohen (2012) link the food-security issue and first-generation biofuel because more cropland was needed to supply feedstock to meet blending targets. According to the IEA (2004), nearly half of the USA's cropland is needed to meet the 15% blending target for transport fuel. Japan needs threefold of its cropland area. The same study concludes that nearly two-thirds of 102 countries face food insecurity owing to insufficient land for feedstock production. The IPCC (2018) agrees that the large scale of bioenergy production can lead to food insecurity.

3.4.2 Arguments for bioenergy in the global south

Recent interest in bioenergy development has emerged in the global south. It is important to assess the bioenergy concerns from the global north to determine which apply to the context in the global south and whether there are additional issues for consideration. The key issues and supporting arguments for biomass energy development are reviewed here.

Energy security

Sustainability is advocated as a prerequisite for the bioenergy pathway to energy security so long as the appropriate social, economic and environmental safeguards are present (FAO 2008). Sustainable bioenergy takes into consideration all of the opposing arguments against bioenergy and supports sustainably sourced, renewable bioenergy for energy security and decarbonization. As a result, several countries have developed, and regularly update, their policies to ensure energy security by promoting sustainable sources of bioenergy. In addition, sustainable bioenergy certification frameworks have been developed, establishing principles and environmental, economic and social criteria that aim to ensure there are no negative impacts from bioenergy production.

Except for a few countries in the Middle East, the rest of the world imports fossil fuels and spends a significant portion of their GDP doing so. All these nations consider bioenergy as an opportunity to reduce their dependency on fossil-fuel importation and save foreign exchange (Rosillo-Calle 2012). For example, the USA and Brazil promote bioenergy to reduce fossil-fuel consumption to save foreign exchange and reduce GHG emissions because the demand for energy is continuously growing. Similarly, developing countries can use bioenergy as their primary energy source and, at the same time, save foreign exchange for investment in other developments.

Complementarity with food security

Rosillo-Calle 2012 argued that the debate on food security and bioenergy has no ground in truth; it is instead a political game to promote the vested interests of certain individuals or companies against the use of biofuels. Brazil, the single-largest producer of bioethanol from sugarcane, has seen biofuels as an opportunity to address energy needs and reduce dependency on imports without negatively impacting food supply and prices (Rosillo-Calle 2012). Demand for biofuel can lead to a more diverse and modern agricultural industry with a sustainable base from which to increase productivity. Models predict that the sustainable intensification of agriculture — agroforestry's 'vertical' intensification is one example (Rice 2008; Rahman et al 2014; Nath et al 2016) — could increase productivity requiring less area to meet the demand of the growing population. Land-use optimization under a more efficient agricultural system could free 240 Mha for bioenergy without jeopardizing food security (IRENA 2017). Pro-biofuel lobby groups argue that modernizing the agricultural production system could provide sufficient food and feedstock for biofuels, replacing 5–20% of fossil fuels without affecting food security (Rosillo-Calle 2012).

Restoration targets

Land degradation is another global environmental problem of the 21st century. Degraded land is estimated to range from less than 1 Bha to over 6 Bha (Gibbs and Salmon 2015). Bioenergy from perennial plants, including forest biomass by planting suitable mixed tree species, offers a 'win-win' solution for restoration of degraded land and GHG emissions (IEA 2010). In addition to providing woody biomass for bioenergy production (Ezeoha et al. 2017), mixed-species tree plantations — aka agroforestry — prevent soil erosion and siltation of waterways, create cooler microclimates, enhance biodiversity by providing suitable habitats for flora and fauna, including pollinators and natural predators (helping to spread risk of loss from pests and diseases) Further, the additional vegetation recuperates the soil and plant life through nutrient cycling and bolstering soil organic carbon, with above- and belowground biomass sequester atmospheric carbon, thereby providing emission reductions (Harvey and Guariguata 2020; ICRAF 2022).

Livelihood support

Community employment is vital to sustain rural economies and support the livelihoods of people in rural areas. Lack of employment or income forces people to migrate to urban areas where they often struggle for a living. Bioenergy production from growing feedstock through to end-use generates employment for local communities working in the value chain. The positive impacts of bioenergy on people's livelihoods in Africa, Latin America, the Caribbean and Asia have been reported (Phalan 2009; Wiek et al. 2015; Brewer et al. 2018; IRENA 2020).

