Food and Agriculture Organization of the United Nations

The role of wood residues in the transition to sustainable bioenergy

Analysis of good practices and recommendations for the deployment of wood residues for energy

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Abbreviations and acronyms

CHP	combined heat and power
EJ	Exajoule
FAO	Food and Agriculture Organization of the United Nations
GBEP	Global Bioenergy Partnership
GHG	greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Agency for International Cooperation)
GJ	Gigajoule
ICS	improved cookstoves
IEA	International Energy Agency
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
LPG	liquified petroleum gas
LUC	land use change
NGO	non-governmental organization
RIL	Reduced-impact logging
SDGs	Sustainable Development Goals
TJ	Terajoule
UBET	Unified Bioenergy Terminology
UNECE	United Nations Economic Commission for Europe

Executive summary

Bioenergy can be produced from different conversion processes and a wide variety of organic materials of biological origin. The combustion of fuelwood, charcoal, agricultural residues and animal dung using basic technologies such as open fires or rustic kilns and ovens is usually referred to as the traditional use of biomass for energy (or traditional bioenergy). This solid biomass represents 90 percent of the total bioenergy demand which was almost 65 Exajoule (EJ) in 2020. Modern bioenergy describes the conversion and use of biomass in high-efficiency energy conversion systems such as electricity generation, combined heat and power, heating technologies in residential space and commercial applications, and transport biofuels.

The Sustainable Development Goals (SDGs) laid out by the United Nations (UN) set out to achieve "access to affordable, reliable, sustainable and modern energy for all" (SDG7). Achieving this goal will likely require a transition from traditional uses of biomass for energy to modern systems of bioenergy production and use.

Modern bioenergy can play an important role in supporting a safer, more resource-efficient and sustainable energy access, notably for cooking, heating and power generation, and contribute positively to progress towards the SDGs.

The forest sector is the most significant contributor to the world's bioenergy mix. Forest products such as charcoal, fuelwood, pellets and wood chips contribute to more than 85 percent of all the biomass used for energy purposes. In 2020, globally industrial roundwood accounted for 51 percent of total roundwood production, as against 49 percent for woodfuel with a production of 1.9 billion m^3 (FAOSTAT). Most of the woodfuel production took place in Africa (36.9 percent of the world total), Asia (36.6 percent), and the Americas (17.1 percent) (mostly south America).

Woody biomass for energy purposes can come from various streams. The main stream for wood residues-derived fuels discussed in this report is generated from the harvested industrial roundwood value chain.

Residues from industrial roundwood value chains can be further subcategorized as:

- primary residues, that is, by-products from forest management activities aimed at roundwood production;
- secondary residues that are by-products from the industrial processing of roundwood; and
- tertiary residues, i.e. post-consumer wood.

The extent to which available residues can be directed to energy use will also be constrained by the competitive demand for the use of wood residues as raw material for other products (for example pulp and paper, textiles, fibreboard and particleboard), and the level of wood cascading within a given value chain.

The analysis of characteristics of world regions regarding energy access and wood uses helps the identification of specific challenges and opportunities for the mobilization of wood residue for energy uses:

- For African subregions, central America, the Caribbean and southern Asia, low energy access (as expressed by energy consumption per capita relative to the world average) and the large share of woodfuel relative to overall roundwood production are priority issues, in terms of encouraging a larger structural transition towards valuation of forest resources.
- For south America and subregions of south-eastern, eastern, central and western Asia, energy access is less of an issue; industrial roundwood value chains are well established and can likely be further developed and mobilized for increasing the recovery of wood residues for modern bioenergy.
- In most Asian subregions, an opportunity also exists for the use of tertiary residues, as they comprise an important share of the total availability of wood residues.
- For northern America, Oceania and most European subregions, competition from other industries for wood residues, among other factors, can impose challenges to the energy use of wood residues and provides opportunities for other forest products.

In instances in many developing countries, the effective management and efficient use of wood residues is often found to be lagging, while the somewhat low efficiency of harvesting and wood processing mills can cause an important generation of residues relative to the main products (e.g. sawnwood). The material balance of sawmilling processes of roundwood reported for some countries show values for the share of sawnwood ranging from 45 to 60 percent for coniferous species, and 45 to 66 percent for non-coniferous species, with the remaining share of roundwood ending up as chips, slabs, sawdust and shavings (along with shrinkage loss).

The by-products generated by industrial roundwood production are sometimes considered as residues with low economic value, and therefore are often abandoned, disposed, or eliminated by open air combustion, depending on the local context. Nevertheless, the production and use of modern bioenergy from wood residues can play an important role in supporting more resource-efficient and sustainable energy access, notably for cooking, heating and power generation. This helps extend the wood value chains and stimulate business development, thus contributing to a transition towards the sustainable development of a forest-based bioeconomy. Whereas the mobilization of wood residues for energy can lead to environmental benefits, it may also raise concerns, depending on the sources and types of residues.

Recommendations

To help address challenges and opportunities for the deployment of modern bioenergy from wood residues, the following recommendations can be made based on the study findings.

- **Support systematic changes in governance to help the modernization of wood energy value chains**

  Effective governance mechanisms for land use and regulations on the use of forest resources are essential for the modernization of wood energy value chains towards a decline in unregulated open access to wood resources and the establishment of a market price for wood that reflects the true costs of sustainable wood production.

- **Raise awareness of the benefits of modern bioenergy**

  The recognition of modern bioenergy as a competitive and sustainable alternative to other energy sources (including fossil fuels and traditional bioenergy) is also a fundamental condition. Direct policies that bridge the gap between the costs of modern bioenergy and fossil fuels can provide incentives and therefore build stronger awareness of the benefits of sustainable bioenergy as a renewable resource. The policy instruments may include capital grants or subsidies, for individuals and companies, for investments in infrastructure and improved bioenergy equipment, feed-in tariffs that ensure long-term guaranteed prices for power generation from modern bioenergy, carbon pricing, etc. There is thus a need for carefully designed information campaigns aimed towards the producers, consumers and policymakers.

- **Develop cooperative solutions for the modernization of the whole wood energy value chain**

  Bioenergy cooperatives can provide and manage integrated energy solutions to communities, including both sustainable and reliable feedstock supply and improved biomass conversion technologies. Such cooperatives bring together producers, entrepreneurs and consumers; they can conduct pilots and demonstrations of promising technologies, promote the open exchange of information and good practices and provide a stronger and united voice for discussions with policymakers. The organizational flexibility of cooperative organization structures makes them well suited to reach out to actors in informal economies such as that of woodfuel and could thus play a key role in the modernization of bioenergy value chains.

- **Improve data on wood flows from the land base to end-users**

  The collection of data is essential to provide information for the traceability of biomass and facilitate the mapping of future trade streams under different policies and scenarios. More thorough assessments of local and national availability of wood resources and the cascading use of wood within the industrial roundwood network should be conducted by regional or national forest services and agencies. This is crucial to understand the current provision and utilization rates of wood residues and their possible competing uses, and to stimulate investments, support sound policies and guide local stakeholders for future development.

- **Stimulate a cascading use of wood resources and increased efficiency in the industrial roundwood network**

  Although multiple factors determine the extent to which roundwood can be converted into higher value-added products, the higher percentage of use of industrial roundwood in the Global North versus substantially lower rates in most of the subregions in Africa and in some Asian and American subregions indicates where there is a clear potential to reverse the trends by maximizing the added value and the cascading use of wood material.

The financial viability of using wood residues for energy and other products is more likely to be ensured if the rest of the industrial roundwood network is based on a diversity of wood products, especially those of high value that maximize roundwood conversion efficiency and minimize waste. This helps increase the financial return for wood products wich, in turn, promote business opportunities for investing in equipment and further upgrading and commercialization of wood residues for energy. This can be encouraged by national policy measures that support the development of new industries and markets for wood products that can thus be seen as an indirect way of encouraging the mobilization of wood residues for energy in developing countries.

- **Develop classification and standardization of systems and practices for wood residues and wood residue-based energy carriers**

  For private stakeholders that seek to develop or improve bioenergy value chains, adequate characterization and sorting of primary, secondary and tertiary wood residues generated along the industrial wood value chain enable the identification of relevant avenues for further cascading use and/or for proper technologies and techniques for pre-treatment and upgrading into standardized energy carriers and energy production.

  A dialogue of policymakers on internationally accepted sustainability standards for bioenergy commodities (based on indicators of GHG balance, air, soil and water quality, etc.), with the guidance of relevant international organizations, could create new opportunities for sustainable mobilization and bioenergy trade. Certification of bioenergy commodities based on such standards could also increase transparency and public acceptance of wood energy carriers in regional and national markets. It can particularly benefit wood residue-based energy carriers, which do not raise most of the environmental concerns that sustainability standards aim to address.

1. Introduction

1.1 Background

While fossil fuels continue to dominate the world energy matrix, the share of renewable energy supply has reached 17.1 percent of total final energy consumption in 2018 (IEA *et al.,* 2021). Bioenergy, i.e. energy from biomass, represents about two thirds of the renewable energy supply; it provided about 11.3 percent of the global energy used in 2018, mainly for heat production, but also for electricity generation and for transport (World Bioenergy Association, 2020).

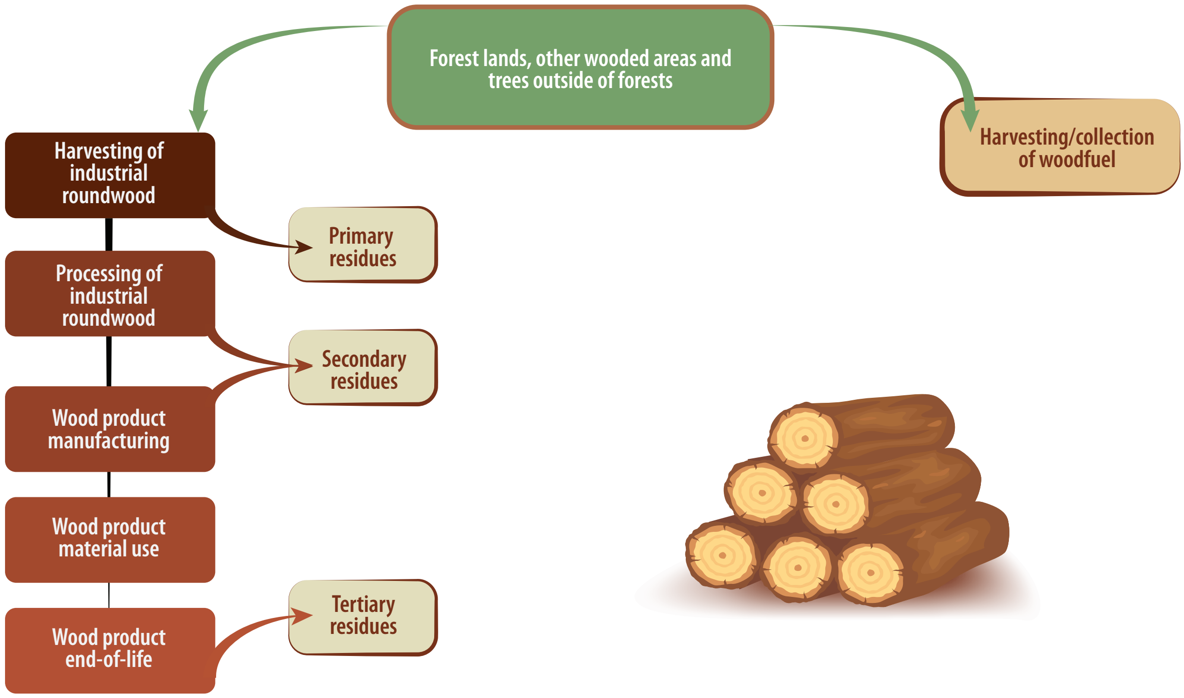
Biomass feedstock for bioenergy production may include various types of organic materials, including main produces, by-products and wastes of biological origin, but excludes material that is fossilized or embedded in geological formations (Verbruggen, Moomaw and Nyboer, 2011). The combustion of firewood, charcoal, agricultural residues and animal dung using basic technologies such open fires or rustic kilns and ovens is usually referred to as the traditional use of biomass (or traditional bioenergy). This solid biomass represents 90 percent of the total bioenergy demand which was almost 65 EJ in 2020 (IEA, 2021). Modern use of biomass for energy (or modern bioenergy) refers to biomass used in solid, gaseous or liquid forms in high-efficiency energy conversion systems; it includes the use of biomass for electricity generation, combined heat and power (CHP) plants, heating technologies in residential space and industrial process, and transport biofuels (Verbruggen, Moomaw and Nyboer, 2011). One of the SDGs laid out by the UN aims to achieve “access to affordable, reliable, sustainable and modern energy for all” (SDG7). Two of the targets of this goal for 2030 are to ensure universal access to affordable, reliable and modern energy services (Target 7.1) and to substantially increase the share of renewable energy in the global energy mix (Target 7.2). In particular, achieving these targets will require a transition from the traditional use to modern use of bioenergy.

The forest sector is the most significant contributor to the world’s bioenergy mix. Forest products such as charcoal, fuelwood, pellets and wood chips contribute to more than 85 percent of all the biomass used for energy purposes (World Bioenergy Association, 2020). In 2020, globally industrial roundwood accounted for 51 percent of total roundwood production, as against 49 percent for woodfuel with a production of 1.9 billion m^3, as reported in FAOSTAT 2020. Most of the woodfuel production took place in Africa (36.9 percent of the world total), Asia (36.6 percent), and the Americas (17.1 percent) (mostly south America).

Woody biomass for energy purposes can come from various streams. The main stream for wood residues-derived fuels discussed in this report is generated from the value chain of harvested industrial roundwood (i.e. harvested wood dedicated to the production of sawn timber, veneer, pulp, etc.) (Figure 1). Residues from industrial wood value chains can be further subcategorized (Dees *et al.,* 2017) as:

- primary residues, that is, by-products from forest management activities aimed at roundwood production;
- secondary residues that are by-products from the industrial processing of roundwood; and
- tertiary residues, i.e. post-consumer wood.

Figure 1: Woody biomass streams from forest land base and trees outside of forests



In some instances, residues generated by wood industries are considered as a valuable resource which can be used as feedstock for other products of the forest sector. For example, industries producing pulp and paper, textiles or fibreboard generally rely on wood chips or by-products provided by sawmilling activities. Residues can also be used for energy generation both to meet the internal needs of wood-processing plants and for external use. In the latter case, residues can be potentially conditioned and processed into densified bioenergy products such as wood pellets or upgraded into gaseous or liquid fuels. As such, valorization of wood residues can be part of a cascading use of wood resources and contribute to the emergence and deployment of a forest-based bioeconomy that encompasses activities based on forest biological resources in primary or subsequent uses, or in the substitution of non-renewable materials or energy resources.

The combination of sustainable forest management and efficient use of harvested roundwood, including the valorization of wood residues, can therefore represent an opportunity to develop modern bioenergy value chains as part of sustainable bioeconomy development.

Processing wood residues into energy carriers and using them in modern systems is already common in a number of industrialized countries, although these countries still greatly differ from one another in terms of the share of residues that feed into bioenergy production, and in terms of the organization and maturity of bioenergy markets (Thiffault, Asikainen and Devlin, 2016). Several of these industrialized countries have policies and incentives that promote investments and the market development of modern wood-based energy for residential and industrial heating and electricity production as part of efforts in energy transition towards sustainable renewable sources. Furthermore, the last decades have seen the expansion of the international wood pellet trade, which represented 36 percent of the direct international trade in bioenergy commodities in 2015 (Junginger *et al.,* 2019). This market is dominated by major exporters like the United States of America, Canada, Russian Federation, and Brazil. The European Unionremains the main destination for heating uses, while Asian markets (Japan and Republic of Korea) and the United Kingdom of Great Britain and Northern Ireland are considered key growth markets for industrial power generation, where pellets replace coal. Overall, the development of wood residue-based supply chains for modern bioenergy production has been found to contribute positively to progress towards some UN Sustainable Development Goals (Blair *et al.,* 2021, Kline *et al.,* 2021). Indeed, patterns of energy production and consumption in countries co-evolve with the economic development of communities, urbanization of populations and shifts in cultural habits and traditions, which have ramifications for all aspects of societies and therefore touch upon almost all facets of sustainable development.

Paradoxically, while modern wood-based energy is considered as part of the global green portfolio, in developing countries (where traditional bioenergy dominates) it is often seen as an undesirable source that should be replaced, and is commonly disregarded in forest and energy policies (GIZ and GBEP, 2015). A large share of the Global South still relies on traditional bioenergy to meet its energy needs for cooking and heating. The wearisome work of collecting firewood and the cost of meeting cooking and heating needs represent important social impacts in developing countries (Chum *et al.,* 2011). Moreover, traditional bioenergy has been found to generate significant negative impacts on human health, especially women and children, due to the air pollutants emitted by the inefficient cooking systems when burning biomass fuels.

On the other hand, in many developing countries, the effective management and efficient use of wood residues is often found to be lagging, while the somewhat low efficiency of harvesting and wood-processing mills can cause an important generation of residues relative to the main products (e.g. sawtimber). The by-products generated by industrial roundwood production are sometimes considered as waste to be abandoned, disposed, or eliminated by open air combustion (GIZ and GBEP, 2015).

The production and use of modern bioenergy from wood residues, along with improved cookstoves (ICS) and other energy efficient technologies, can play an important role in supporting more resource-efficient and sustainable energy access for cooking and heating. It can also contribute to provide renewable energy alternatives for electricity generation and industrial processes, as well as generating opportunities for participation in the growing international market of bioenergy commodities. This can reduce the pressure on natural forests, create new wood-based value chains and help revitalize rural economies and stimulate business development, thus contributing to a transition towards the sustainable development of a forest-based bioeconomy. Interestingly, replacing conventional wood-fuel-burning heating equipment with wood-pellet-based systems in households has been found to create large savings in human health costs, largely resulting from decreased emissions, even in developed countries (Pa, Bi and Sokhansanj, 2013).

1.2 Objectives and scope

This report provides an overview of the potential use of wood residues as feedstock for bioenergy production as part of the transition towards a sustainable and circular forest bioeconomy. While data and examples are abundant from developed countries, a specific focus will be put on the role and potential of wood residue-based energy in developing countries.