3.5 Key benefits of wood-based bioenergy

Wood-based bioenergy has been used to produce electricity, facilitate heating and produce second-generation liquid biofuels (Eckhoff and Mackes 2010). Leading countries have advanced the use of biofuels sourced from woody biomass to reduce use of fossil fuels. Policies and legislation changes, fuel standards and incentives have enhanced bioenergy and led to replacement of fossil fuels. Many bioenergy-related publications advocate the benefits of sustainable wood-based bioenergy. The section below summarizes the key benefits of wood-based bioenergy production and use.

3.5.1 Promote sustainable forest management

Sustainable forest management involves operations to maximize the forest yield or enhance the growth of intended forest products, which produces forest residues as a by-product of forest management operations. The removal of forest residues benefits the forest and the owner in the following ways: 1) reduces fuel loads and thereby reduces fire risk; 2) enhances forest health and productivity by maintaining healthy trees; 3) reduces susceptibility to pests and diseases; 4) restores degraded land and supplies biomass for bioenergy (Borchard et al. 2017).

In developing countries, more than a quarter of traditional fuelwood is obtained from unsustainable sources (Bailis et al. 2015), leading to deforestation or forest degradation. Adopting of sustainable forest management practices in plantations of short-rotation, fast-growing species minimises unsustainable harvesting of biomass or timber, ensures the sustainable supply of biomass for bioenergy generation, supports climate-change mitigation and, as part of a landscape approach, provides habitat for biodiversity. Brazil, for example, has advanced research on energy yield of various Eucalyptus species in different sites (da Cunha et al. 2021).

3.5.2 High energy efficiency and low cost of production

Forest biomass produces advanced or cellulosic ethanol from the cellulose content with a ten-times greater energy efficiency (Stacey 2008) and approximately seven-times more volume than ethanol from grain (Andrews 2008). The low production cost and higher energy efficiency ensure that advanced or cellulosic ethanol has growth potential (Ezeoha et al. 2017).

3.5.3 Significant reductions in GHG emissions

Wood-based bioenergy has up to 90% less GHG emissions than fossil diesel whereas maize-based ethanol only reduces emissions 10–20% (Montenegro 2006). When the life cycle is considered, grain-based ethanol produces net emissions attributed to the release of nitrous oxide (N2O) during ethanol production (Ezeoha et al. 2017).

3.5.4 Generate employment and income

Biofuel production can generate new employment opportunities for local communities in rural areas that help people's livelihoods and food security (von Braun and Pachauri 2006). Smallholders can supply biomass resources to modern bioenergy plants and receive a sustainable income source (GBEP 2011). The economic viability of bioenergy production using modern biomass has been demonstrated in many locations and can provide financial returns on the investments needed to build projects (IFC 2017).

3.5.5 Added value for woody biomass

The technology development for second-generation biofuels via the conversion of lignocellulosic feedstock obtained mainly from wood-based biomass has offered a new market opportunity with value addition to biomass that would typically not be used (UNCTAD 2016). One of the second-generation biofuel technologies estimates a yield ratio of 1:100, that is, 100,000 tonnes of biofuel produced from 1 million tonnes of wood biomass (wet) (Ranta 2014). Another estimate suggests 310 litres of biofuel from 1 tonne of woody biomass (Mackes et al. 2008). The demand for woody biomass for bioenergy creates a market for forest residues and waste, which account for about 40% of the total biomass harvested. The additional income from such biomass will motivate smallholders and larger-scale private growers to produce woody biomass from their marginal land.

3.5.6 Support rural economy and diversify energy supply

Rural community employment and a new income source to smallholders can boost rural economies. In addition, by generating modern energy locally — and end-use locally and externally — bioenergy can circulate through the economy. This further enhances local capacity and promotes sustainable development based on a clean, green economy.

3.5.7 Socioeconomic and health benefits

In developing countries, about 50% of woody biomass is estimated to be used as fuelwood for cooking and heating (Bailis et al. 2015). However, fuelwood for cooking is considered an inefficient use of biomass energy and is responsible for serious health issues in women and children. Therefore, the displacement of fuelwood with modern bioenergy can bring socioeconomic and health benefits (IPCC 2019), especially to rural women and children, by saving their time in fuelwood collection and minimizing exposure to smoke.

4 Wood-based bioenergy: a way forward for energy supply in the global South

Bioenergy has emerged as a primary means to achieve GHG reduction targets, ensure energy security by reducing fossil-fuel dependency and save foreign exchange by leveraging economic development. In this context, bioenergy sustainability has received considerable attention to address its challenges (GBEP 2011; Goh et al. 2020) and encourage use and reaping of benefits. Bioenergy sustainability means that the energy derived from bio-resources complies with social, economic and environmental sustainability criteria, is recognized as an indispensable and integral part of the bioeconomy and contributes to a circular economy via its by-product value addition and waste minimization.

With the potential to reduce GHG emissions by replacing fossil fuels with renewable energy sources, bioenergy is a crucial strategy for low-carbon economic development and the growth of a bioeconomy. In addition, an economy based on bioenergy is considered more equitable than a fossil-fuel economy because it allows all developing countries to harness bioenergy's economic potential (Johnson 2017). Johnson (2017) suggests that integrating bioenergy into landscape-scale production systems delivers several co-benefits, directly and indirectly, relevant to the SDGs. Bioenergy sustainability (Destek et al. 2021) is acknowledged to directly contribute to five out of the 17 SDGs: affordable and clean energy (SDG 7); climate change (SDG 13); decent work and economic growth (SDG 8); life on land (SDG 15); and good health and well-being (SDG 3). The economic benefits from bioenergy via local employment and contribution to community health and well-being (Jagger et al. 2019) indirectly address another four SDGs: no poverty (SDG 1); industry, innovation and infrastructure (SDG 9); responsible consumption and production (SDG 12); and reduce inequalities (SDG 10) (Figure 5).

Various bioenergy sustainability frameworks have been developed to ensure that the whole life-cycle process from feedstock to end-use of bioenergy meets sustainability principles and criteria (for example, GBEF 2011; Köppen et al. 2013; RSB 2016). These frameworks are designed to provide social, economic and environmental safeguards. In particular: no negative impacts on the environment owing to land-use change; no loss of biodiversity; no water scarcity; and no worsening of food insecurity. Table 4 compares institutional aspects of the bioenergy sustainability frameworks developed by the Global Bioenergy Partnership and the Roundtable on Sustainable Biomaterials.

The GBEP bioenergy sustainability framework applies social, economic and environmental sustainability principles with eight measurable

Figure 5. Bioenergy sustainability and the direct (solid line) and indirect (dotted line) roles in addressing the SDGs

indicators for each principle, whereas the RSB provides a comprehensive framework including standards, procedures and guidance documents comprising ten different components. Note that the engagement of an RSB-accredited certification body is required to assess biomass production and bioenergy generation and issue a compliance certificate to the standard based on the minimum requirements set out by the RSB.

Table 4. High-level comparison of bioenergy sustainability frameworks by Global Bioenergy Partnership and the Roundtable on Sustainable Biomaterials

	Global Bioenergy Partnership (GBEP)	Roundtable on Sustainable Biomaterials RSB (version 3.0)
Reference	**GBEF (2011)**	**RSB (2016)**
Aim of the institution	Promote modern bioenergy in developing countries to meet their national goals and sustainable development	Promote sustainable production and processing of biomass, biofuels and biomaterials globally ensuring best practices
Structure of the framework	Three pillars (environmental, social and economic). Relevant themes under each pillar; 24 Indicators based on the identified themes (eight environmental indicators, eight social indicators and eight economic indicators)	A comprehensive framework with standard, procedures and guidance documents comprising ten different components 12 principles and 39 criteria based on a management and risk-oriented approach identified through multi-stakeholder consultations globally Full member of International Social and Environmental Accreditation and Labelling Alliance
Methodology	Provides methodological approach, units, applicability, data source and gap, limitation and references	An additional module to assess risk of indirect land-use change Criteria are further elaborated into 153 minimum requirements, which are specified at two levels of operators (biomass producers and industrial operators), feedstock, region, and whether to be met immediately or over time (progressive) Certified by RSB-accredited certification body (third party)

5 Sustainability framework for wood-based bioenergy

An IPCC special report (2019) acknowledged — with 'high confidence' — both positive and negative impacts of using biomass for bioenergy. Further, it clarified that the consequences were context-specific and attributed to various factors, including the scale of bioenergy production; previous land use and carbon stock; biomass feedstock types (wood-based or agri-based); climate region; and management regime. For instance, at the stand level, woody biomass residues obtained from land-use change or old-growth forests can result in significant GHG emissions; taking hundreds of years to achieve net GHG benefits from bioenergy (Nabuurs et al. 2017). Nasi (2018) warned that the time debt to achieve carbon neutrality after tree harvesting for bioenergy will not help climate-change mitigation efforts now.