The study is structured around the following four main objectives, each corresponding to a chapter:

- define key terms and concepts related to wood residues and bioenergy value chains (Chapter 2);
- characterize the status and trends in renewable energy, modern bioenergy and the forest-based bioeconomy and evaluate the theoretical potential of wood residues for energy (Chapter 3);
- determine general success factors, common lessons learned and constraints on the utilization of wood residues for energy (Chapter 4); and
- formulate recommendations (Chapter 5).

The overall aim is to inform new policies and programmes through the identification of optimal conditions whereby the use of wood residues for energy can offer a competitive alternative to other fuels in developing countries and contribute towards reaching the UN SDGs.

2. Terms and concepts related to wood residues and bioenergy

This section provides the definition of the key terms and concepts used in the report. It is based on glossaries and terminology proposed by different international organizations such as the Food and Agriculture Organization of the United Nations (FAO), the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). Sources from national and international organizations such as the European Commission and the U.S. Energy Information Administration were also consulted.

2.1 Biomass streams

Roundwood: All roundwood felled or otherwise harvested and removed. This comprises all wood obtained from removals, i.e. the quantities removed from forests and from trees outside the forest. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form (e.g. branches, roots, stumps and burls, where these are harvested) and wood that is roughly shaped or pointed (FAO, 2021). In FAO statistics on forestry production and trade, it represents the sum of industrial roundwood and woodfuel.

A sub-category of roundwood that will not be specifically discussed further in this report, but that is still worthy of mention, is that of dedicated/purpose-grown woody energy crops, often known as energy plantations. These are usually based on fast-growing species that are managed on short harvest rotation and that resprout after each harvest (coppicing).

Woodfuel: Roundwood that is used as fuel for purposes such as cooking, heating or power production. In FAO statistics, it includes wood harvested from main stems, branches and other tree parts which are then harvested for fuel, including wood that is converted into charcoal, wood pellets and other agglomerates. It also includes wood chips to be used for fuel that are made directly (i.e. in the forest) from roundwood. It excludes the end products of wood charcoal, pellets and other agglomerates. However, woodfuel is also sometimes used to refer to any solid or liquid energy carrier made from wood as defined in FAO Unified Bioenergy Terminology (UBET). In FAO's terminology, woodfuel includes all type of biofuels derived directly or indirectly from wood, such as fuelwood (also known as firewood).

Industrial roundwood: This term is used in FAO statistics on forestry production and trade to describe roundwood that is harvested for purposes other than direct use as woodfuel; it includes roundwood destined for sawnwood, veneer sheets, pulp, wood-based panels, etc.

2.2 Waste and residues

Waste: The Waste Framework Directive of the European Union (2008/98/EC) defines waste as any substance or object which the holder discards or intends to discard.

Residue: According to the Renewable Energy Directive (2015/1513) and the Fuel Quality Directive (2009/30/EC) of the European Union, the term residue is applied to substances which are not the end products that a process directly seeks to produce.

The breakdown of wood residues into primary, secondary and tertiary sources is based on the categorization proposed by the “Delivery of sustainable supply of non-food biomass to support a resource-efficient bioeconomy in Europe” project (S2Biom project) (Dees *et al.,* 2017).

Primary wood residues: By-products of forest management activities related to industrial roundwood production, including harvesting but also thinning, pruning and other silvicultural treatments. They are sometimes referred to as logging or harvesting residues. They include tree tops, branches, bucking and trimming materials and small/non-commercial trees. In some instances, roots and stumps are also considered as primary residues.

Secondary wood residues: By-products of wood processing and product manufacturing at sawmills and veneer plants (e.g. bark, wood chips, rejects, slabs, edgings, trimmings, sawdust, shavings, etc.) and paper mills (e.g. black liquor). Some of these materials, such as wood chips and sawdust, can be recovered and directed to other industries, for example to be used as feedstock for pulping, particle and fibreboard production and other bioproducts.

Tertiary wood residues: Comprised of wood from products at their end-of-life, i.e. post-consumer wood, and other recovered wood derived from socio-economic activities outside of the forest sector. For example, this includes construction and demolition wood consisting of woody debris generated during the construction, renovation and demolition of buildings and other infrastructure. Some of these residues can also be recovered and recycled back within the wood product value chain for further use.

2.3 Woody biomass conversion technologies and related products

Pelletizing and briquetting: Mechanical compression of previously screened, ground and dried biomass, which is passed through a die at high temperature and pressure, causing the wood lignin to melt and gluing the particles together, and re-formed as a pellet or briquette upon cooling. Pelletization is sometimes preceded by torrefaction (see definition below in Thermochemical conversion).

Biochemical conversion: Process that involves the use of a biological agent to break down the biomass structure and produce energy carriers through anaerobic digestion or fermentation. For woody biomass the conversion of lignocellulosic substrates through pre-treatment of biomass and subsequent acid or enzymatic hydrolysis is needed before the resulting sugars can be converted to ethanol through the fermentation. This conversion process is still at the pilot stage (Bajpai, 2020) facing significant technology challenges due to its complexity and high production costs, but there is potential expansion for future efficient cellulosic ethanol production (Padella, O'Connell and Prussi, 2019).

Thermochemical conversion: Process that involves the use of heat in the presence or absence of oxygen to convert biomass into energy carriers and chemical products. The most common thermochemical processes include combustion, gasification, pyrolysis or carbonization and torrefaction.

Combustion consists of a reaction in which biomass and oxygen are combined in a high-temperature environment to produce heat and exhausted gases mainly made up of CO_2, water vapor, and nitrogen.

Gasification is the partial oxidation of biomass, resulting in a mix of gases of variable energy content which can be used to generate electricity from standard gas turbines.

Pyrolysis involves the carbonization of biomass without oxygen, and results in the production of gases (syngas), liquid (pyrolytic oil or bio-oil for direct use or further upgrading as fuel) and solid (charcoal) fractions in various proportions depending on the temperature and the rate of the process.

Torrefaction is a pre-treatment process that substantially changes the physical and chemical composition of biomass, which involved slowly heating biomass at 200 to 300°C in the absence of oxygen. With torrefaction, biomass becomes hydrophobic and loses the ability to actively absorb water during storage; its weight is also reduced and its combustion heat is increased. This process increases the energy density and durability of pellets and limits the risk of biological degradation (Tumuluru *et al.,* 2011).

2.4 Energy carriers

Energy carrier: A transmitter of energy, occupying the intermediate steps in the energy supply chain between primary sources and end-use applications. Fuels in solid, liquid and gaseous forms can be considered as energy carriers. For example, wood logs, wood chips, wood charcoal and densified products such as briquettes and pellets are solid energy carriers; biogas and liquid biofuels such as pyrolytic oil and bioethanol are also possible energy carriers produced from wood residues. The choice of an energy carrier for an intended end-use will depend on the accessibility (convenience, cost, efficiency), availability (in terms of quality and reliability) and acceptability of the various carriers (Metz *et al.,* 2007).

Wood charcoal: Solid energy carrier derived from the carbonization of woody biomass, usually retaining some of the microscopic texture of the original woody tissues. Charring of woody biomass increases the concentration of carbon and reduces the amount of oxygen and hydrogen, thereby increasing the energy density of the biomass. Charcoal can also serve in non-energy applications, such as a reducing agent in metallurgy where it is used as an absorption or filtration material and for improving soil functions (biochar).

Wood chips, pellets and briquettes: Wood chips is wood deliberately reduced to small pieces with different techniques during the manufacture of wood products and is a suitable for use as fuel, or for other purpose. Wood chips have a sub-rectangular shape with a length of normally between 5 and 50 mm. **Wood pellets** are solid energy carriers made from wood chips, wood shavings, bark, sawdust or other pulverized woody material. These materials are compressed or bound together, usually in a die (a metal part with holes, in which the roller forces raw material under intense pressure to produce pellets), taking a roughly cylindrical shape of varying dimensions (typically 5 to 30 mm in length and 5-10 mm in diameter). This process increases the energy density relative to wood residues and gives the final product a low moisture content (usually <10 percent of mass), making it easier to transport over long distances. **Wood briquettes** are made from similar material but are generally produced in bigger sizes and usually take a cubic or cylindrical form and have <15 percent moisture. Pellets and briquettes can also be manufactured from feedstock other than woody biomass (e.g. agricultural residues such as rice hulk, cotton stalks, etc.) or from a mix of various feedstocks (e.g. sawdust and agricultural residues).

Synthesis gas, syngas and producer gas: Biomass is converted to a gaseous fuel by a thermochemical process. The gas produced can be composed by a different mix of carbon monoxide, hydrogen, methane, carbon dioxide, and small amounts of water and other gases. It can be used directly as fuel or through various other processes such as reforming and conditioning. This gas may be burnt in boilers or may be used (after the removal of contaminants) to power gas engines and gas turbines to generate heat and electricity. It can also be reformed to produce fuels such as methanol or hydrogen (Bajpai, 2020).

Hydrogen: The generation of hydrogen from lignocellulosic biomass gasification represents a promising option as fuel in future energy systems (Solarte-Toro *et al.,* 2021), especially in the transport sector. But more research is required in the areas of production, storage, transportation and utilization of hydrogen for its use as an energy carrier (Bajpai, 2020).

Biofuels: Biofuels are fuels derived from biomass. They can be subdivided by type (solid, liquid and gas) and by origin (forest, agriculture and municipal waste). In some context, it may refer only to biofuels in liquid form.

Liquid biofuels: The term encompasses fuels of biological origin in a liquid form. Used principally for transport (as a substitute for gasoline, diesel, bunker and jet fuels), but also in industrial processes. Liquid biofuels produced from lignocellulosic materials such as woody biomass are called **second-generation biofuels** (in contrast to first-generation biofuels derived from sugar, starch or lipids from crops). Second-generation liquid biofuels include, for example, ethanol, methanol and pyrolytic oil produced from the biochemical or thermochemical breakdown of wood. The term advanced liquid biofuels is used to describe drop-in products that are similar in quality and specifications to their fossil equivalent (IRENA, 2016).

2.5 Bioenergy end-uses

Industrial sector: Bioenergy can play a role by providing low, medium and high-temperature heat for industrial processes. Wood residues can also be used internally within wood-processing industries for electricity and/or heat generation. Apart from energy use, woody biomass such as wood residues can also be used as feedstock to produce cellulosic fibres, bioplastics and other biomaterials.

Building/residential sector: Bioenergy can be used for space heating through community-scale district heating systems or individual furnaces. It is widely used for cooking, particularly in developing countries. However, traditional use of bioenergy currently dominates this end-use in developing countries and is often associated with several environmental and health issues; the adoption of modern technologies such as clean and efficient cookstoves is key for limiting negative impacts.

Power sector: Direct combustion or gasification of woody biomass are possible options to generate electricity. Power generation is often coupled with heat production in CHP systems.

Transport sector: Liquid biofuels present alternatives to fossil fuels for internal combustion engines in passenger and truck vehicles and can also be used in the shipping and aviation sectors.

2.6 Cascading use, supply and value creation

Cascading use: This concept is defined by Vis, Mantau and Allen (2016) as the "efficient utilization of resources by using residues and recycled materials to extend total biomass availability within a given system". Cascading use aims to preserve products, materials and resources in the economy for as long as possible with a maximization of added value by optimizing wood transformation stages and extending total biomass availability thereby also creating more jobs. The term can refer to the sequential use of woody biomass in which energy use is only considered after single or multiple material uses.

Biomass supply chain: A supply chain is defined as a set of activities for the procurement, conversion and logistics of a product. The main activities in woody biomass supply chains for bioenergy production are feedstock collecting/sourcing, handling, pre-treatment, storage and transport. Pre-treatment can include steps such as comminution (i.e. size reduction), drying, de-ashing, compaction and densification, which are used to convert the biomass as received from the collection site to a secondary energy carrier with precise characteristics, which will then be used for final conversion into energy.

Bioenergy value chain: The value chain is the entire sequence of activities or parties that provide or receive value in the form of products or services. This term is also used to describe the series of activities leading to the production of bioenergy. However, it carries the idea that the main purpose of the chain is value creation and not simply conveyance of a product to respond to a need.

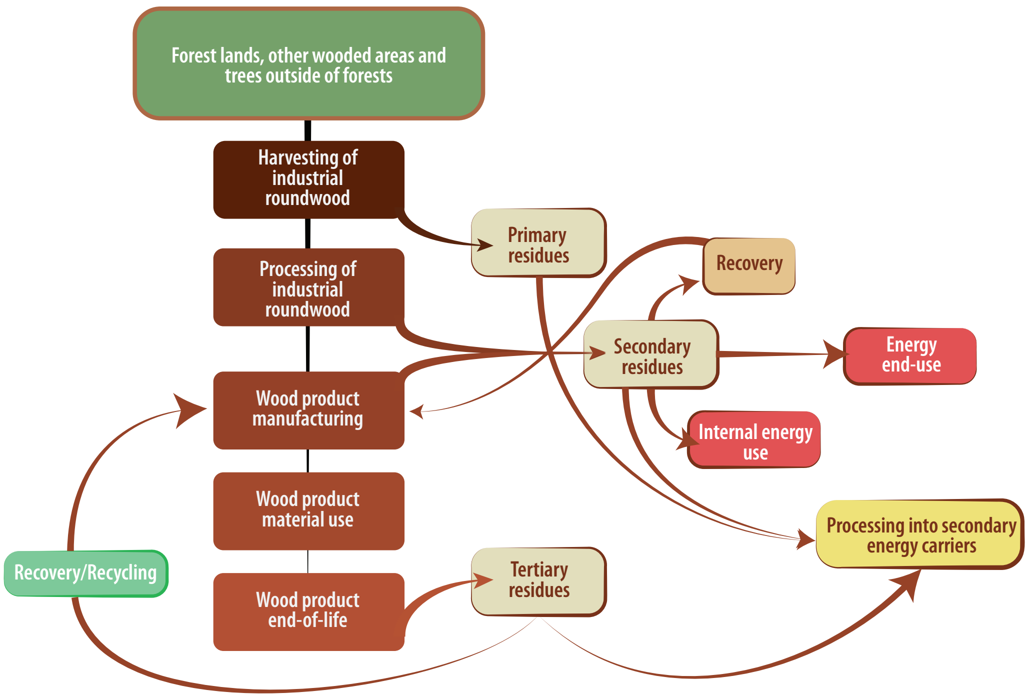
Circular economy: This term refers to an economic system based on business models that reuse, recycle and recover materials in production, distribution and consumption processes for achieving sustainable development (Kirchherr, Reike and Hekkert, 2017). This is also known as the three Rs of sustainability or the 3R-approach. The cascading use of woody biomass is one of the strategies for such business models.

Bioeconomy: The bioeconomy refers to the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors (Hetemäki and EFI, 2014; Winkel, 2017; Wolfslehner *et al.,* 2016). The vision for a bioeconomy is a system where materials, chemicals and energy are based on renewable biological resources, moving away from a fossil-based economy. A bioeconomy is not necessarily about being circular as such but rather about breaking our dependence on non-renewable resources. The concept of a forest bioeconomy can be thought to encompass the economic activities that sustainably use forest and wood resources in first or additional uses or in substitution for non-renewables, while ensuring biodiversity and environmental protection.

3. Analysis for mobilization of wood residues for energy

Woody biomass streams that can provide feedstock for bioenergy are highly interdependent (Figure 2). First, woodfuel and industrial roundwood can both potentially be harvested from the same lands, including forests and other wooded lands, and from trees outside of forests. The potential for the industrial processing of roundwood is therefore constrained both by the overall roundwood supply and by the demand for woodfuel. Second, wood residues are available in proportion to the amount and efficiency of industrial roundwood harvesting (which generates primary residues), processing and manufacturing (which generate secondary residues), and by consumption of wood products (which can eventually end up as tertiary residues). The extent to which residues can then be directed to energy use will be constrained by the economic competitiveness and demand for bioenergy and by the demand for residues from other industries, which is driven by the characteristics of the residue and the presence of industries using cascading woody materials as feedstock (e.g. particleboard, textiles, pulp and paper industries), which can recover and recycle residues from the industrial roundwood chain.

Figure 2: Woody biomass streams for material and energy uses



At a macro level, the potential for the mobilization of modern wood residue-based energy is therefore associated with the energy portfolio and markets, the state of the forest bioeconomy and the level of cascading wood use for a given region. This section provides a brief analysis of global trends in energy consumption and in the production of roundwood and wood products across regions of the world, and a theoretical estimation of wood residue availability, to evaluate the potential for deployment of modern bioenergy from wood residues.

3.1 Primary energy, renewable energy and modern bioenergy

An analysis of total primary energy, renewable energy and modern bioenergy consumption for regions of the world provides an overview of the current state of energy mix and progress towards the targets of SDG7. Countries from eastern Asia (mainly China) and northern America had the largest total primary energy consumption in 2021 (Table 1). When calculated per capita, the average national primary energy consumption is highest among countries of northern America and northern Europe, although both saw a decrease in energy consumption per capita over the 2011–2021 period. Such a decrease can either be due to changes in population demographics (i.e. rapid increases in population) or an increase in energy efficiency (i.e. a decoupling of economic growth and energy consumption). For example, European countries saw both a decrease in total primary energy consumption and in average primary energy consumption per capita over the 2011–2021 period, which may indicate a transition towards more energy-efficient processes and technologies.

On the other hand, the countries of the African continent, especially of middle and eastern Africa, are among the lowest consumers, both in terms of total primary energy consumption and per capita energy consumption. Moreover, while the countries of western Africa saw a significant progression of energy consumption per capita over the 2011–2021 decade, perhaps due to an increase in energy access for their populations, countries of middle Africa actually saw a decrease. For their part, Asian countries all saw an important progression of total primary energy consumption, and this translated into a substantial increase in energy consumption per capita, notably in southern Asia. For central America and the Caribbean, while there was an increase in the total primary energy consumption, this did not lead to an increase in energy per capita, with the average from this region remaining in the bottom third among regions of the world.

Countries in northern America and eastern Asia had the highest total consumption of renewable energy in 2021. Eastern and middle Africa and northern Europe had the highest share of renewable energy in 2021 relative to total primary energy consumption and several world regions (including middle Africa, eastern Asia and northern Europe) saw a progression of this share over the 2011–2021 period, varying from 6 to 15 percent of (Table 2). Most of this progression came from hydro, solar or wind, with modern bioenergy occupying only a small share of total energy consumption. Finally, most European countries have experienced significant growth in terms of modern renewable energy; in northern Europe, this was partly due to increases in modern bioenergy.