In contrast to EU countries, those in the global South are uniquely placed to benefit from wood-based bioenergy by sustainably sourcing feedstock from fast-growing and short-rotation species suitable for growing on degraded and marginal land without threatening food security and conversion of natural forests. Moreover, wood-based bioenergy can enhance people's access to clean electricity or substitute powerplants using fossil fuels and generate employment or income to rural people in support of their livelihoods. Besides, bioenergy production and use generate co-benefits supporting climate-change mitigation, energy diversification and security.

Applying our understanding of the bioenergy life-cycle's drivers and factors, and arguments for and

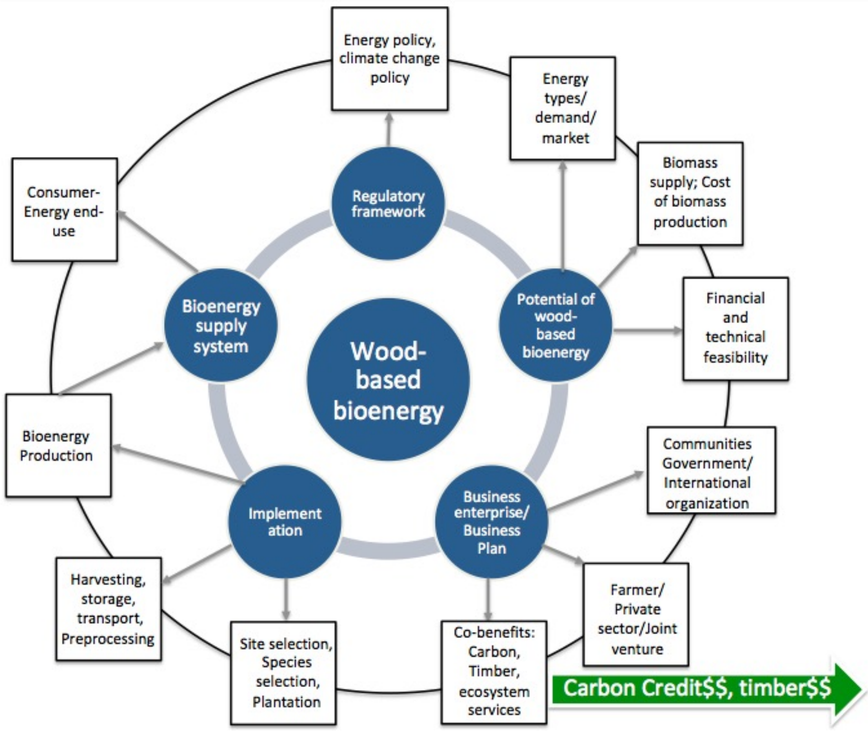

Figure 6. Wood-based bioenergy development process encompassing the bioenergy life cycle

Source: The authors

against bioenergy, we have developed a framework for wood-based bioenergy (Figure 6). Developing countries can use this framework as guidance for evaluating and benefiting from unused land resources for producing bioenergy, restoring ecosystem services, mitigating climate change and achieving the SDGs. The framework has five major elements and 11 sub-elements.

5.1 Regulatory frameworks

A regulatory framework provides policy certainty and creates an investment opportunities to develop wood-based bioenergy by integration into national, regional and local energy systems. National development policies, priorities, regulations, strategies and action plans should be encouraged to include bioenergy and encourage uptake by providing tax credits or subsidies to ensure competitiveness with fossil fuels. Mandatory energy mix requirements in the USA, Brazil and Indonesia encourage bioenergy production and use. Policy certainty boosts market confidence and opportunities, encouraging investment. For example, the Government of Indonesia has set targets for renewable energy to represent at least 23% of the energy mix by 2025 and at least 31% by 2050 (BKPM 2022). The main types of renewable energy deployed for power generation in Indonesia are (in decreasing order of installed capacity) hydropower, geothermal, biomass and biogas, solar and wind. The state electricity company (PLN) plans to generate 21.50 GW of electricity from renewable sources by 2026. Indonesia's Renewable Energy Guide (2022) highlights the use of renewable energy sources for national electricity purposes[7].

5.2 Potential of wood-based bioenergy

Taking into consideration energy end-use demand and the type and quantity of sustainable biomass supply and production costs, it is possible to assess the potential of wood-based bioenergy for countries in the global South. Further, understanding the energy types and demand help identify the market and the size of the bioenergy processing capacity needed to meet demand.

Estimation of available biomass must focus on marginal and degraded land and exclude existing forest and conservation and protection areas unless biomass is supplied under a sustainable forest management regime. A conservative value for biomass yield should be used based on species, climatic conditions, site quality and management regime to avoid overestimating supply. Agricultural residues other than woody biomass can account for additional biomass requirements of a given bioenergy powerplant.

Estimating biomass production includes costs associated with establishing the plantations and continuing management. The average cost of establishment of a plantation has been estimated at USD 1500 per hectare in Africa (Reij and Winterbottom 2017). However, the cost could be less if communities are involved in establishing and managing nurseries to grow seedlings and planting and management is carried out using a community-based approach. Costs could be further offset if biomass production is part of an agroforestry system that provides co-benefits, such as food, fruit, nuts, medicines.

5.3 Business enterprise and business planning

Commercial enterprises typically prepare business plans, which describe how a wood-based bioenergy plant is established and operates to provide potential revenue sources, such as from a 'carbon farming' programme and supply of high-value timber to the market. Business plans typically explore, and bring together, interested parties, including communities, the larger private sector, banks, governments and non-governmental and international organizations.

Securing finance is critical to successfully establishing and operating a wood-based bioenergy system. However, the high initial capital cost for second-generation biofuels can be a major financial barrier (UNCTAD 2016) unless the investment comes from the government, high-net-worth donors or direct foreign investment (IEA 2010). Small-scale, wood-based bioenergy powerplants

7 "Indonesia has issued a regulation to encourage renewable energy use in one of the world's biggest carbon emitters, including a plan to retire some coal plants early, a presidential decree said." https://www.reuters.com/markets/asia/indonesia-unveils-new-regulation-boost-renewable-energy-use-2022-09-15/

can increase access to clean energy for rural people and replace fossil-fuel-based power generation. Individuals, the larger private sector and other institutions can collectively organize finance to use wood-based bioenergy, often through the establishment of a 'multi-stakeholder platform' or discussion forum consisting of government agencies, banks and finance institutions, companies and communities that receives all perspectives and seeks to optimise benefits.

5.4 Implementation pathways for bioenergy production

The implementation phase involves two distinct operations: 1) biomass production; and 2) bioenergy plant operation.

Biomass production includes identifying suitable areas, establishing appropriate species, managing growth and harvesting. The choice of species should include high-yielding, multi-purpose, locally suitable tree species. Bamboo can be used for high biomass yield, especially, in steep areas prone to soil erosion, or as windbreaks for coffee and tea plantations. Smallholders can also generate biomass by adopting an agroforestry system, which also provides diverse income sources. The oilseed-bearing tree species' Pongamia pinnata, Calophyllum inophyllum (Bochard et al. 2018) and Reutealis trisperma (Holilah et al. 2015)) are suitable for carbon farming, generating revenue from credits from the carbon sequestered in the above- and belowground biomass. In addition, the harvesting of mature timber species can yield timber and forest residues and waste can be used for bioenergy production.

Establishing pre-processing and bioenergy units at a suitable site (Waewsak et al. 2020) in a convenient location reduces biomass transportation costs. The spatial analysis capability of a geographic information system (GIS) is useful for optimising locations of biomass production areas and bioenergy production facilities (Jaung et al. 2018; van Holsbeeck and Srivastava 2020; Rodrigues et al. 2020). Coordination between the biomass and bioenergy production teams enhances the efficiency and operations of the bioenergy plant. Bioenergy production should use the latest technologies and focus on a circular economy by minimizing production-system wastes and producing value-added by-products from intermediary products. Capacity building for local people to produce bioenergy generates employment opportunities and guarantees the availability of a workforce.

5.5 Bioenergy supply systems

Bioenergy supply systems are key to distributing bioenergy from production sites to consumers. A network is needed to supply energy to businesses, industries and household consumers based on the bioenergy types. In addition, the system requires maintenance to ensure energy security.

For many countries in the global South, large-scale bioenergy systems are challenging and risky owing to the high capital costs of second-generation biofuels and sustainable biomass supply. However, with about half of the biomass used for traditional heating and cooking in developing countries in Africa and Asia (Bailis et al. 2015) and the availability of marginal and degraded land, there is a real opportunity for effective and efficient, small-scale, wood-based power generation that helps achieve SDG 7: access to affordable, reliable, sustainable and modern energy for all by 2030 (UNDP 2016).