Table 1: Total primary energy consumption and average national primary energy consumption per capita in 2021, and percentage change over the 2011–2021 period (including all energy sources)

REGION/SUBREGION	PRIMARY ENERGY CONSUMPTION IN 2021 EJ	% CHANGE 2011–2021	PRIMARY ENERGY CONSUMPTION PER CAPITA IN 2021 GJ PER CAPITA	% CHANGE 2011–2021
NORTHERN AMERICA	106.91	0%	322.13	-9%
CENTRAL AMERICA + CARIBBEAN	11.08	2%	38.73	-4%
SOUTH AMERICA	24.76	2%	56.89	-10%
NORTHERN AFRICA	8.44	26%	45.02	13%
EASTERN AFRICA	2.34	40%	4.67	7%
MIDDLE AFRICA	1.06	42%	5.74	-4%
SOUTHERN AFRICA	5.17	-4%	53.12	-13.4%
WESTERN AFRICA	2.98	72%	7.22	32%
EASTERN ASIA	193.81	29%	164.32	-2%
SOUTH-EASTERN ASIA	27.35	30%	153.78	12%
CENTRAL ASIA	6.42	16%	156.93	14%
SOUTHERN ASIA	53.51	45%	42.75	22%
WESTERN ASIA	33.14	24%	255.06	1%
NORTHERN EUROPE	14.82	-8%	211.66	-5%
EASTERN EUROPE	44.66	1%	123.67	-2%
SOUTHERN EUROPE	15.14	-10%	94.85	-9%
WESTERN EUROPE	30.96	-6%	179.03	-14%
OCEANIA	6.57	2%	193.38	-13%
WORLD	589.12	14.3%	75.61	2.2%

Source of data: BP 2022. Statistical review of world energy 2022. 71st edition. London, UK. Cited 10 October 2022 www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Note: Country composition of world regions are based on the FAOSTAT classification.

Table 2: Consumption of total renewable energy and consumption of modern bioenergy and other renewables, excluding hydro, wind and solar in 2021, and percentage share relative to total primary energy consumption in 2011 and 2021

REGION/SUBREGION	RENEWABLE ENERGY CONSUMPTION IN 2021 FOR POWER EJ	% SHARE 2011	% SHARE 2021	MODERN BIOENERGY AND RENEWABLES OTHER THAN HYDRO, WIND AND SOLAR CONSUMPTION IN 2021 EJ	% SHARE 2011	% SHARE 2021
NORTHERN AMERICA	14.07	10%	13%	0.94	1%	1%
CENTRAL AMERICA + CARIBBEAN	1.60	9%	14%	0.19	1%	2%
SOUTH AMERICA	9.03	34%	36%	0.83	2%	3%
NORTHERN AFRICA	0.32	3%	4%	0.00	0%	0%
EASTERN AFRICA	0.84	35%	36%	0.07	2%	3%
MIDDLE AFRICA	0.32	23%	30%	0.00	0%	0%
SOUTHERN AFRICA	0.19	1%	4%	0.17	0%	3%
WESTERN AFRICA	0.24	10%	8%	0.00	0%	0%
EASTERN ASIA	26.23	6%	14%	2.56	0%	1%
SOUTH-EASTERN ASIA	2.8	5%	10%	0.59	1%	2%
CENTRAL ASIA	0.11	1%	2%	0.00	0%	0%
SOUTHERN ASIA	3.96	6%	7%	0.42	1%	1%
WESTERN ASIA	1.43	3%	4%	0.19	1%	1%
NORTHERN EUROPE	5.01	20%	34%	0.98	3%	7%
EASTERN EUROPE	3.28	5%	7%	0.24	0%	1%
SOUTHERN EUROPE	3.06	13%	20%	0.39	1%	3%
WESTERN EUROPE	5.40	10%	17%	0.97	2%	3%
OCEANIA	1.08	10%	16%	0.12	2%	2%
WORLD	78.97	9%	13%	8.54	1%	1%

Source of data: BP 2022. Statistical review of world energy 2022. 71st edition. London, UK. Cited 10 October 2022 www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Note: The column on renewable energy includes renewable power and biofuels (i.e. hydro, wind, solar, modern use of biomass, geothermal, and other marginal renewable sources; it excludes the traditional use of biomass. Modern bioenergy and renewables other than hydro, wind and solar includes only the use of biomass for power and excludes data on other modern use of biomass for heat and for production of liquid or gaseous biofuels. Country composition of world regions are based on the FAOSTAT classification.

3.2 Roundwood production

Statistics on the production of woodfuel (which is used directly for energy) and industrial roundwood provides an indication about the share of forest and wood resources that can further contribute to value creation and the transition towards a forest bioeconomy. Table 3 and Figure 3 describe the use of roundwood production for industrial roundwood and woodfuel across the regions and subregions.

In 2020, globally industrial roundwood accounted for 51 percent of total roundwood production, against 49 percent for woodfuel (Figure 3). However, the proportion of total roundwood production going to industrial roundwood vs. woodfuel varies considerably across the regions. The highest percentages of industrial roundwood production are reported in northern America, (89 percent), in eastern and northern Europe (85 percent) and in western Asia (72 percent); on the other hand, woodfuel accounted for between 87 and 96 percent of total roundwood production in all the African subregions, with the exception of southern Africa at 52 percent. In Asia, woodfuel production is highest in central Asia (95 percent), southern Asia (87 percent), south-eastern Asia (47 percent) and eastern Asia (45 percent), but lower in western Asia (28 percent).

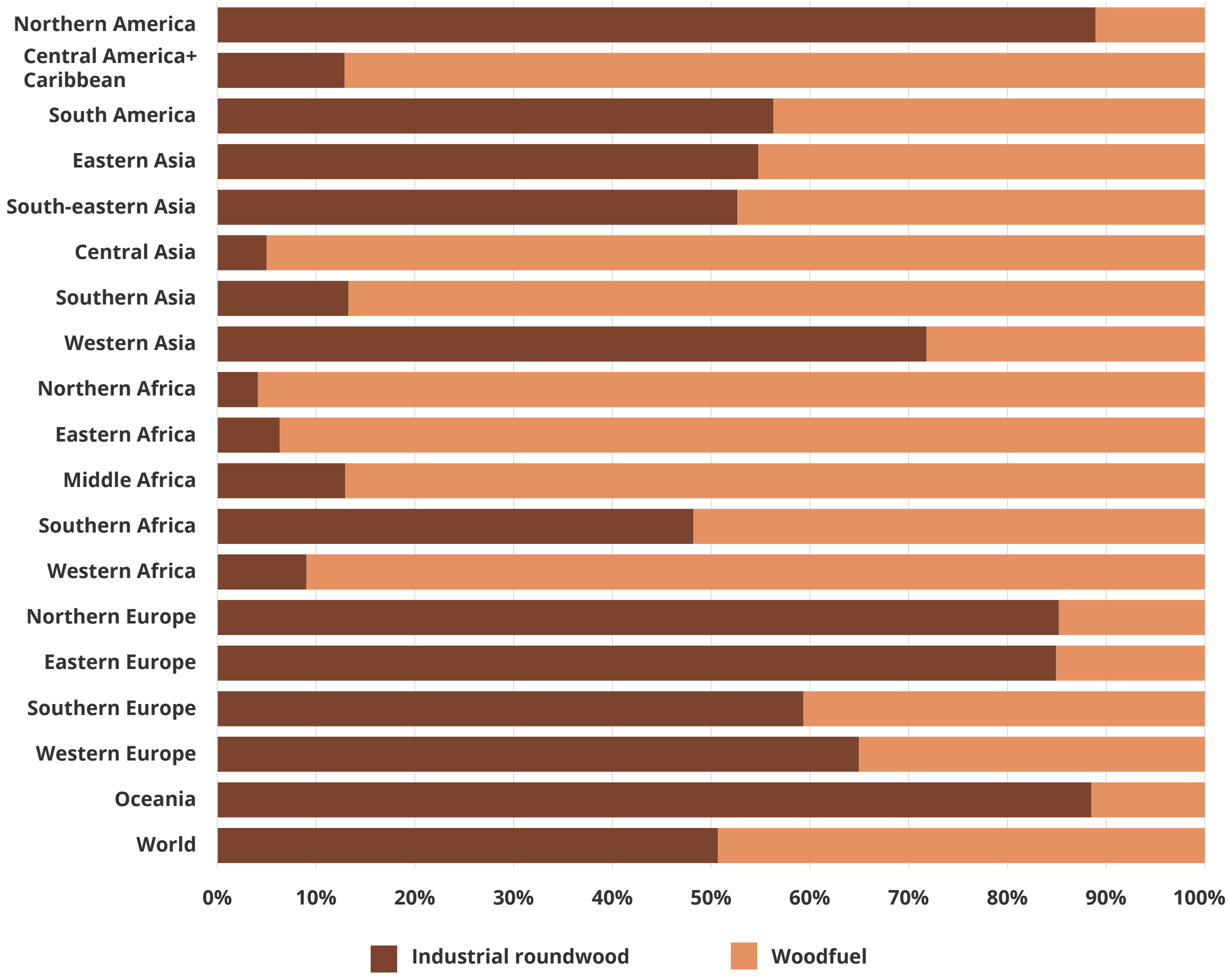
Multiple biological and technical factors determine the extent to which roundwood can be converted into higher value-added wood products. Nevertheless, the higher percentage of use of industrial roundwood in the Global North versus substantially lower rates in most of the subregions in Africa and in some of Asia and Americas indicates where there is a clear potential to reverse the trends by maximizing the added value and a cascading use of wood material.

Table 3: Roundwood production in 2020 in millions of cubic metres of solid wood (excluding bark)

REGION/SUBREGION	INDUSTRIAL ROUNDWOOD MILLIONS m^3	WOODFUEL MILLIONS m^3
NORTHERN AMERICA	499.6	62.3
CENTRAL AMERICA + CARIBBEAN	12	87.7
SOUTH AMERICA	228.9	179.6
NORTHERN AFRICA	2	53.5
EASTERN AFRICA	21.0	313.9
MIDDLE AFRICA	18.	116.9
SOUTHERN AFRICA	17.7	18.2
WESTERN AFRICA	20.4	210.0
EASTERN ASIA	210.8	171.2
SOUTH-EASTERN ASIA	160.1	141.9
CENTRAL ASIA	0.2	4.0
SOUTHERN ASIA	58.3	379.4
WESTERN ASIA	23.6	9.3
NORTHERN EUROPE	169.3	29.5
EASTERN EUROPE	314.2	55.7
SOUTHERN EUROPE	44.1	29.1
WESTERN EUROPE	105.7	56.2
OCEANIA	76.8	10.0
WORLD	1 983.7	1 928.3

Source of data: FAOSTAT. 2020. Forestry Production and Trade. Online at www.fao.org/faostat/en/#data/FO

Figure 3: Proportions of industrial roundwood and woodfuel, by region/subregion, by 2020



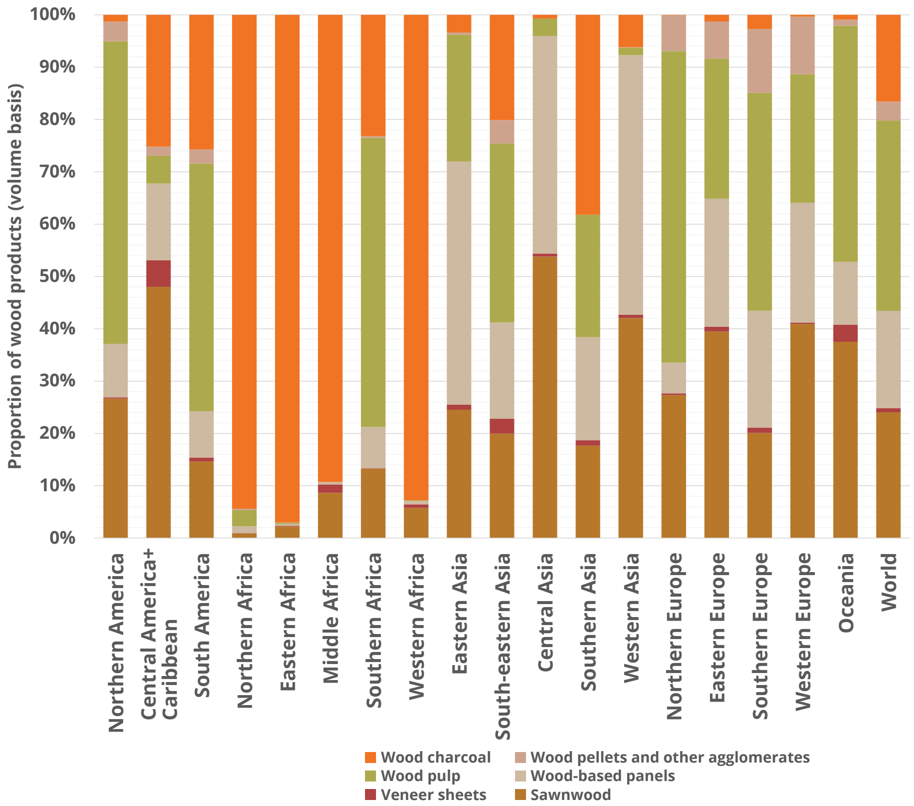
Source of data: FAOSTAT. 2020. Forestry Production and Trade. Online at www.fao.org/faostat/en/#data/FO

3.3 Wood products and energy carriers

An analysis of the main categories of products that arise from roundwood production, wood processing and manufacturing (excluding firewood that is used directly for energy and not further reported as specific products in FAOSTAT) provides an overview of the possible pathways for value creation from forest and wood resources for each region (Figure 4). This includes energy carriers made from wood and wood residues and the potential competitive material uses for wood residues.

The proportions of wood product categories generated from roundwood, show a very high (>80 percent) material use of wood (such as sawnwood, veneer, panels and pulp) in Oceania, northern America, Europe and eastern, central and western Asia. Central America and the Caribbean, south America, southern Africa and south-eastern Asia also show high levels of material use (>70 percent).

Figure 4: Proportion of wood products generated from roundwood expressed on a solid volume basis (excluding bark)



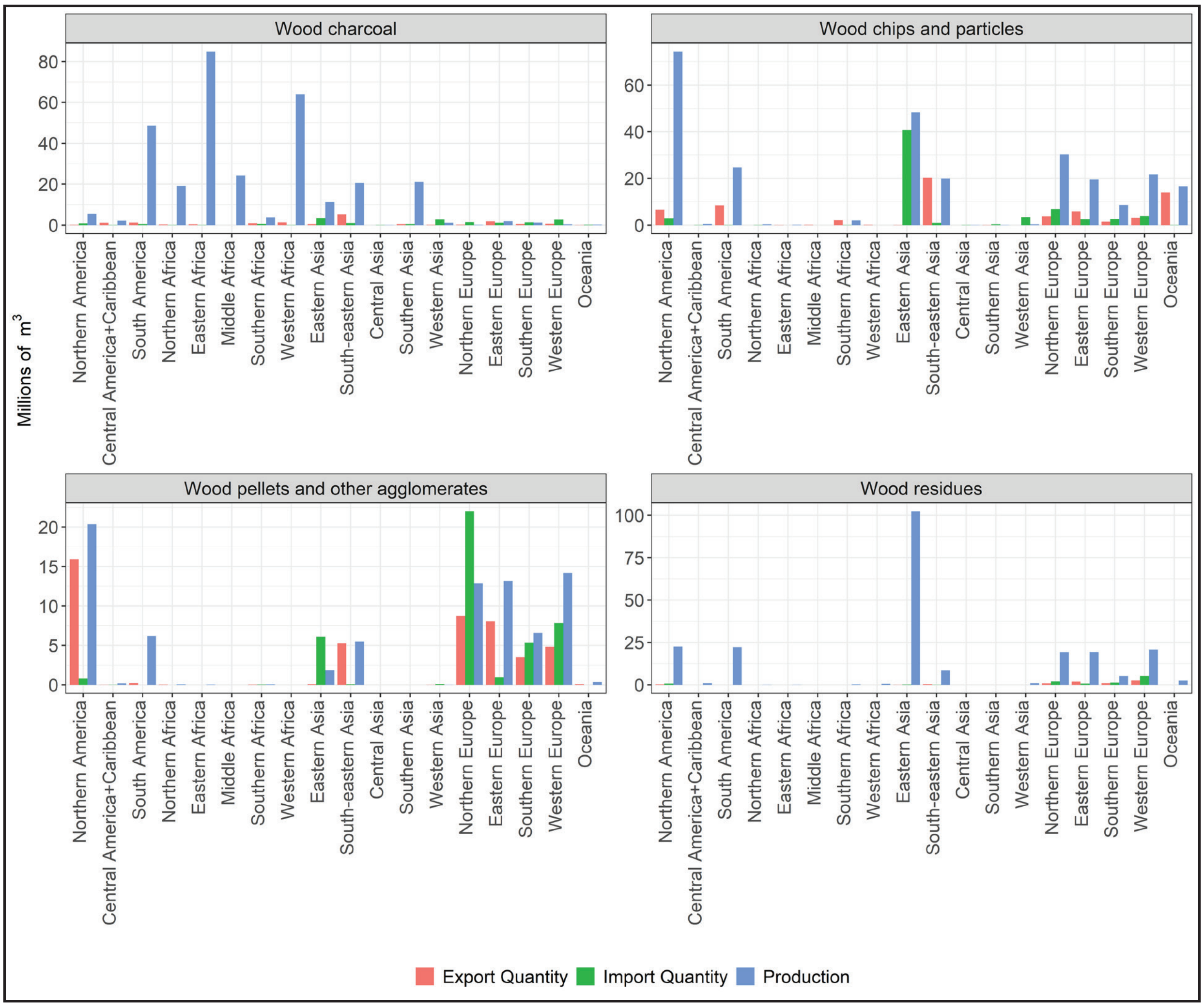
Source of data: FAOSTAT. 2020. Forestry Production and Trade. Online at www.fao.org/faostat/en/#data/FO

Note: Product categories follow classifications and definitions of FAOSTAT. Firewood that is directly used for energy and not further reported as specific products in FAOSTAT is excluded. Data for wood charcoal, wood pellets and other agglomerates, and wood pulp were converted to cubic metres of solid wood; see Appendix A for conversion factors. Country composition of world regions are based on the FAOSTAT classification.