This study offers the following points as guidance to establish sustainable, wood-based bioenergy supply in developing countries in the global South.

1. **Landscape-level planning and management:** This means establishing a strategic vision for an integrated land-use approach that focuses on identifying the resource base, land tenure and appropriate land use across whole landscapes, typically mixed use. Marginal and degraded land and any other type of abandoned land (land not used for food production) may be considered for use for biomass production for power generation. The potential productivity of the land, the species, area available and status of local communities will determine the sustainable biomass supply from a local or regional area. Biomass supply must not be sourced from any existing natural forest or conservation areas.

2. **Use of marginal and degraded land:** As indicated above, land eligibility criteria for biomass production can be established that

safeguard natural forests, wetlands, peatlands, high conservation value and cultivation land. The criteria should also provide measures to avoid indirect land-use change owing to biomass production. For example, RSB certification requires that land must not have been used for provisional [ecosystem] services in the three years prior to 1 January 2018 (UNCTAD 2016).

3. **Mixed-species plantations:** The choice of species must consider the species' suitability to the land and people by assessing the biophysical and social factors. Mixed, high-yielding and drought-resistant species suitable for the area are ideal for a sustainable supply of biomass (IPCC 2011b). Besides tree species, bamboo on degraded areas can aid restoration and provide, for example, a biomass yield of up to 9.45 t/ha from a managed plantation of *Guadua* bamboo (van der Lugt et al. 2018).

4. **Seamless monitoring system:** monitoring systems based on 'smart' technology, such as smartphone-based monitoring applications, can provide evidence regarding the biomass supply chain and bioenergy production in real time.

5. **Local initiative:** Biomass power generation should focus on local needs and provide energy access for market certainty. Bioenergy initiatives should develop strong partnerships and collaboration between stakeholders, including smallholders, communities, larger private sector, research and academic institutions, and government and non-governmental bodies.

6. **Conflict management:** All stakeholders involved in a bioenergy initiative should agree upon a conflict management protocol by considering all potential conflict scenarios. A stakeholder representatives committee can assist with review and resolution of conflicts.

7. **Governance of the biomass supply system:** Local government authorities should integrate the biomass supply system's governance into their system to ensure sustainable biomass production.

8. **Documentation and record-keeping:** a project document and monitoring report are essential to demonstrate that the biomass supply chain and bioenergy value chain adhere to the principles and criteria of bioenergy sustainability. Biomass and bioenergy producers should separately prepare a project document, providing details of all activities, inputs and expected outputs, including a monitoring plan identifying the parameters to be monitored, methods and monitoring frequency. This includes preparation of an annual monitoring report and record of implemented activities and parameter measurements. The project document should be submitted with the annual monitoring report to the responsible government authority. The authority or a third party chosen by the authority can undertake verification of the project to confirm that biomass production and bioenergy generation comply with the bioenergy sustainability framework.

For local, wood-based, bioenergy production, several monitoring indicators are proposed to ensure that biomass production and bioenergy generation adhere to social, economic and environmental safeguard goals and principles (Table 5).

Table 5. Monitoring indicators for sustainable, wood-based bioenergy production

Monitoring indicator	Unit	Monitoring frequency	Sustainable Development Goal	Safeguard principles
a. Area of land restored	ha/year	continuous	SDG 15 (Life on land)	Environment
b. Amount of biomass harvested	tonne/year	continuous	SDG 12 (Responsible consumption and production)	Environment
c. Amount of biomass used for bioenergy	tonne/year	continuous	SDG 12 (Responsible consumption and production)	Environment