Conversely, for the subregions of northern, eastern, middle and western Africa, the main wood product (>89 percent) is wood charcoal (excluding firewood not further reported as a specific product in FAOSTAT). In the subregions of central America and the Caribbean and central Asia, more than 50 percent of roundwood is processed into sawnwood and veneer, which are usually high-value wood products. For their part, the subregions of northern America, southern Africa, eastern Asia, and northern and southern Europe have important production levels of pulp and panels (representing more than 60 percent of wood products), two industries that have the potential to use the residues cascading within the industrial roundwood value chain as feedstock. For their part, wood pellets and other agglomerates, which are also processed from residues to serve for energy use, represent 7 to 12 percent of the wood product basket in European subregions and 3 to 4 percent in the Americas and in south-eastern Asia.

Looking at the production and trade of products that can serve for wood and wood residue-based energy carriers (Figure 5), it can be seen that wood charcoal and wood residues are mostly produced and consumed locally, although they are likely subjected to an important local trade (i.e. within localities or regions/subregions of a given country).

Figure 5: Production, import and export of wood- and wood-residue-based energy carriers



Source of data: FAOSTAT. 2020. Forestry Production and Trade. Online at www.fao.org/faostat/en/#data/FO

Note: Product categories and country composition follow classifications and definitions of FAOSTAT.

Wood chips and particles, which can serve as feedstock for both energy and materials, are traded internationally, with south-eastern Asia and Oceania appearing as important regions for export, while eastern Asia is a large importer. For wood pellets, international trade is even more significant. Global wood pellet trade currently originates mainly from northern America and south-eastern Asia. Over the last decade, the predominant destinations for globally traded wood pellets have been European regions and eastern Asia.

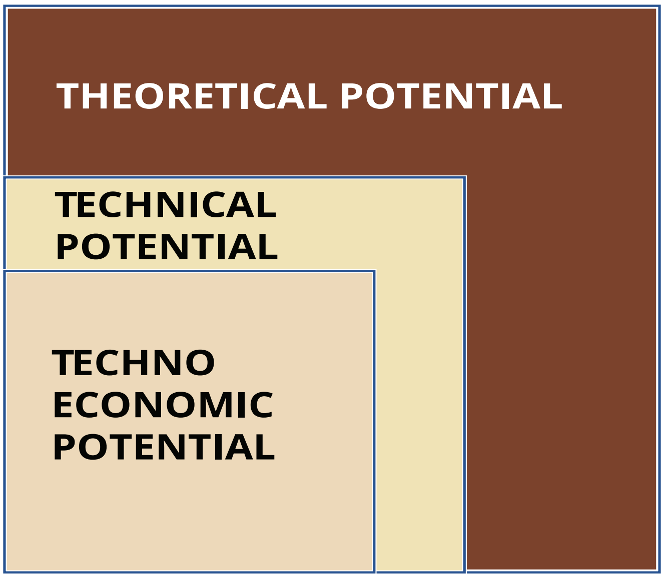
3.4 Potential availability of wood residues for energy

Accurate, documented and spatially explicit estimates of biomass feedstock availability are crucial for proper analysis and planning of bioenergy development at local, country or regional level. The accuracy of this information correlates directly with the risk associated with decision making, i.e. higher accuracy lowers the risk that decisions related to deployment of bioenergy supply chains and technologies will miss their intended goals (DBFZ and IRENA, 2013). However, while global streamlining of data and assessments have greatly advanced for other sources of renewable energies such as wind and solar (IRENA, 2021), progress has been more difficult for biomass due to its intrinsic complexity and relationships with land uses, agricultural and forestry practices and forecasts for food and product demands.

There is as no standard methodology to estimate biomass potentials, and any estimate would be very sensitive to variations in local contexts. Variations in the definition of 'biomass potential' are one important source of discrepancies in the literature (DBFZ and IRENA, 2013). To help provide some clarity, the following classification and definitions of different potentials have been suggested by various authors (Figure 6):

- **Theoretical potential:** theoretical maximum energy supply that is physically available in a given region for a specific period of time.
- **Technical potential:** The fraction of the theoretical potential that can be used after considering the losses through technical conversion processes, the structural, ecological, administrative and social limitations and the legal requirements.
- **Techno-economic or economic potential:** The fraction of the technical potential which is economically profitable in a given set of conditions.

Figure 6: Concepts of biomass potential



In the case of wood residues, the main driving factors influencing estimates of their potential are notably:

- **Assumptions on the current and projected land base that is available for forest production.** Since the generation of wood residues is dependent on industrial roundwood production, the total area of forests and other wooded lands that can be dedicated to such production is a major factor determining projections of their availability. However, land uses and land ownership might be difficult to assess due to regional circumstances. Moreover, the evolution of the forest land base is somewhat connected to population growth, urbanization, agricultural practices, eating habits and food deficit, which are difficult to project. Other factors such as the evolution of biodiversity protection policies that may result in conservation areas on which industrial roundwood production is restricted, and afforestation (i.e. conversion of land that has not been forested historically) and reforestation (i.e. renewal of the forest cover on land that has historically been forested) policies also play a role.

- **Assumptions on industrial roundwood production.** Many studies derive the potential of wood residues from statistics on the production and processing of industrial roundwood for a given region or country. The quality of these statistics will thus directly influence the quality of wood residue estimates. Moreover, projections of future estimates will depend on assumed forest yields across the forest land base, which often neglect considering future impacts of climate change on forest productivity. Future estimates would also need to consider the interplay between demand for woodfuel (for traditional bioenergy) and timber, which in turn are influenced by demographic development.
- **Assumptions on the efficiency of residue generation and their recoverability.** Potentials from wood residues can be calculated using residue generation factors that are multiplied with roundwood harvesting and processing volumes. These factors often do not distinguish between tree species and provide rough estimates of processing efficiency that determine the share of wood that end up in materials vs. residues. The competing recovery of residues for material production (e.g. pulp, panels) should also determine the share that can serve for energy use. However, in the context of cascading use, it can be assumed that after one or more cycles, wood would ultimately end up as energy feedstock. Moreover, projections on the recoverability of residues depend on assumptions on the availability of technologies and infrastructure to capitalize on this feedstock for both material and energy uses.

Taken together, these assumptions create large uncertainties, and global estimates should only be considered as rough approximations. Considering these caveats, first-order estimates of the theoretical potential of primary, secondary and tertiary residues generated in industrial roundwood value chains are provided here in Table 4 (details of the calculations can be found in Appendix B). Based on the bottom-up methodology proposed by Smeets and Faaij (2007), theoretical estimates of primary and tertiary residues are calculated from roundwood production and consumption as compiled by FAOSTAT, estimates for secondary residues are taken directly from FAOSTAT. FAOSTAT data are consistently compiled and reported for countries and regions over time with internationally comparable methodologies, thus reducing uncertainties associated with estimates.

Note that further calculations and modelling would be necessary to provide estimates of the techno-economic potential of residues, which would consider the specific industrial structure of the forest sector, including competition from other industries that can use residues as feedstock for materials production.

Table 4: Theoretical potential availability of primary, secondary and tertiary wood residues associated with industrial roundwood value chains, based on 2010–2020 average

REGION/SUBREGION	PRIMARY RESIDUES MILLIONS m^3 YEAR-1	SECONDARY RESIDUES MILLIONS m^3 YEAR-1	TERTIARY RESIDUES MILLIONS m^3 YEAR-1	TOTAL THEORETICAL AVAILABILITY MILLIONS m^3 YEAR-1	POTENTIAL ENERGY GENERATION FROM RESIDUES EJ YEAR-1	TOTAL THEORETICAL AVAILABILITY OF WOOD RESIDUES IN COMPARISON TO CURRENT WOODFUEL PRODUCTION %
NORTHERN AMERICA	76.75	107.42	276.48	460.65	2.56	739
CENTRAL AMERICA+ CARIBBEAN	1.67	1.22	10.62	13.51	0.08	15
SOUTH AMERICA	33.43	44.70	48.38	126.52	0.70	70
NORTHERN AFRICA	0.35	0.37	9.78	10.50	0.06	20
EASTERN AFRICA	2.92	0.17	2.23	5.32	0.03	2
MIDDLE AFRICA	2.31	0.02	0.84	3.17	0.02	3
SOUTHERN AFRICA	2.49	2.55	6.54	11.59	0.06	64
WESTERN AFRICA	3.02	0.56	3.69	7.27	0.04	3
EASTERN ASIA	28.79	144.28	331.81	504.88	2.80	295
SOUTH-EASTERN ASIA	21.80	26.97	43.41	92.18	0.51	65
CENTRAL ASIA	0.02	0.02	4.62	4.65	0.03	116
SOUTHERN ASIA	8.76	0.01	33.45	42.21	0.23	11
WESTERN ASIA	2.89	1.41	26.29	30.59	0.17	329
NORTHERN EUROPE	24.48	49.41	85.05	158.94	0.88	539
EASTERN EUROPE	42.97	36.70	69.91	149.58	0.83	251
SOUTHERN EUROPE	5.80	13.30	40.35	59.45	0.33	204
WESTERN EUROPE	14.20	42.26	84.88	141.33	0.79	251
OCEANIA	9.84	18.54	15.09	43.47	0.24	435

Source: Authors' own elaboration.

Note: See Appendix B for detail of calculations. Country composition of world regions are based on the FAOSTAT classification.

Eastern Asia and northern America are the regions with the highest theoretical availability of wood residues globally, due to high industrial roundwood production and consumption. south America and European regions also had a somewhat high overall theoretical residue availability. For middle and eastern Africa, the largest potential residue availability is estimated to come from primary (i.e. logging) residues. On the other hand, in the regions with small forest production such as in northern Africa and central Asia, the largest potential residues are from wood waste (tertiary residues) such as discarded furniture, demolition wood and wastepaper. In south America, northern Europe and Oceania, residues from industrial wood processing (i.e. secondary residues) represent an important share (>30 percent) of the theoretical potential for these regions.

When compared to current production of woodfuel (Table 4), the theoretical availability of residues remains small for most African subregions (eastern, middle, northern, western), central America and the Caribbean, and southern Asia, representing 20 percent or less of woodfuel production (on a wood volume basis). This suggests that the use of wood residues for energy would not be able to replace a large share of traditional bioenergy at least for some countries. However, the mobilization of wood residues for energy could still contribute to increase the overall value of wood and the economic appeal of industrial roundwood value chains. For other regions such as south America, southern Africa and south-eastern Asia, the quantity of residues generated by industrial roundwood could replace a larger share of woodfuel production (60–72 percent), representing a good opportunity for transition towards modern forms of bioenergy.

For other regions, the theoretical availability of wood residues represents several times that of the production of woodfuel. When compared with current energy consumption profiles, the theoretical energy generation from residues could significantly increase the share of total renewable energy consumption, especially in central and south America, southern Africa, and eastern and south-eastern Asia.

National circumstances greatly influence the actual volume of residues available in each country (techno-economic potential).

For example, the fraction of the harvested tree that ends up as primary residue during roundwood harvesting probably varies according to the overall availability/access of wood resources in a given region. Timber recovery is likely higher, and the generation of primary residues lower in a region with a wood deficit and/or tight regulations for access to wood resources. It can also be assumed that industrial roundwood harvesting of trees located outside of forests (De Foresta *et al.,* 2013) probably generates smaller amounts of residues due to higher timber recovery (Enters, 2001).

Moreover, secondary residues can also be either used for internal energy production within mills, transferred to other industrial processing facilities, for pulp or particleboard production for example, or dedicated to other uses, such as brick making, tobacco curing or artisanal furniture production. The exact share of secondary residues that is dedicated to other uses is difficult to assess, as it is not systematically reported, or is part of an informal economy for which reliable statistics are not available.

Also, the distance between residue-generating activities (e.g. harvesting, wood processing) and potential competitors for residues (e.g. location of panel or particleboard factories) largely determines the extent to which residues are not recovered for other uses and could thus be available for bioenergy. In fact, transport distances are also a major factor in determining the techno-economic potential of wood residues as part of bioenergy value chains. For example, in Malaysia, wood panel producers have invested in their own tree plantations close to their industrial facilities, as this was deemed a more economical way to procure affordable feedstock, rather than transporting wood residues from other industries over long distances (Enters, 2001).

The availability of tertiary residues, generated from packaging materials (e.g. pallets), demolition wood, timber from building sites and other post-consumer wood from residential, industrial and commercial activities, can be largely influenced by a more attention for circularity and recycling and changes in consumption patterns. This waste/ residue is usually highly dispersed, and the recover costs involved represent a main challenge. However, possible development could be achieved with improved collection systems.

3.5 Potential for mobilization of wood residues for energy

The statistics associated with energy and the forest-based bioeconomy discussed in sections 3.1 to 3.4 can be synthesized into indicators as part of a conceptual framework, with different levels of analysis relating to the mobilization potential of wood residues for energy in regions and countries (Table 5). Analysis levels are ordered from larger societal aspects related to energy and forest resources to more technical aspects more closely related to wood residues.

Table 5: Conceptual framework for analysis of the mobilization and deployment of wood residues for energy

INDICATORS	STATISTICS ON WHICH THE INDICATOR ARE BASED	KEY CHARACTERISTICS OF REGIONS/ SUBREGIONS RELATIVE TO THE WORLD AVERAGE
Access to energy and renewable energy, including bioenergy	Primary consumption of energy per capita Proportion of primary energy consumption met by modern bioenergy and other renewable energy	Low to high energy access Small to large share of energy consumption met by modern bioenergy and other renewable energy
Production of woodfuel relative to roundwood and wood material use	Proportion of woodfuel relative to total roundwood production Proportion of sawnwood, veneer sheets, wood-based panels and pulp produced relative to total wood products	Small to large share of roundwood production going towards woodfuel Small to large share of material products processed from industrial roundwood
Potential of wood residues for transition from traditional to modern bioenergy	Total theoretical availability of wood residues relative to production of woodfuel	Low to high availability of wood residues relative to current production of woodfuel
Competition for secondary residues for material use	Proportion of wood-based panels and pulp produced relative to total wood products	Small to large share of pulp and panel production that can use secondary wood residues as feedstock
Availability and relative contribution of primary, secondary and tertiary wood residues	Proportion of primary, secondary and tertiary residues relative to total theoretical availability of wood residues	Largest potential from primary, secondary or tertiary wood residues

Source: Authors' own elaboration.

Note: See sections 3.1 to 3.4 for definitions and sources of statistics that underpin each indicator.

As an example of the application of this conceptual framework, the average value of indicators for each subregion in relation to the global world average can be used to rate them (see Appendix C for details):

- For Africa, central America and the Caribbean and southern Asia, low energy access and the large share of woodfuel relative to overall roundwood production, and the concomitant small share of forest resources that transit through industrial roundwood value chains, appear as important issues. This should likely be addressed first to encourage a larger structural transition towards the valuation of forest resources.

- For south America and south-eastern, eastern, central and western Asia, energy access does not appear as a superseding issue. Industrial roundwood value chains seem to already be in place and can likely be further developed and mobilized for increasing the recovery of wood residues for modern bioenergy.
- Competition for secondary residues from other industries (such as pulp and panels) can, however, be an issue in some instances, such as in eastern Asia.
- For all the Asian regions, except for south-eastern Asia, there also seems to be an opportunity for the mobilization of tertiary residues, as they comprise an important share of the total availability of wood residues.
- For northern America, Oceania and most European regions, competition from other industries for access to wood residues, and the specific logistical and environmental challenges of mobilizing sources of available primary, secondary and/tertiary residues, appear as the main challenges.

Considering this analysis, opportunities and challenges for the promotion of modern bioenergy from wood residues raise a number of key considerations. These considerations will be discussed in the next chapter.

4. Challenges, opportunities and lessons learned on the use of wood residues for energy

The analysis of the potential availability of wood residues for energy (see Section 3.4) and the associated challenges, opportunities and lessons are discussed taking into account the following considerations.

- Land tenure and use rights of forest resources
- Consumer preferences
- Economic impact of bioenergy
- Economic role of traditional bioenergy
- Valuation of industrial roundwood and residues
- Cascading use of wood
- Logistics of wood residue supply chains
- International trade of modern bioenergy from wood residues
- Impact of bioenergy development on land use change
- Mitigation of GHG emissions
- Soil, water and air quality

Examples from developing countries are also highlighted.

4.1 Land tenure and use rights of forest resources

Forest land tenure, which involves forest ownership, the level of law enforcement, and the level of overlap between different land uses, has been identified as the most significant issue for sustainable forest management and the ability to extract forest products and obtain income from forests (GIZ and GBEP, 2015). This has relevance when considering the potential constraints facing a transition to modern wood-based energy.

Unregulated and/or unchecked access to forest resources can also lead to inefficient production and wasteful use of wood, since it encourages the idea that wood is 'free' (GIZ and GBEP, 2015). This, in turn, discourages the valorization of wood residues and thus ultimately represents an important barrier to their mobilization for modern bioenergy (BOX 1).

BOX 1: Towards a well-regulated approach for sustainable and modern woodfuel

A study of wood charcoal production in sub-Saharan Africa (Schure *et al.,* 2019) has shown that the unregulated and informal status of actors involved in the production is a significant impediment to the improvement of processes.
Conversely, an enabling institutional framework with simple taxation schemes, that facilitates access to permits and funding leads to more sustainable and efficient practices of woody biomass sourcing and carbonization.

Tenure security and clarity in user rights with respect to forest land and resources contribute to providing proper incentives for the sustainable management of woody biomass. Conversely, the absence of security and clarity can hide forest overexploitation and associated negative impacts.

Land tenure/ownership (state, community, or privately owned) (BOX 2) also interplays with the type of production management (government, corporate, individual, or NGO-led; bioenergy for own use or for domestic or international sale) to define the kind of impacts and benefits that can be expected from wood-based bioenergy value chains.

BOX 2: Land ownership and production management – the case of Uganda

Insights from Uganda show how different models of land ownership and production management for modern wood-based energy production can have distinct benefits and drawbacks (Hazelton, Windhorst and Amezaga, 2013):

- small private production facilities can be profitable but are likely to be of little benefit to the landless poor;
- larger projects could produce greater financial benefits, but the natural resource impacts could harm neighbouring communities;
- bioenergy initiatives that allowed the landless poor to have a collaborative stake were found to be the most useful in achieving rural development objectives.

Evidence from bioenergy projects based on agricultural biomass also provides some insights on the effects of governance aspects related to land tenure and production management (BOX 3). For example, a comparison has been made between two models from United Republic of Tanzania for the production of jatropha: 1) a decentralized smallholder model in which farmers cultivate jatropha as hedgerows around their agricultural plots and sell the seeds to processing plants, which complements their agricultural production; and 2) a centralized plantation model in which the oil-producing company owns jatropha plantations and hires labour to cultivate them. Results indicate that both models can lead to positive social impacts, but the smallholder model scores better in terms of the protection of land rights and reaches more people. The plantation model creates more employment and higher local prosperity for a smaller number of people but could lead to decreased food security caused by the loss of local populations land rights (Van Eijck *et al.,* 2014).

For modern bioenergy from wood residues to be successful, attention should be paid to governance aspects along the value-added chain, such as the optimal share/devolution of control and power over land, feedstock supply and conversion processes among governments, communities, user groups and individual households.

BOX 3: Local energy communities for modern bioenergy

Energy communities are a model of energy development often found in developed countries. They are decentralized community-scale energy systems that directly target the development and empowerment of communities to produce and consume their own energy and engage in decision making processes. This can be organized through cooperatives, where beneficiaries share infrastructure and services.

An analysis of energy access in sub-Saharan Africa (Ambole *et al.,* 2021) reveals that several renewable energy projects in this region resemble the energy community model. Community-managed and operated projects have been found to provide cheaper electricity to the local citizens and can drive efforts to extend energy access to areas that do not have access to the national grid.

In such projects, local management committees should oversee the supervision, operation, and maintenance of installed energy systems, as well as the collection of revenue to ensure local actors benefit most from the initiatives.

4.2 Consumer preferences

Despite the obvious drawbacks associated with traditional bioenergy, the switch to modern bioenergy, such as energy carriers derived from wood residues, is not straightforward. There is generally a rural-urban pattern in fuel use (with rural households mostly directly relying on woody biomass for energy production, while urban populations mostly using charcoal) (Ekouevi and Tuntivate, 2012). The affordability and availability of fuel remain major concerns in most developing countries. Table 6 provides examples of additional factors influencing the choice of fuels and cooking/heating equipment within households in developing countries (BOX 4). For example, the benefit of time saving in woodfuel collection by the use of modern wood energy carriers in ICS might be negated by the extra time needed to operate the new cookstove (Gitau *et al.,* 2019).

The promotion and mobilization of wood-residue energy value chains need to address aspects that are deeply rooted in the social and cultural fabric of communities.

Table 6: Factors influencing fuel and stove choices

SOCIAL/CULTURAL	ECONOMIC	TECHNICAL
FAMILY SIZE	HOUSEHOLD INCOME	EFFICIENCY
GENDER AND AGE OF HOUSEHOLD HEAD	STOVE AFFORDABILITY	EMISSIONS
EDUCATIONAL LEVEL	USAGE COSTS	SAFETY
TASTE OF FOOD	FUEL AVAILABILITY	STOVE QUALITY/DURABILITY
COOKING HABITS/CUSTOMS	FUEL AFFORDABILITY	FUNCTIONALITY OF COOKING
CONVENIENCE OF FUEL		CONVENIENCE/PORTABILITY
FOOD PREFERENCE		AESTHETIC FEATURES

Source: GIZ & GBEP. 2015. Towards sustainable modern wood energy development: Stocktaking paper on successful initiatives in developing countries in the field of wood energy development. German Federal Ministry for Economic Cooperation and Development (BMZ).

BOX 4: Factors influencing household uptake of improved cookstoves

In Mali and Senegal, programmes for disseminating ICS (Ekouevi and Tuntivate, 2012) have been found to be more successful than similar programmes in other countries due to:

- carefully designed information and educational campaigns;
- support to local producers of technologies that allowed financial profits to benefit communities;
- awareness raised in communities and households about the recognition that improved bioenergy technologies effectively reduces fuel consumption and translates into money savings.

4.3 Economic impact of bioenergy

Various examples from developed countries provide insights into the potential economic impact of bioenergy deployment:

- The south-east of the United States of America has recently become the highest producing area of wood pellets worldwide. The pellet production in the United States of America has reached 8.4 million tonnes in 2020 (FAOSTAT) which is mostly exported to the European Union and the United Kingdom of Great Britain and Northern Ireland market. The pellets supply chain in this region has contributed to creating employment, although at a modest scale largely because it represents an alternative to long-established forestry extraction and has principally offset the recent decline in pulp production, rather than opening up new opportunities (Diaz-Chavez *et al.*, 2019).
- The average unit production cost of electricity generated in the United Kingdom from wood pellets imported from the United States of America was estimated to be 30 percent higher than electricity generated from coal without any price support. In the presence of payment mechanisms, the production cost of electricity from imported wood pellets was about 16 percent lower than electricity generated from coal. On the other hand, the production of electricity from imported wood pellets could save greenhouse gas emissions relative to coal-based electricity in the United Kingdom (Dwivedi *et al.*, 2016). There however exist debates and arguments on the actual effect for GHG emission reduction of burning wood pellets for power generation.
- Weldegiorgis and Franks (2014) compared coal and woody biomass as energy suppliers in Australia and found that biomass suppliers contributed significantly to direct employment at the regional level. Positive employment impacts were also reported for the large-scale deployment of biomass resources (mostly wood) for energy in several countries, such as the Netherlands (Hoefnagels *et al.*, 2013a) and Austria (Trink *et al.*, 2010).
- The use of wood pellets for co-firing in south and west Alabama was also found to have positive economic impacts in the form of increased employment, incomes and value-added, as well as replacing imported coal with local wood resources (Kebede, Ojumu and Adozssi, 2013).
- Hodges, Stevens and Rahmani (2010) reported increases in GDP, employment and government revenues, and a decrease in imported fossil fuel in Florida associated

with an increase in the use of woody biomass. Employment, income creation and abatement of greenhouse gas emissions are reported to be positively influenced by an increase in modern bioenergy deployment.

However, increased demand for industrial roundwood and its by-products may both directly and indirectly affect the larger forest sector through higher alternative values for wood residues. Companies involved in forest harvesting and sawmilling operations could benefit from higher prices for logs and secondary residues. However, negative economic impacts are possible for paper and panel manufacturing due to increased input prices from competition for wood (Hodges, Stevens and Rahmani, 2010, Schwarzbauer and Stern, 2010).

For instance, a detailed analysis of the Norwegian forest sector revealed that sawmills increased their production as a result of bioenergy development due to the higher prices yielded by their secondary sawmilling residues for energy production. However, particleboard, which is characterized by low profit margins and reliance on the same low-grade residue material that is used as feedstock for bioenergy, was negatively affected. On the other hand, fibreboard production, which in Norway is characterized by high product prices and a relatively low cost share for wood feedstock input and specialty pulp and paper industries – niche markets within the larger pulp and paper sector – did not see any significant decline (Trømborg and Solberg, 2010).

In addition to the forest sector, the development of wood-based bioenergy also involves interaction/competition with other renewable energy options. For instance, rapidly declining costs for solar and wind energy production have been observed in the past, driven by technological progress and reductions in installation costs. However, much more irregular cost movements have been found for bioenergy, notably due to the high variability of capital and installation costs (Yao, Xu and Sun, 2021).

4.5 Economic role of traditional bioenergy

It is estimated that the traditional bioenergy sector employs more than 40 million people globally, representing 1.2 percent of the global workforce (FAO, 2014). Compared with other energy alternatives, for example, charcoal provides substantially more employment opportunities, at an estimated 200-350 job-days per terajoule (TJ) of energy consumed, compared with 80-110 job-days per TJ for electricity, 10-20 job-days per TJ for LPG and 10 job-days per TJ for kerosene (GIZ and GBEP, 2015). Since traditional bioenergy contributes substantially to the total energy supply of some developing countries, woodfuel may represent an important share of their economies (GIZ and GBEP, 2015). The economic role of traditional wood-based bioenergy in developing countries is therefore an important consideration when assessing the potential transition towards more modern forms of bioenergy in the context of sustainable development (BOX 5).

However, the economic contribution of woodfuel is often poorly documented and therefore usually underestimated. Firewood and charcoal are regularly traded in informal sectors and thus evade contributions to government revenues and tax bases. Woodfuel producers can be unwilling to formalize their business, notably due to the difficulty and high cost of normalization and a general distrust in official processes (GIZ and GBEP, 2015).

One consequence of this is that the prices of woodfuel do not capture the real economic value of trees. As mentioned in Section 4.1, this seemingly 'free' access to wood discourages efforts in sustainable forest management. Additionally, it does not provide any incentive for investments in improved value chains. For example, the production of charcoal is still predominantly characterized by low efficiencies and poor handling (Mensah, Damnyag and Kwabena, 2020). This therefore represents an important barrier to the economic valorization of wood residues for energy uses, as there is little incentive to invest in supply chains aimed at mobilizing more sustainable forms of biomass feedstock. Moreover, the fact that wood-based energy mostly runs as a shadow economy reduces its political interest and hampers the development of policy frameworks for modern bioenergy (GIZ and GBEP, 2015).

In countries where the woodfuel sector plays an important role in the energy mix, the regulation and formalization of this sector can be seen as a precondition for an effective energy transition and meaningful deployment of modern and sustainable bioenergy.

BOX 5: Income earning opportunities of woodfuel in developing countries

Traditional wood-based bioenergy employs a significant workforce, providing regular income to a large portion of the population, which tends to be poor and work as small-scale producers/collectors, traders, transporters, or retailers and have few other income alternatives (Africa Renewable Energy Access Program, 2011).

In Côte d'Ivoire, the annual revenue generated by woodfuel value chains is estimated to be worth about three times that of the processing and export of industrial timber (Louppe and N'Klo, 2013).

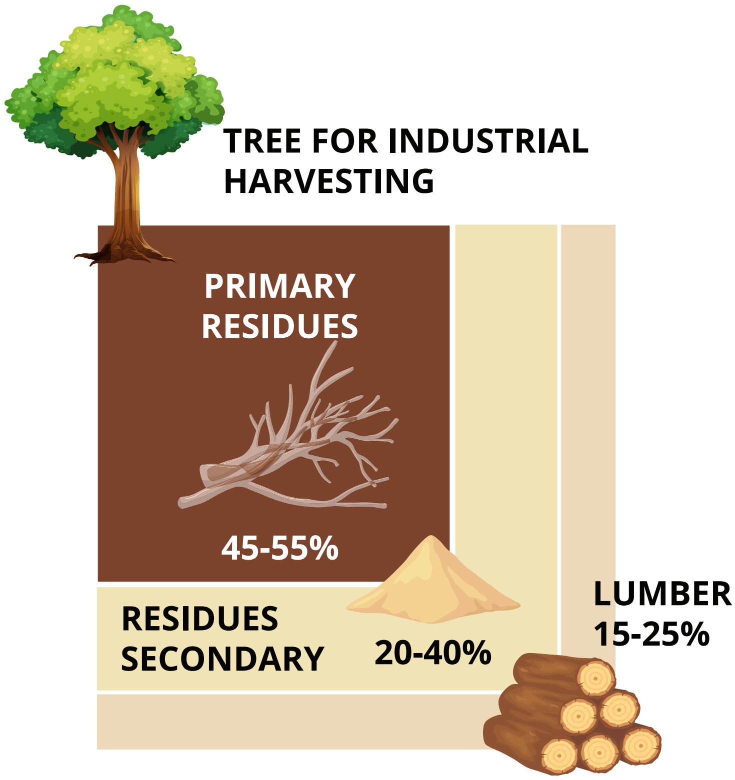
In Ethiopia, the charcoal value chain (based on the charcoaling of native tree species such as Acacia and Combretum) has been found to be well organized, to involve multiple actors and to generate large revenues. It is, however, mostly invisible, since the financial circulation associated with it is heavily reliant on informal systems (Rawat and Tekleyohannes, 2021).

4.6 Valuation of industrial roundwood and residues

Somewhat related to the valuation of forest resources is the proportion of harvested industrial wood that is effectively converted into lumber and other solid wood products relative to the proportion that ends up as wood residues. While the global averages provided by Smeets and Faaij (2007) referred to in Section 3.4 are often cited in the literature, value ranges provided by GIZ and GBEP (2015) for developing countries state that about 45-55 percent of trees felled for industrial roundwood are left as primary residues; 55-70 percent of processed roundwood further end up as secondary residues; in total, between 75 and 85 percent of trees dedicated to industrial harvesting finish as residues (adapted from data in GIZ and GBEP, 2015).

By way of comparison, in Canada, around 3-15 percent of merchantable roundwood is estimated to be left as primary residues during industrial roundwood harvesting operations (Smyth *et al.,* 2017). Estimates for secondary residue generation at sawmills range from 37 to 61 percent of industrial roundwood volume (Krigstin *et al.,* 2012).

Figure 7: Outputs from a tree harvested for industrial roundwood in developing countries

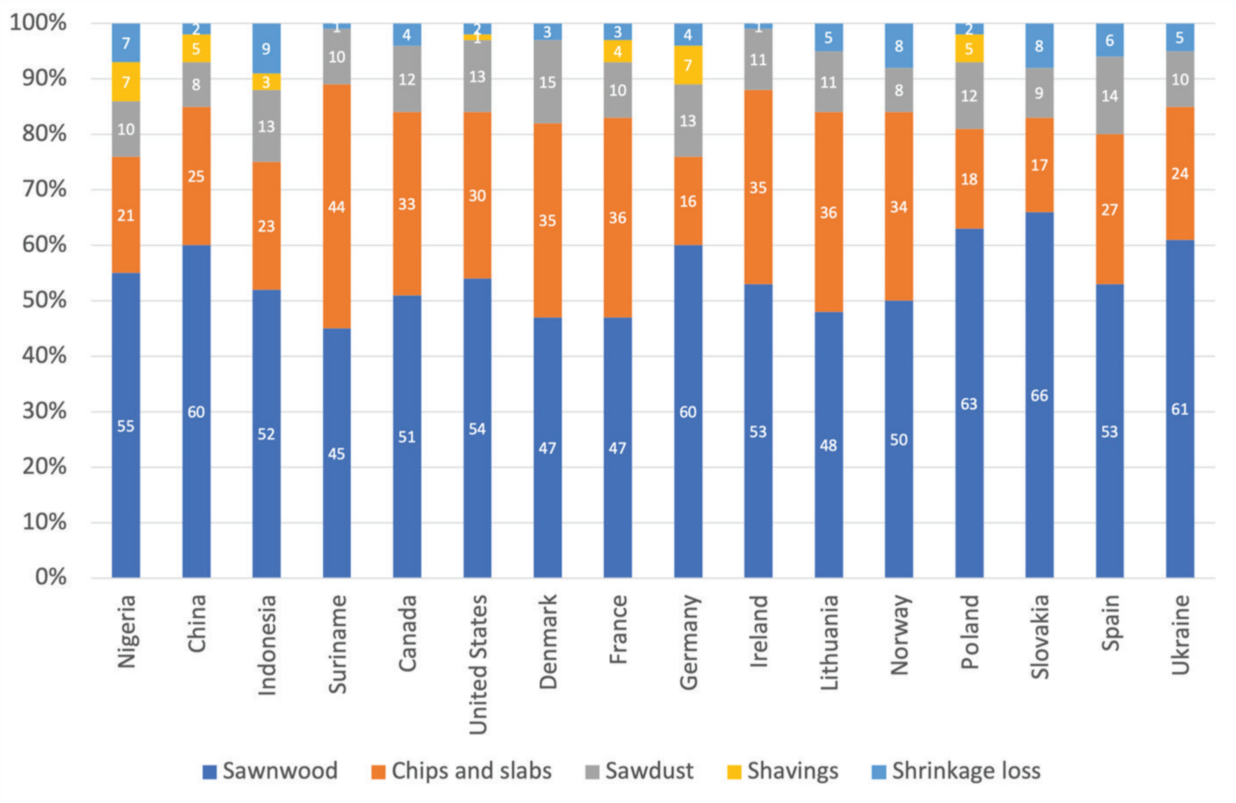


Source: Adapted from data in GIZ & GBEP. 2015. Towards sustainable modern wood energy development: Stocktaking paper on successful initiatives in developing countries in the field of wood energy development. German Federal Ministry for Economic Cooperation and Development (BMZ).

In many developing countries the recovered portion of the log in the sawn timber industry is often very low. The high quantities of wood residues generated from inefficient processing mills are mainly due to the use of basic technology and obsolete equipment in addition to the occasional lack of fully understanding of the potential gains of valorizing wood residues (BOX 6). The material balance of the sawmilling processes of roundwood reported for a set of countries by FAO, ITTO and United Nations (2020) shows values for the share of sawnwood ranging from 45 to 60 percent for coniferous species, and 45 to 66 percent for non-coniferous species, the remaining share becomes chips, slabs, sawdust, shavings and shrinkage loss (Figure 8).

While this underlines the significant feedstock potential for bioenergy in developing countries (see Section 3.4), evidence suggests that the financial profitability of wood residue-based value chains largely depend on the optimal and efficient co-production of lumber products. For example, case studies in Canada demonstrate that when the share of residues sent to bioenergy is too high relative to higher value sawnwood products, the viability of bioenergy production is strongly compromised (Barrette *et al.,* 2017; Béland *et al.,* 2020).

Figure 8: Material balance in the sawmilling process for non-coniferous sawnwood



Source of data: FAO, ITTO & United Nations. 2020. Forest product conversion factors. Rome. https://doi.org/10.4060/ca7952en

However, the profitability of wood-based bioenergy and forest product value chains as a whole can be increased if the procurement and removal of wood residues generates savings in the value chain (Béland *et al.,* 2020). For instance, recovering primary residues from roundwood harvest cutblocks has been found to significantly decrease the costs of site preparation and regeneration for the renewal of the forest area (Gan and Smith, 2007; Gouge, Thiffault and Thiffault, 2021). While this type of effect may be specific to the type of forest ecosystem, and removal of primary residues may raise environmental concerns (Thiffault *et al.,* 2011) (see Section 4.3). The accumulation of secondary residues in sawmills has been found to cause negative impacts on operations and even represent hazards to workers (whereas practices such as combustion in open fires or dumping in natural habitats can have environmental consequences, see Section 4.3).