continued on next page

Table 5. Continued

Monitoring indicator	Unit	Monitoring frequency	Sustainable Development Goal	Safeguard principles
d. Number of households/ smallholders participating in the bioenergy programme	number	continuous	SDG 8 (Decent work and economic growth)	Social
e. Access to energy: number of households/individuals obtaining access to modern energy	number	continuous	SDG 7 (Affordable and clean energy)	Social
f. Carbon stock of the standing biomass	tCO-2e	biannual	SDG 13 (Climate change)	Environment
g. Climate change: amount of the GHG emissions reduced through replacing fossil fuels, traditional fuels and energy efficiency	tCO-2e	continuous	SDG 13 (Climate change)	Environment
h. Employment generation: employment for local men and women	number (women) number (men)	continuous	SDG 8 (Economic growth)	Economic
i. Income generation: total income to local people	Currency of the state	continuous	SDG 1 (No poverty)	Economic
j. Contribution to the rural economy	currency of the state	continuous	SDG 8 (Decent work and economic growth)	Economic
k. Contribution to local infrastructure development	currency of the state	continuous	SDG 9 (Industry, innovation and infrastructure)	Economic
l. Number of beneficiaries of the infrastructure development	number of people	annual	SDG 9 (Industry, innovation and infrastructure)	Social
m. Contribution to community human development (capacity building, skills and knowledge transfer)	number (women) number (men)	annual	SDG 10 (Reduce inequalities)	Social
n. Impact on biodiversity: sighting and record of flora and fauna	number (flora) number (fauna) ecological status	continuous	SDG 15 (Life on land)	Environment
o. Impact on water availability in the catchment	increased / decreased (qualitative)	continuous	SDG 15 (Life on land)	Environment
p. Impact on water quality	yes/no (qualitative)	continuous	SDG 15 (Life on land)	Environment
q. Impact on soil stability and organic matter	positive / negative	continuous	SDG 15 (Life on land)	Environment
r. Impact on agricultural productivity in the catchment	increased / decreased (qualitative)	continuous	SDG 15 (Life on land)	Environment

6 Conclusion

The potential of bioenergy to mitigate climate change and energy security by substituting non-renewable, carbon-intensive fossil fuels and diversifying energy sources is well documented. As a result, both developed and developing countries have adopted bioenergy as a critical mitigation and energy security strategy. However, when bioenergy is not applied sustainably, there are food security issues, accelerated GHG emissions and environmental problems caused by the conversion or use of agricultural products and land-use change from natural forest to bioenergy production. In this context, bioenergy sustainability has emerged as a prerequisite, and sustainability frameworks and certification systems have been instrumental in achieving social, economic and environmental sustainability.

It must be borne in mind that there are differences in bioenergy benefits and negative impacts between the global North and South; with benefits generally outweighing negative impacts in the global South, particularly, in meeting rural electricity provision and demand; higher biomass productivity; the need for socio-economic benefits such as expanded livelihood opportunities; and greater opportunities to combine restoration of degraded land, biodiversity enhancement and need for revenue generation.

The study estimated about 1.4 Bha of land potentially available for bioenergy production. Integrating bioenergy with landscape-scale production systems can contribute to several SDGs and generate opportunities for developing countries to support local communities, create a more equitable economy and enhance energy access. Small-scale, wood-based power generation has a promising outlook owing to half of the biomass being used for traditional heating and cooking in Africa and Asia and the availability of marginal and degraded land requiring immediate rehabilitation or restoration. Countries may need to refine their environmental sector policies and strategies, including natural resources, climate, energy and land use, to adapt wood-based bioenergy production by taking into account the country's social, economic and environmental conditions and circumstances. Bioenergy sustainability frameworks are available for adoption that include monitoring indicators, building capacity and partnerships between public, private and other stakeholders. A global South forum would support dialogue, learning and cooperation and help to ensure that positive and transformative aspects of bioenergy development are realized and deleterious ones avoided. An example of such a platform is the CIFOR-ICRAF Circular Bioeconomy Transformative Partnership Platform (https://www.cifor.org/cbe).

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Many countries have recently adopted bioenergy as part of a critical strategy to reduce greenhouse gas (GHG) emissions to meet targets under the Paris Climate Agreement. Because of increased efficiency and lower production costs, along with legislative support and investment incentives, bioenergy use is swiftly becoming a renewable energy substitute for fossil fuels. The study provides a better understanding of bioenergy issues, potential and sustainability to inform countries in the global South and provide guidance on integrating bioenergy into their national energy plans by proposing a simplified sustainability framework for wood-based bioenergy.

Arguments are reviewed against biomass energy expansion, mainly developed in the context of the global north. The benefits of biomass energy expansion are also reviewed with a focus on conditions common to the global south. A sustainability framework is presented to illustrate better use of low-value land resources, produce bioenergy, restore ecosystem services, and mitigate and adapt to climate change. The study recommends guidance to establish sustainable, wood-based bioenergy supply in developing countries in the global South, which help ensure that biomass supply chains adhere to the principles and criteria of bioenergy sustainability.

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Republic of Korea