BOX 6: The untapped potential of using secondary wood residues

Sawmilling in Uganda is characterized by many small, mobile, informal sawmills, which currently produce more sawn products than the formal sawmills. There is a large amount of waste produced each year, with both formal and informal sawmills operating at very low recovery rates. Modern sawmills can achieve in excess of 50 percent product output. The search for profitable markets for secondary wood residues such as sawdust, shavings and other solid wood waste is often initiated due to a need to reduce the costs of waste disposal (McEwan, 2021).

A survey of the Moratuwa Woodworking Industry Cluster in Sri Lanka has shown that about 55 percent of wood residues produced within the cluster was further used (notably for energy production), while the remaining 45 percent was taken to landfills or discarded in natural habitats such as waterways (Himandi *et al.,* 2021).

In sub-Saharan Africa, residues are sometimes used for internal heat production (e.g. for wood drying), but can be accompanied by overconsumption of heat in low-efficient processes (Nzotcha and Kenfack, 2019).

A study of sawmills in Cameroon showed that secondary residues were often mounted in heaps around the workplace, occupying space, impeding workers' movement and access to equipment, and slowing down work (Veeyee *et al.,* 2021).

In Ghana, the absence of management or valorization plans for secondary residues has been found to be caused by a lack of awareness, technical know-how, adequate equipment, and resources within companies (Asamoah *et al.,* 2020; Simo and Siyam Siwe, 2000).

Technological learning and awareness within companies on the modern technologies for processing the timber and utilizing wood residues play an important role for enhancing material efficiency and avoiding wood loss and waste in harvesting and processing.

Resource cascading, i.e. the sequential use of a material before it reaches final disposal, is a method to create added value as long as possible in circular economy practices. It is applicable to all types of resources (both renewable and non-renewable), but it is most often referred in the context of materials of biological origin, such as wood.

Two main sources for cascading are recognized within the industrial roundwood value chain (Vis, Mantau and Allen, 2016):

- the residues produced during wood processing (i.e. secondary residues); and
- the waste following consumption or decommission of a wood product (i.e. tertiary residues).

Table 7 summarizes examples of cascading use of wood, with technical possibilities of utilizing secondary or tertiary residues as feedstock for the production of various wood products and their further use as feedstock for other material and energy extraction at their own end-of-life.

In the examples of cascading use of wood reported in Table 7, it can be seen that:

- the cascading potential for industrial wood-processing residues is significant, as they can serve for many different material uses, before ultimately being directed to energy;
- paper products can also be easily recovered for multiple cycles if proper separate waste collection practices are in place;
- the material use of recovered solid wood products such as sawnwood and boards is more limited, as they can only serve mostly as inputs for particleboard production. Indeed, the presence of adhesives or impurities in post-consumer wood, and the

degradation of its physical properties, often represent a significant technical barrier to its recovery and remanufacturing into new material products, although research is on going to enable and facilitate its cascading use.

Table 7: Examples of cascading use of wood

	Can serve as feedstock for the production of:		Can further be recovered for the production of:
Secondary residues, recovered paper →	Paper	→	Recycled paper or energy after several cycles
Recovered sawn wood, recovered particleboard and oriented-strand board (OSB) →	Particleboard	→	Energy and fraction for reuse in particleboard
Industrial roundwood, secondary residues →	Medium-density fibreboard (MDF) and OSB	→	Energy and fraction of OSB for reuse in particleboard
Industrial roundwood →	Plywood	→	Energy
Industrial roundwood →	Sawn wood for construction	→	Particleboard
Industrial roundwood, secondary residues →	Wood plastic composites	→	Still in development
Industrial roundwood, secondary residues →	Biobased chemicals from biochemical conversion	→	Still in development
Industrial roundwood, secondary residues, recovered (clean) wood →	Biobased chemicals from thermochemical conversion	→	Still in development

Source: Adapted from Vis, M., Mantau, U. & Allen, B. 2016. Study on the optimised cascading use of wood. Project no 394/pp/ent/rch/14/7689. Final report. Brussels European Commission

If waste wood (tertiary residues) is recovered for further material use (such as particleboard production) to reduce the use of virgin industrial roundwood, it can have significant environmental benefits, for instance by reducing overall GHG emissions through increasing carbon storage in materials and reducing the use of fossil-based products (Budzinski, Bezama and Thrän, 2020; Sathre and Gustavsson, 2006). It also has positive socio-economic effects since higher added value is created from harvested industrial roundwood (Suominen *et al.,* 2017).

However, since smaller amounts of primary and secondary residues become available in a wood value chain with a high level of cascading use, the potential for direct residue-based energy production can be decreased (BOX 7). Nevertheless, despite these caveats, the overall energy balance of the cascading use of wood has been found to be mostly beneficial and the socio-economic and environmental impacts mostly positive.

BOX 7: Example of an increased cascading use of wood residues

The Moratuwa Woodworking Industry Cluster in Sri Lanka is a geographically concentrated group of furniture manufacturers, carpentry shops and sawmill. The improvement of wood residue sorting practices at the mill and the aggregation of wood residues produced within the cluster have been shown to significantly increase the mobilization of these residues for further cascading use (Himandi *et al.,* 2021).

To promote the cascading use of wood, the following recommendations were proposed by Vis, Mantau and Allen (2016):

- Improve the tracking and reporting of wood flows through the forest value chain, from the land base to the end-of-life of products, including transfer between industries and countries.
- Standardize and offer better categorization of wood waste assortments and improve wood waste collection.
- Harmonize energy and material policies regarding wood, so that the energy and material uses of wood are not considered or promoted in isolation but rather as a synergy.

- Consider the suitability of each wood fraction for material and energy use, as well as the local or regional context of the wood value chain in terms of forest resources and the industrial network.

The cascaded material product could ultimately be used as energy and the increased value given to forest resources could stimulate the entire value chain for both material and energy products.

4.7 Logistics and quality standards along wood residue supply chains

Most potential sources of wood residues produced along industrial roundwood value chains share common features (Routa *et al.,* 2013):

- they have a scattered spatial occurrence and low spatial density, therefore often requiring long transportation distances to a large number of end-user points;
- they are low in energy and bulk densities;
- they have heterogeneous physical, chemical and thermal properties;
- they often have high, or highly variable, moisture content; they are hygroscopic and difficult to handle;
- there is also often the presence of contamination, which can increase ash content, tear, wear, and damage to equipment and machines.

Typical contaminants of primary residues include rocks and dirt. Secondary residues can sometimes contain plastic or metal waste from sawmilling operations (Thiffault *et al.,* 2019). Tertiary residues can often contain heavy metals due to surface treatments of wood products, along with traces of adhesives, metal and plastic parts (Jermer, Ekvall and Tullin; 2001, Krook, Mårtensson and Eklund, 2006).

The characteristics that determine the quality of wood-based energy carriers notably include moisture and ash content, calorific value, particle size distribution, bulk density, chemical composition, the amount of impurities and other variables depending on the fuel (BOX 8).

BOX 8: Strategies for mobilization and deployment of wood residues

Several studies have looked at the combustion characteristics of densified energy carriers made from wood residues that are blended with other sources of agricultural and municipal biomass residues and/or charcoal. For example, briquettes made from a mix of wood charcoal fines and up to 20 percent of pine sawdust, bound with an extract of cassava peels, have shown suitable calorific values and chemical characteristics for energy production in domestic and industrial applications (Ajimotokan *et al.,* 2019). This suggests that wood residues can be successfully valorized as part of a larger mobilization of local biological resources.

In the city of Lages, in the state of Santa Catarina in Brazil, a cogeneration plant generating electricity from wood residues was established in 2004. The plant uses bark, sawdust and industrial wood chips from local suppliers. A study of the evolution of the physical and chemical properties of these residues has shown that the overall quality of the feedstock has significantly improved over time. This improvement is thought to have been caused by the implementation of technological innovation in the supply chains and by technological learning by suppliers and plant operators themselves (Deboni *et al.,* 2019).

The specific features of wood residues represent significant barriers to their procurement for bioenergy feedstock and are often poorly documented or accounted for. Nevertheless, several pre-treatments exist to improve the characteristics of wood residues (Figure 9). Firstly, some pre-treatment processes that can be implemented at the beginning of the industrial roundwood value chain have proven successful in Nordic countries to facilitate the procurement of primary residues (BOX 9). These processes include:

- passive drying of primary residues on the forest cutblock and/or by the roadside;
- covering to prevent re-moistening; and
- chipping.

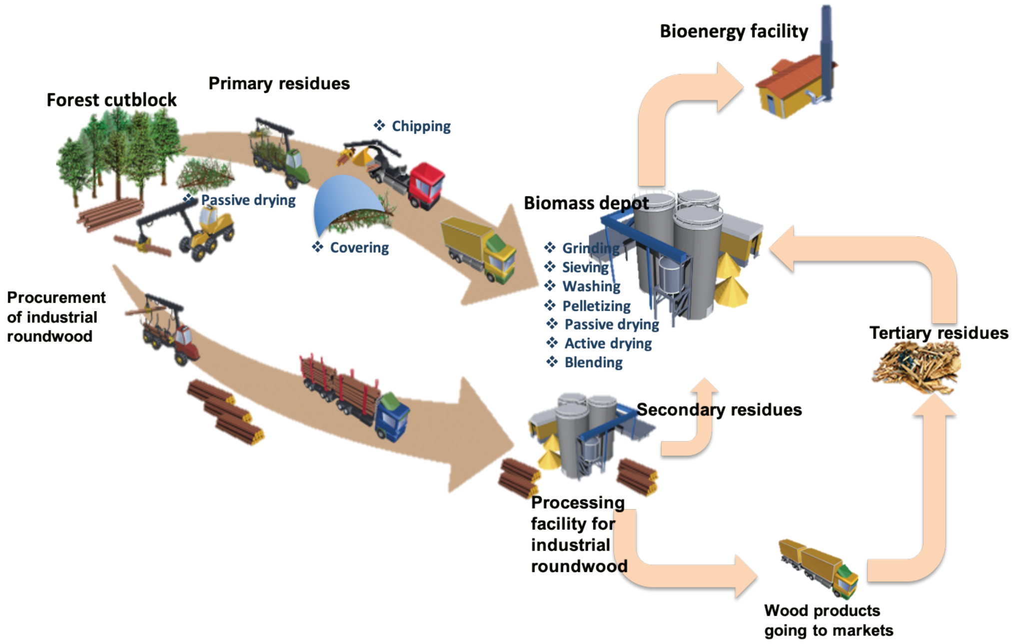
The implementation of pre-treatment processes can be made easier by the close integration of residue removal with the planning of stem wood harvesting. This ensures that the utilization of available machinery is optimized and that residues are handled and piled in a way that simplifies downstream processes.

Proper implementation of pre-treatment at this early stage in the chain can considerably increase the energy density of the material and therefore significantly reduce transportation costs per unit of energy, a key aspect of bioenergy profitability (BOX 10). This is especially relevant when the spread of residue sources occurs in low densities across large areas (Dymond *et al.,* 2010; Mansuy *et al.,* 2017). For tertiary residues, careful source separation and residue screening can help decrease the level of heavy metal contamination (Krook, Mårtensson and Eklund, 2006).

Other pre-treatment processes that can serve to improve the characteristics of residues and provide high-quality energy carriers include (Thiffault *et al.,* 2018):

- physical property management by grinding and sieving;
- ash content management by washing; and
- density management by pelletizing or briquetting.

Figure 9: Opportunities for pre-treatment processes of wood residues along the value chain



Source: Thiffault, E., Sokhansanj, S., Ebadian, M., Rezaei, H., Oveisi, E., Ghiasi, B., Yazdanpanah, F., Asikainen, A. & Routa, J. 2018. Biomass pre-treatment for bioenergy. Case study 2: Moisture, physical property, ash and density management as pre-treatment practices in canadian forest biomass supply chains. IEA Bioenergy. www.ieabioenergy com wp-content/uploads/2018/10/CS2-Forest-biomass-pre-treatment.pdf

Research results suggest that a biomass depot within a supply chain can lead to cost reductions of 11 to 31 percent relative to a reference value chain without a depot, notably because it increases the capacity for moisture management of feedstock, with consequent benefits for transportation costs (a crucial component of profitable value chains) and energy conversion efficiency (Gautam, LeBel and Carle, 2017).

Equipment for pre-treatment processing of residues can be grouped within a biomass depot. The role of such depots for the mobilization of profitable woody biomass supply chains is increasingly being demonstrated.

BOX 9: The role that pre-treatment processes can play in bioenergy value chains in Canada

The supply costs of primary harvest residues, in the absence of any significant pre-processing technologies, were estimated to range from USD 1.70 to 3.18 per GJ for heat plants, USD 7.21 to 41.39 per GJ for power plants, and USD 13.39 to 29.45 per GJ for CHP plants (Xu *et al.,* 2017).

Case studies in British Columbia and Quebec suggest that the cost of pre-processing operations for pellet production varies from 1.78 to USD 2.96 per GJ (Mobini, Sowlati and Sokhansanj, 2013). The pre-processing operations leading to pellet production would therefore add a proportionally high cost for heat plants, but a more reasonable cost to CHP plants.

Another case study for a gasification plant in British Columbia estimated at about USD 23,000 the total annual capitalized costs of simple pre-processing technologies for moisture and physical properties that translated into significant improvement in both transportation and conversion efficiencies. The reduction in the moisture content of delivered wood chips at the gasification plant brought cost savings for the supplier and increased benefits for the end-user. A reduction in moisture content from 50 to 20 percent resulted in a minimum cost savings of over USD 50,000 annually for the supplier. Moreover, this reduction resulted in an increased daily profit of USD 642, equivalent to an increase of 16 percent, for the gasification plant by generating more steam (Thiffault *et al.,* 2018).

BOX 10: Finland promotes efficiency along the wood residues-based energy supply chain

In local supply chains with short distances between feedstock and final end-user, a direct sourcing of residues, without any significant pre-processing phases, may give the highest overall efficiency both in thermal and economic terms. For instance, Finland has been experimenting with the Fast Track model (Kinnunen, 2016), an alternative operational model where part of the woody biomass feedstock is taken to the CHP plant directly without any specific pre-processing steps. Procurement costs for energy use can be decreased by using Fast Track, but it can only be profitably used for very specific supply needs.

Finally, the availability of a skilled workforce is one important driver of the quality of wood residues used as bioenergy feedstock (Autio, 2009; Leskinen, 2010; Pelli, 2010). For example, in eastern Finland, bioenergy entrepreneurs identified poor supply chain management, skills and attitudes as one of the biggest problems affecting biomass quality. Poor skills and attitude problems have an influence not only on fuel quality but also on business-to-business relationships (Jahkonen, 2014).

The logistics of bioenergy value chains need to be locally adapted and based on a properly trained workforce, especially where generally low fossil fuel and energy prices call for high levels of agility.

4.8 International trade of modern bioenergy from wood residues

Incentives that promote the use of bioenergy as part of a renewable energy or climate strategy, such as quota systems for renewable energy, taxation of fossil fuels, emission trading schemes and government support influence bioenergy demand and also its trade (Lamers *et al.,* 2012). Relative to other renewable energy sources, biomass energy carriers may be produced far from conversion and consumption points. They are therefore well suited for international trade (Daioglou *et al.,* 2020). While regions with high demand for bioenergy have been found to be technically able to supply sufficient domestic biomass (Lamers *et al.,* 2014), in a global competitive setting, internationally traded woody biomass is often cheaper and thus preferred over more expensive local biomass (BOX 11).

Whereas local trade (i.e. within localities or regions of a given country) of wood charcoal, wood chips and other residues can be significant, international trade of wood energy carriers mostly involves wood pellets (see Section 3.3). This large trade in wood pellets can be explained by increased demand in the residential heating and industrial sectors (Proskurina *et al.,* 2019a). Global wood pellet trade currently originates from countries with a strong forest sector but a comparatively small domestic market for pellets, including Canada, United States of America and Russian Federation.

BOX 11: Potential trade opportunities for modern bioenergy carriers

Vietnam has an abundance of forest resources and wood residues, notably from wood product manufacturing, along with relatively low labour and shipping costs; it is considered as a key pellet producer and exporter. In 2018, it produced almost 70% of the total Asian fuel pellet production.

Other Asian countries such as Malaysia, Indonesia and Thailand also have potential for further development. For example, Malaysia has seen a growth in its pellet export over the past decade, notably due to increased demand from Republic of Korea and Japan (Nuramin, Saadun and Harun, 2020). Recent projections suggest that other regions (such as Latin America and Africa) could ultimately become more competitive exporters of bioenergy products over the next decades, notably due to higher land availability and lower costs (Daioglou *et al.,* 2020).

Due to the expected demand increase under policy projections and limited regional resources, the European Union, Republic of Korea, Japan, and a range of other countries are expected to remain net importers of forest biomass for energy (Kranzl *et al.,* 2014). Although world regions differ significantly in production costs notably due to the costs of raw material and labour, past trade growth patterns have proven to be very policy dependent (Thrän *et al.,* 2019), with some trade contracts (e.g. in the wood pellet industry) even being directly linked to the time period of specific policies (Thrän, Peetz and Schaubach, 2017).

Woody biomass for energy can also be subject to indirect trade through the circulation of wood for material purposes. For example, when logs and chips are imported as feedstock for sawmills and pulp mills, a fraction of them ends up as secondary residues that can be utilized for energy. Furthermore, imported wood and wood products may end up as tertiary (post-consumer) residues and may thus ultimately contribute further to bioenergy purposes in the importing country. Also, exported paper or cardboard can return to the producing country as product packaging and later be utilized for energy purposes. However, accounting for indirect trade is fraught with a high level of uncertainty due to the many assumptions that need to be made. Nevertheless, it is assumed to represent a sizeable share of global trade for bioenergy (Proskurina *et al.,* 2019b).

Trade barriers in the form of import taxes and duties, which are common for liquid biofuels, have not yet been applied to woody biomass on a larger scale. Also, the previous lack of internationally recognized technical standards and uniform contracts has been addressed in the past few years. The remaining key challenges for woody biomass trade include phytosanitary restrictions (to prevent the global spread of regional wood vermin and fungi), logistic cost reductions, and policy frameworks aimed at ensuring sustainable sourcing (Junginger *et al.,* 2014).

The increase in wood pellet production capacity in the United States of America and Canada is directly linked to export market developments in Europe and Asia. International trade can enable the creation of logistic systems that can then benefit the regional/national consumption of biomass. For example, the current expansion of wood pellet production capacity in the United States of America destined for export to the European Union could provide a market and logistical "stepping-stone" for the scale-up of the wood-based biorefining industry. According to Kaygusuz, Toklu and Avci (2017), the current conditions in the international wood pellet market might not yet favour a large-scale role for developing countries. Still, some countries with adequate infrastructure for exports and proximity to international export routes are already active in this regard. Growing trade and opportunities for higher revenues could create interest in other developing countries to shift from domestic uses of wood to modern bioenergy exports. Investments in verified improved sustainable supply chains that can meet certification standards will likely be required.

However, the exact role of international trade in bioenergy for the achievement of the SDGs needs to be clarified. The openness of trade, i.e. the sum value of imports and exports relative to GDP, could have either a positive or negative effect on countries depending on their economic status. For example, while trade openness has been found to intensify ecological degradation in developing countries, notably due to increased pressure on ecosystems (which are often poorly protected/regulated), it can conversely reduce degradation in higher income countries through increased competition in green technologies and innovations (Destek, Sarkodie and Asamoah, 2021).

The growing international trade of biomass energy carriers and the concomitant emergence of a domestic bioeconomy are expected to create interest in developing countries. Therefore, the standards and certification schemes should be adapted by accredited international bodies to support a reliable supply of raw materials and ensure sustainable and modern bioenergy.

4.9 Influence of bioenergy development on land use change

Many climate change mitigation scenarios show that bioenergy needs to play a key role in global energy portfolios to meet climate targets (Clarke *et al.,* 2014). However, the increasing contribution of biomass to the global energy supply has also been generating concerns about environmental sustainability. One such concern arises from the risk of (direct and indirect) land use change (LUC), which occurs when land is transformed from one use to another (e.g. from forest to agricultural land or to urban areas). In the context of bioenergy, direct LUC can occur if there is a shift from food crop cultivation or animal grazing to producing bioenergy feedstocks. Displaced food producers may re-establish their operations elsewhere by converting natural forest ecosystems to agriculture land, causing indirect land use change and causing a loss of carbon stocks (Berndes *et al.,* 2013).

Nevertheless, documented cases of direct or indirect LUC effects due to bioenergy deployment concern almost exclusively the production of dedicated bioenergy crops (Chum *et al.,* 2011). The use of wood residues generally avoids LUC. Moreover, LUC due to a growing demand for wood residues for energy is highly unlikely (Abt *et al.,* 2014). Alternatively, in the south-eastern United States, it is predicted that an enhanced demand for wood-based bioenergy will increase timberland area by increasing the value of forest resources, in a context where land use is strongly market-driven, and forestry is competing with other land uses such as agriculture or housing development (Galik and Abt, 2015).

In developing countries, there is a hope that the increased mobilization of wood residues for energy would reduce pressure on remaining natural forests and create an incentive for forest protection. For this to happen, there must be effective restrictions on the access to timber, combined with investment incentive policies, that would both force an improvement of wood-processing efficiency and the valorization of by-products.

4.10 Mitigation of greenhouse gas emissions

Reducing greenhouse gas (GHG) emissions through the displacement of fossil fuels is one of the main policy rationales for supporting deployment of bioenergy. Indeed, biomass energy carriers are made of carbon that was previously sequestered by plants through photosynthesis. This carbon will be released upon combustion, but will be re-sequestered again if the biomass production system is sustainably managed (Berndes *et al.,* 2013). Conversely, fossil fuels transfer carbon dioxide (CO_2) from stable storage into the atmosphere. Bioenergy can thereby theoretically help stabilize the amount of CO_2 in the atmosphere over time when used to displace fossil fuels (IPCC, 2014).

Several studies have looked at global trends between CO_2 emissions and bioenergy, including both traditional and modern forms and all types of feedstocks (from agriculture and forestry). Research findings from these studies are somewhat ambiguous, showing either increases or decreases in CO_2 emissions as a function of an increase in bioenergy use (Adewuyi and Awodumi, 2017, Danish and Wang, 2019, Solarin *et al.,* 2018). Overall, bioenergy has been found to cause less emissions than fossil fuels (BOX 12). Moreover, important emissions associated with bioenergy are usually linked to feedstock sources that cause land use change, and to conversion technologies with low efficiency, i.e. not features of modern wood residue-based energy.

BOX 12: Modern bioenergy from wood residues for the substitution potential over fossil fuels

GHG substitution effect of using wood residues for energy in place of fossil fuels can be calculated according to the rules of Life Cycle Assessment. These substitution effects for each of the life cycle stages of a product (i.e. production, use, cascading and end-of-life) are reported in several studies finding an increment across the substitution factors by about 0.4 - 0.8 kg C / kg C, depending on the fossil fuel replaced. Stump harvesting can provide an additional substitution benefit of 0.2 - 0.5 kg C / kg C. In addition, the substitution benefits from the end-of-life stage (up to 0.4 kg C / kg C) are mainly due to energy recovery from tertiary wood residues instead of fossil fuels. Overall, substitution benefits are higher (up to 1 kg C / kg C) when recovered wood is used to substitute carbon-intensive coal, and lower when it substitutes gas or oil (Leskinen *et al.,* 2018).

The accounting of bioenergy emissions in national and international GHG emission schemes follows the Kyoto Protocol, in which bioenergy emissions are excluded from the energy sector, on the assumption that any emission associated with woody biomass is already accounted for in the land use sector. However, this "carbon neutrality" assumption has been widely criticized (Johnson, 2009, Searchinger *et al.,* 2009). Two main points of critique exist:

1. combustion of biomass will emit its carbon content to the atmosphere immediately, whereas if left unused, it would decompose and emit its content over a longer period of time; and
2. the energy output per unit of content emitted is lower for biomass than for fossil alternatives.

This creates a so-called carbon payback time, i.e. the time lag before a wood-based bioenergy system starts providing GHG emission reductions relative to an equivalent fossil fuel system (Laganière *et al.,* 2017). Moreover, some authors argue that GHG accounting of wood-based bioenergy systems sometimes relies on overly optimistic assumptions about the improvement of forest management practices as a response to biomass feedstock demand (Giuntoli *et al.,* 2020).

Overall, the payback time is assumed to be particularly long for coarse woody debris or any material in conditions with very slow decomposition rates. Conversely, the payback time is found to be shortest, and possibly negligible, for residues that would otherwise be burnt without heat recovery (Lamers and Junginger, 2013). Also, using tertiary wood residues (e.g. wood waste generated by construction and demolition activities) for energy production as a substitute for coal instead of landfilling them provide climate GHG mitigation benefits, especially in the absence of methane recovery in landfills (Morris, 2017).

Nevertheless, discussions related to the payback time and carbon debt of bioenergy often obscures the fact that bioenergy production based on wood residues will most of the time eventually procure long-term GHG reductions as compared to fossil alternatives (Dehue, 2013). Besides, important carbon emission reductions can be obtained by adopting reduced-impact logging (RIL) techniques and wood-processing practices that increase recovery of sawnwood (Sasaki *et al.,* 2016).

BOX 13: GHG climate benefits by replacing fossil fuels in United Republic of Tanzania

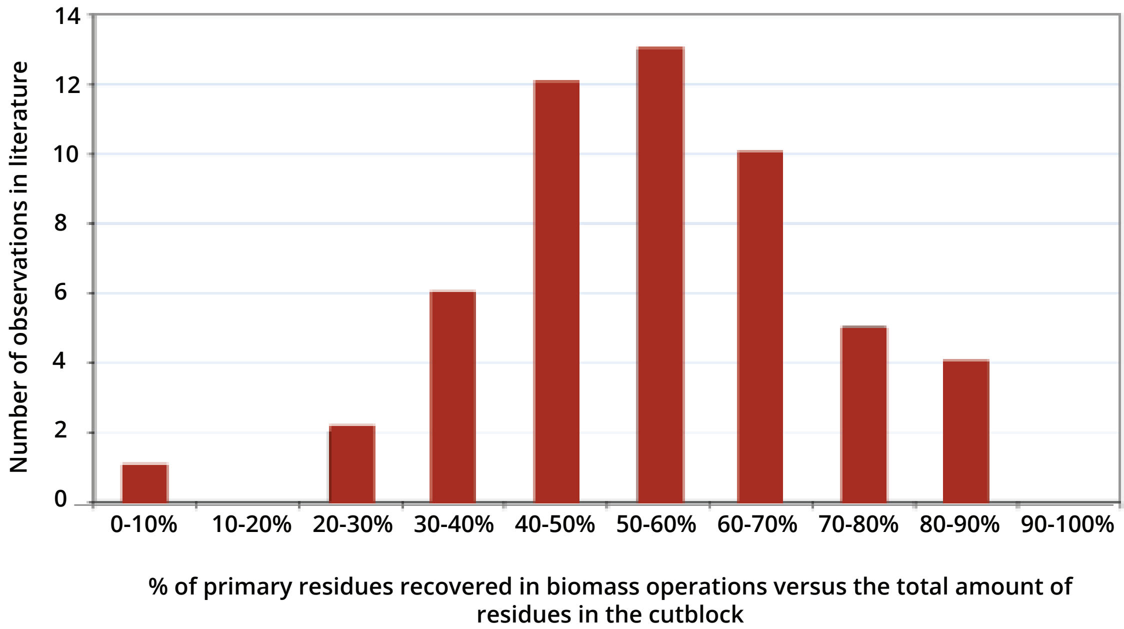
The net GHG effect of using charcoal briquettes and powder produced with sawmill residues for industrial and household uses was assessed in United Republic of Tanzania. Replacing coal in cement manufacturing with wood residue-based charcoal powder can reduce GHG emissions by 455–495 kg of CO_2eq MWh^{-1}, corresponding to a 83–91 percent decrease, while replacing charcoal sourced directly from woodlands with residue-based charcoal briquettes can lead to a reduction of 78–557 kg of CO_2eq MWh^{-1} (i.e. a 42–84 percent decrease) (Sjølie, 2012).

Efficient sawmilling practices and cascading uses of wood through both material and energy valorization of residues can contribute to GHG reduction and climate change mitigation.

4.11 Soil, water and air quality

A review of operational recovery rates of primary residues (treetops and branches) for energy production showed that the average recovery rate in boreal and temperate forests is around 52 percent of available primary residues (Figure 10). Higher values were found in countries with a long history of mobilization of wood residue-based supply chains (e.g. Nordic countries) and lower values were observed in regions with emerging bioenergy markets (Thiffault *et al.,* 2014). This average is generally considered adequate for preserving forest ecosystem functioning and biodiversity (Work, Brais and Harvey, 2014). However, a shift in bioenergy policy, a growth in (or a change in access to) bioenergy markets and upward movements along the technological learning curve (e.g. improvements in machinery, better training of operators) could increase biomass recovery rates and potentially cause damage to forest ecosystems. This therefore calls for strong science-based governance when it comes to establishing proper sustainable guidelines for logging residue procurement (Thiffault *et al.,* 2010).

Figure 10: Recovery rate of primary residues for bioenergy from industrial roundwood harvesting operations



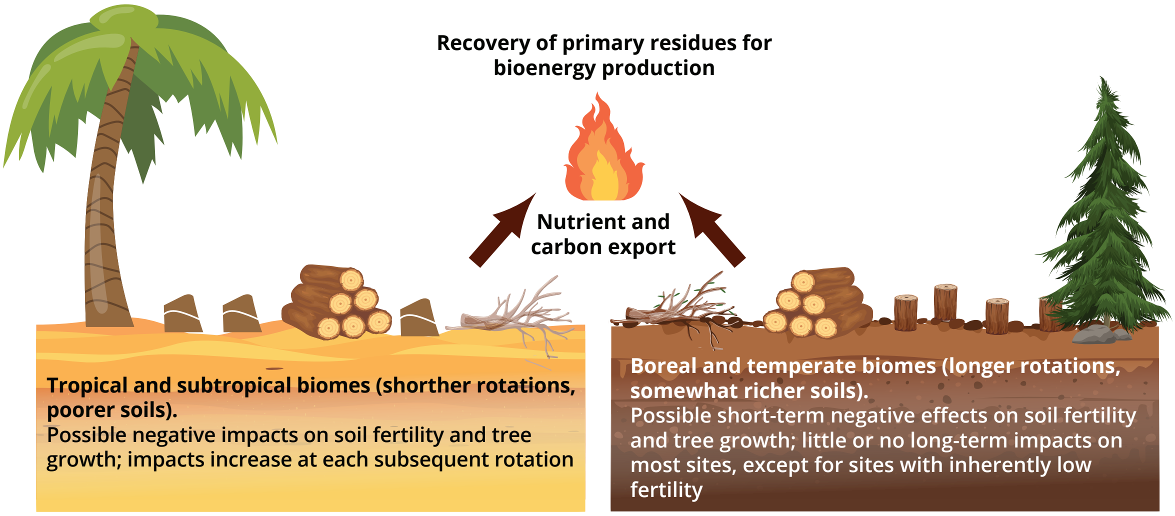
Source: Thiffault, E., Béchard, A., Paré, D. & Allen, D. 2014. Recovery rate of harvest residues for bioenergy in boreal and temperate forests: A review. Wiley Interdisciplinary Reviews: Energy and Environment, 4(5): 429-451.

Existing literature about the boreal and temperate biomes suggests that there are no consistent and universal effects of primary residue removal (i.e. tree branches and tops) on forest soil and site productivity, as effects are site-specific (Vance *et al.,* 2014). Negative effects of incremental removal of biomass have also been found on some sites with inherently low fertility, relative to a baseline scenario of harvesting for roundwood only (Achat *et al.,* 2015, Thiffault *et al.,* 2011). However, longer-term trials have shown that reductions in forest productivity, if any, are only temporary (Egnell, 2011) (Figure 11).

Conversely, negative effects have been found to be much more important under tropical/subtropical climates, where major decreases (up to 20 percent) in stand yield of the next rotation have been observed following residue removal and are getting worse in subsequent harvest rotations (Mendham *et al.,* 2014, Rocha *et al.,* 2018). The much shorter stand rotations that are typical of forest management under these climates increase the carbon and nutrient drain caused by residue removal and reduce the time for the soil to replenish its resources. Furthermore, soils under these climates are generally inherently poorer than soils of the boreal and temperate biomes (Figure 11). While fertilizers can replace the nutrients that are exported in residues and somewhat help to maintain stand productivity in some instances, they cannot compensate for negative impacts on other soil properties, such as structural stability, water-holding capacity and microbial activity, which rely on organic matter inputs.

Removal of primary residues requires careful site-specific evaluation of constraints to ensure that no negative impacts are caused to soils.

Figure 11: Possible impacts of primary residue removal on soil and stand productivity



For their part, removal and further use of secondary residues can usually have positive effects on soil and water (BOX 14).

BOX 14: Valorization of wood residues for energy purposes in Cameroon

Heaps of sawmill residues in Cameroon that had been mounted around the mill were found to block runoff during the rainy season and eventually served as a dumpsite for other waste types, increasing the risk of environmentally damaging leaching to soil and water and, in other instances, residues were thrown into bushes and swamps (Veeyee *et al.,* 2021).
In such cases, valorization of residues in bioenergy value chains can provide substantial environmental benefits.

In contrast to soil and water, issues related to air quality mostly concern the energy conversion phase rather than the biomass feedstock procurement phase. Air pollutant emissions from bioenergy production depend on technology, fuel properties, process conditions and installed emissions reductions (Chum *et al.,* 2011). In fact, the utilization of biomass in its traditional form in open fires and inefficient stoves for heating and cooking, causing indoor pollution, represents a global environmental health risk, especially for women and children (WHO, 2021). Although the risk posed by household air pollution from solid fuels decreased globally over the 2010–2019 period due to social and economic development (Murray *et al.,* 2020), around 4 million people still die prematurely from illnesses attributable to household air pollution from inefficient cooking practices using inefficient stoves paired with traditional bioenergy and kerosene (WHO, 2021). Air pollution arises due to the incomplete combustion of biomass, emitting particulate matter, heavy metals, organic compounds and carbon monoxide. Wood heating has also been associated with high levels of particulate matter in the air due to improper heating technologies, causing important negative health effects, including across Europe and in northern America (Chafe *et al.,* 2015).

Raw (untransformed) biomass emits more air pollutants than charcoal and fossil fuels such as LPG, as its combustion is often less complete and/or less efficient. Thus, any practice that increases the energy density of biomass feedstock, and also reduces variations in its moisture content and size, should help to improve air quality.

However, air quality issues can be primarily solved by using improved biomass conversion technologies, such as ICS.

Several initiatives in developing countries have been devoted to the promotion of the adoption of ICS, with varying degrees of success (GIZ and GBEP, 2015). Indeed, dissemination of ICS in practice remains fraught with numerous difficulties, including high up-front investments, a lack of technical standards and quality assurance, insufficient production capacity and market outreach, and low consumer awareness (Guta, 2012) (BOX 15). Programs for ICS have been most successful when targeted to specific areas with high prices for wood, which are an incentive for the use of more efficient stoves that consume lower amounts of feedstock (World Bank, 2012).

BOX 15: The adoption of energy-efficient cookstoves in Pakistan

A study of the adoption of energy-efficient cookstoves in Pakistan (Jan and Lohano, 2021) has shown that household socio-cultural and economic variables (e.g. education level, land ownership) have a large influence on the uptake level of ICS.

The presence of organizations, especially NGOs, working to promote ICS and media campaigns disseminating. information about ICS, also had a significant influence for the adoption of more fuel-efficient cookstoves by households.

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5. Recommendations

The analysis of the literature according to the three pillars of sustainable development provided examples of good practices, lessons learned and constraints related to the diffusion of modern bioenergy from wood residues in the energy portfolio of communities and countries, and gave rise to the following six recommendations:

1. **Encourage systematic changes in governance to enable the modernization of wood energy value chains**

Land tenure and access to forest resources are recognized as some of the most significant issues creating barriers to sustainable forest management and the transition from traditional bioenergy to a sustainable and modern bioenergy from woody biomass. These issues have been discussed several times before and possible solutions have been detailed elsewhere (e.g. GIZ and GBEP (2015)) but since they supersede any other action, they need to be mentioned here.

Governance mechanisms for the formalization and regulation of the use of forest resources are essential to any plan for the modernization of wood energy value chains.

The ultimate goal should be **a decline in unregulated open access to wood resources and the establishment of a market price for wood that reflects the true costs of sustainable wood production.** This is an indispensable goal for the successful emergence of modern bioenergy from wood residues as part of sustainable industrial wood value chains in developing countries that currently rely heavily on woodfuel in their energy mix.

For this to happen, **national governments**, with the help of relevant **international organizations**, need to put in place proper institutional mechanisms, considering the potential consequences for local communities. Examples of measures include:

- differentiated taxation systems in favour of community-based, sustainably sourced wood;
- revenue sharing with communities;
- strengthening of decentralized forest authorities for law enforcement and land use planning;
- easily enforceable permit systems for access to wood resources based on simple management plans developed with local stakeholders.

2. Raise awareness of the benefits of modern bioenergy

Another overarching condition for the deployment of wood residue-based energy is the **recognition of modern bioenergy as a competitive and sustainable alternative to other energy sources** (including fossil fuels and traditional bioenergy). Such recognition is most likely to blossom if it is within the context of the emergence of a sustainable bioeconomy, climate change mitigation and poverty alleviation, as defined by the SDGs.

Direct policies enacted by governments that **bridge the gap between the costs of renewable energy and fossil fuels** are also needed. Again, examples of such policy solutions have been discussed elsewhere (IRENA, 2020) and include:

- capital grants or subsidies for individuals and companies investing in infrastructure and equipment;
- feed-in tariffs that ensure long-term guaranteed prices for renewable energy; and
- carbon pricing.

There is thus a need for **carefully designed information and campaigns targeted at producers, consumers and policymakers:**

- **For biomass producers and processing industries**, information campaigns should be promoted to support viable investments and ensure **fair and competitive pricing** of end woodfuel products. The campaigns should give attention to operational aspects and the best approaches for securing a **constant supply** of modern woodfuel with **minimum quality standards**. In addition, the forest industry should pilot **certification schemes** for sustainable woodfuel production at the national and regional levels. The role of **bioenergy cooperatives** could play a key role in promoting these campaigns.
- **For communities and households**, campaigns should be targeted at areas where the lack of fuel affordability and availability is a big concern. They should provide information about the fact that improved bioenergy equipment (e.g. ICS) can effectively reduce fuel consumption and translate into financial savings and that reliability of fuel supply will be higher with standardized, regulated wood biomass feedstock. **Campaigns led by NGOs that are constantly present and active within communities** have been found to be the most suitable choice to reach the general population.
- **At the policy level**, awareness should be raised about the cross-sectorial nature of wood energy, the need for the harmonization of social, energy, forestry, agricultural and environmental policies to ensure a successful transition towards modern bioenergy, and the need for an institutional capacity to develop, implement and enforce regulations related to forest resources. For outreach to policymakers, **international organizations** play a key role. Examples of guidelines for the development of such policies are provided in the Africa Bioenergy Policy Framework and Guidelines (African Union Commission and United Nations Economic Commission for Africa, 2013).

3. Develop cooperative solutions for the modernization of the whole wood energy value chain

Successful replacement of traditional use of woodfuel by modern bioenergy from wood residues is based on the **synergy between sustainable and reliable feedstock supply and improved biomass conversion technologies**. Measures that only target one aspect of the value chain are less likely to lead to long-term, durable changes in habits and practices because inefficiencies will persist in the value chain.

An innovation that has proven to be effective for increasing the penetration of modern woodfuel in developed countries is the introduction of **bioenergy cooperatives**. Bioenergy cooperatives provide and manage integrated energy solutions for communities, including the provision and maintenance of biomass boilers and wood residue supply (from local sawmills and forest operation activities). Such cooperatives **bring together producers, entrepreneurs and consumers, conduct pilots and demonstrations of promising technologies and promote information exchange and good practices,** ensuring the convenience, affordability and reliability of bioenergy production for the end-user. They also provide a stronger and more united voice for discussions with policymakers.

Small-scale energy cooperatives and rural biomass markets that have emerged in some developing countries can provide similar benefits. They serve as centralized points for the commercialization of biomass products, but also provide sorting and upgrading, allow financial profits to benefit the communities, and facilitate the traceability of biomass from its production point to the end-user. Such structures could also serve for the promotion of locally produced, improved cooking and heating technologies that would bring additional positive socio-economic externalities at a local level. The organizational flexibility of cooperative organization structures makes them well suited to reach out to actors in informal economies such as that of woodfuel and could thus play a key role in the modernization of bioenergy value chains.

Furthermore, support for cooperative organization structures (including the development of professional corps, associations, and formal educational programmes) can also be a way to increase **workforce training** in modern wood energy value chains.

Governmental policies and strategies are needed for promoting and regulating the development of cooperatives. **International instances** can also play a role. In 2002, the International Labour Organization published the Promotion of Cooperatives Recommendation (No. 193), which provides a framework for governments to develop institutional instruments (laws, administrative systems and policies) to support cooperatives. An information guide was also published to provide practical implementation tools (Smith, 2014).

Stakeholders within bioenergy value chains (i.e. individuals and entrepreneurs) must then take advantage of the institutional framework and form cooperatives.

Cooperative unions, i.e. groups of two or more primary cooperatives, can also help achieve greater economies of scale and increase the political power of cooperatives.

4. Improve data on wood flows from the land base to end-users

Any strategy to increase the mobilization of wood residues for energy requires a **better assessment of feedstock availability**. There is a crucial need to analyze in greater detail the potential of residue supplies, considering local conditions such as costs, ownership patterns, quality requirements, infrastructure availability and environmental considerations by **forest services and agencies at the national or regional levels**. Examples of such assessments include:

The Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) is a method adapted for developing countries. It allows **the analysis of national or regional availability of wood resources,** the prevailing woodfuel flows and the associated human dynamics, which can then serve to identify action priorities for promoting the transition towards modern bioenergy and residue feedstock (Drigo, Masera and Trossero, 2002).

A methodology developed by Vis, Mantau and Allen (2016) for the European Commission for calculating and analyzing the cascading use of wood within a national or regional wood industrial network, gives a framework for identifying opportunities for residue mobilization for energy as part of the larger industrial wood value chain.

However, such methodologies need to rely on high-quality statistics which are notably lacking for post-consumer/waste wood recycling, energy use and wood end-user markets.

For such analyses, high-quality data are crucial to understand the current provision and utilization rates for residues, possible competing uses and occasions to increase material and energy recovery. Specific data are notably needed for:

- the movement/transfers of processing residues within national industrial wood value chains (e.g. circulation of wood chips and particles between mills);
- the use of wood in end-user markets, which consists in a broad variety of products and material mixtures, is a key aspect of wood cascading processes.

The Joint Wood Energy Inquiry, run by the United Nations Economic Commission for Europe (UNECE) and the FAO, is an example of an instrument used to gather data about the sources and uses of wood for energy within the UNECE region at the national level. Such an instrument could be adapted or expanded by **international agencies** to other world regions, such as developing countries for which high-quality data are scarcer.

Centralized data collection such as FAOSTAT could also play a role in **streamlining wood flow datasets across national and international institutions**. This would provide essential information for the traceability of biomass and facilitate the mapping of future trade streams under different policy and potential trade regime scenarios.

Nevertheless, such data collection first requires **operators within value chains** to properly document their activities at the processing and market level, and for **regional and national agencies** to then compile and share data transparently.

5. Stimulate a cascading use of wood resources and increased efficiency in the industrial roundwood network

Although multiple biological and technical factors determine the extent to which roundwood can be converted into higher value-added products, higher percentage of industrial roundwood use in the Global North versus substantially lower rates in most of the subregions in Africa and in some of Asia and the Americas indicates where there is a clear potential to reverse the trends by maximizing the added value and a cascading use of wood material.

The financial viability of using wood residues for energy and other products is more likely to be ensured if the rest of the **industrial roundwood network is based on a diversity of wood products, especially those of high-value that maximize roundwood conversion efficiency and minimize waste**. Similarly, the profitability of material products is often dependent, or at least closely correlated, to the presence of outlets for the residues that are generated along the value chains.

Policy measures that incentivize and support the development of new industries and markets for material wood products can thus be seen as an indirect way to encourage the mobilization of wood residues for energy in developing countries. Also, industries that use wood chips and particles as feedstock to produce specialty pulp and paper, fibreboard and other higher-priced products have a higher ability to pay feedstock on the margin and are less dependent on low-grade wood residues. They are therefore less likely to compete with wood residue-based energy and could more easily harmonize them.

Moreover, **wood-processing practices that maximize roundwood conversion efficiency and minimize waste** help increase the financial return for material wood products. In turn, financially sound material product industries can afford investments in proper and comprehensive equipment for collection, storage, sorting and further upgrading and commercialization of wood residues for energy.

Managers and operators of mills can implement the recommendations for increasing roundwood conversion efficiency and these include:

- optimizing primary log breakdown technology and techniques;
- developing finger-jointing and glued-laminated product lines in downstream operations to turn residues and low-value wood into products; and
- improving operator training and monitoring to ensure awareness and implementation of measures.

At a policy level, **economic instruments can help promote the efficiency of wood resource conversion and cascading use**. Examples of such instruments that can be implemented by **national governments** include:

- legally binding targets for material recovery;
- extended producer responsibility for wood products; and
- the taxation of forest and wood resources.

6. Develop classification and standardization of systems and practices for wood residues and wood residue-based energy carriers

Adequate characterization and sorting of primary, secondary and tertiary wood residues generated along the industrial wood value chain, based on their size, moisture content, chemical composition and level of contamination, allows the identification of relevant avenues for further cascading use into material products and of proper technologies and techniques for pre-treatment and upgrading into standardized energy carriers and energy production.

Tools such as Bio2Match, developed as part of the S2Biom project can be used by **stakeholders that seek to develop or improve bioenergy value chains**: this tool provides potential matches between biomass characteristics and technologies. They can then be used for identifying optimal bioenergy solutions for various residue types (Lammens *et al.,* 2016).

The **presence of biomass depots** can play a key role for residue sorting, pre-processing and upgrading; such depots are often associated with **cooperative organization structures** described earlier. Biomass depots make it possible to access low-grade, diffuse and variable sources of residues. Larger biomass volumes make it easier to justify the investments needed for the implementation of biomass sorting and pre-treatment equipment (e.g. drying, comminuting, sieving, washing, pelletizing/briquetting etc.) with which biomass characteristics and quality can be actively addressed, improved and documented.

The **development of classification and technical standardization systems for wood residues/wood residue-based energy carriers**, either by the **private sector** or by **government agencies**, can also enable their mobilization. Such systems can help to respond to legal obligations for reducing waste or limiting environmental risks (e.g. air pollution due to the presence of contaminants in biomass feedstock).

For example**, legal frameworks put in place at the national level for the classification of wood waste** (tertiary residues) exist in some countries. The standardization of technical specifications for wood energy carriers can facilitate upsizing operations along the bioenergy value chain, which can enable economies of scale and help achieve cost-competitive production and conversion levels.

Technical standardization can also help to remove trade barriers such as phytosanitary restrictions. For example, wood pellet **producer associations** in several regions and countries have developed and promoted their own sets of standards and have started to compare and align them to facilitate international trade.

Apart from technical standards, there is also a need to **substantiate the sustainable production of woody biomass. A dialogue among policymakers** to come to internationally accepted sustainability standards for bioenergy commodities (based on indicators of GHG balance, air, soil and water quality, etc.) could create new opportunities for sustainable mobilization and bioenergy trade. Certification of bioenergy commodities based on such standards could also increase transparency and public acceptance of wood energy carriers in regional and national markets. It could particularly benefit wood residue-based energy carriers, which do not raise most of the environmental concerns that sustainability standards aim to address.

6. Conclusions

This working paper set out to provide an overview of the potential contribution of wood residues as feedstock for bioenergy production as part of the transition towards a sustainable and circular forest bioeconomy. The main indicators that underpinned the analysis of the potential for the transition from traditional to modern bioenergy and the deployment of wood residue-based energy among world regions were:

- access to energy, renewable energy and bioenergy;
- the production of woodfuel relative to industrial roundwood and wood material use;
- the potential of wood residues from industrial wood value chains for the transition from traditional to modern bioenergy;
- the competition of secondary residues for material use; and
- the availability and relative contribution of primary, secondary and tertiary wood residues.

The analysis of regional characteristics allows the identification of specific challenges and opportunities for the mobilization of wood residue-based energy:

- For African subregions, central America and the Caribbean and southern Asia, low energy access and the large share of woodfuel relative to overall roundwood production (and the concomitant small share of forest resources that transit through industrial roundwood value chains) appear as important issues, that should likely be addressed first to encourage a larger structural transition towards valuation of forest resources.
- For south America and for subregions of south-eastern, eastern, central and western Asia, energy access does not appear as a superseding issue. Industrial roundwood value chains seem to be already in place and can likely be further developed and mobilized to increase the recovery of wood residues for modern bioenergy production and displacement of traditional bioenergy.
- Competition for secondary residues from other industries (such as pulp and panels) can be an issue in some instances, such as in eastern Asia.
- In most Asian subregions (except for south-eastern Asia), there also seems to be an opportunity for the mobilization of tertiary residues, as they comprise an important share of the total availability of wood residues in these regions.
- For northern America, Oceania and most European subregions, competition from other industries for access to wood residues, and the specific logistical and

environmental challenges of mobilizing sources of available primary, secondary and tertiary residues, can impose challenges to the energy use of wood residues and provide opportunities for other forest products.

The analysis allowed the identification of specific barriers and opportunities in various regions, notably for developing countries, where systemic conditions related to land use and the valuation of wood resources emerge as important issues. A literature review of the three pillars of sustainable development provided examples of good practices, lessons learned, and constraints related to the diffusion of modern bioenergy from wood residues in the energy portfolio of communities and countries.

Recommendations can be made for key categories of stakeholders and ordered, going from a systemic/structural level, which needs to be addressed first to offer conditions conducive to the development of industrial wood value chains, to a technical level that may help residue mobilization within value chains (Table 8).

Table 8: Recommendations for the mobilization of wood residues-based energy

KEY CATEGORIES OF STAKEHOLDERS	RECOMMENDATIONS
Governments International organizations and NGOs	Encourage systematic changes in governance to enable the modernization of wood energy value chains Raise awareness of the benefits of modern bioenergy
Governments Cooperative unions Operators within the value chain	Develop cooperative solutions for the modernization of the whole wood energy value chain
International organizations National/regional forest services and agencies Operators within the value chain	Improve data on wood flows from the land base to the end-users to quantify and characterize wood residue potential
Governments Operators within the value chain and within mills	Stimulate a cascading use of wood resources and increased efficiency in the industrial roundwood network
Governments Producer associations Cooperatives	Develop classification and standardization of systems and practices for wood residues and wood residue-based energy carriers

Source: Authors' own elaboration.

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Appendix A: Conversion of units for wood products

For compilation of the production in wood product categories for regions, conversion factors were based on median values for regions compiled by FAO, ITTO and United Nations (2020). The following unit conversions were performed:

- Wood charcoal production values were converted from tonnes to m^3 of solid volume using the factor: 6 m^2 of solid volume per tonne of wood charcoal.
- Pellet production values and other conglomerates were converted from tonne of pellets and conglomerate to m^3 of solid volume using the following factors:

  2.24 m^3 of solid volume per tonne for northern America and European regions;

  2.25 m^3 of solid volume per tonne for other regions.
- Pulp production values were converted from air-dried tonne to m^3 of solid volume using the following factors:

  3.76 m^3 of solid volume per air-dried tonne for northern America and European regions;

  3.80 m^3 of solid volume per air-dried tonne for Asian and African regions and Oceania;

  3.43 m^3 of solid volume per air-dried tonne for central America + the Caribbean and south America.

Appendix B: Methodology for the calculation of the theoretical availability of wood residues and their energy generation potential

Availability of primary and tertiary residues

The methodology for calculating the theoretical availability of primary and tertiary residues is adapted from Smeets and Faaij (2007). It is based on a bottom-up approach that derives the availability of residues from the production and consumption of industrial roundwood, since these residues are assumed to be generated by their value chain (see Figure 2).

For primary residues, availability in m^3 of solid volume per year is calculated as a function of industrial roundwood production for a given region, as it assumes primary residue supply would be generated during harvesting. Values for industrial roundwood production were taken from FAOSTAT forestry production and trade statistics since they are consistently compiled and reported for countries and regions over time with internationally comparable methodologies.

For this analysis, the annual averages for the period 2010–2020 were used for all data.

A residue generation factor then describes the share of roundwood that is assumed to end up as residues. A residue recoverability fraction describes the share of residues that can be realistically recovered.

The following equation is used:

$$PRA = IRWP * rgf * rrf$$

Where:

PRA is primary residue availability in m^3 per year
IRWP is industrial roundwood production in m^3 per year
rgf is the residue generation factor
rrf is the residue recoverability fraction

Tertiary residue availability in m^3 of solid volume per year is assumed to arise from the supply of discarded wood-based products. The amount for these products is estimated based on the industrial roundwood consumption for a given region. Roundwood consumption within a region is estimated as the amount of roundwood production of the region. It then also factors in the trade movements of roundwood: exports and imports are respectively subtracted and added to the total quantity of industrial roundwood. A residue generation factor describes the share of industrial roundwood consumption that is assumed to end up as residues. A residue recoverability fraction describes the share of residues that can be realistically recovered.

The following equation is used:

$$TRA = IRWC * rgf * rrf$$

Where:

TRA is tertiary residue availability in m^3 per year
IRWC is industrial roundwood consumption in m^3 per year, calculated as: production - export + import (based on the FAOSTAT forestry production and trade statistics; annual averages for the 2010–2020 period were used).
rgf is the residue generation factor
rrf is the residue recoverability fraction

The residue generation factors and residue recoverability fractions used for primary and tertiary residues were taken from Smeets and Faaij (2007), which based their estimates on a review of the global literature:

SOURCE OF RESIDUES	RESIDUE GENERATION FACTOR (RGF)	RESIDUE RECOVERABILITY FRACTION RRF
PRIMARY	0.6	0.25
TERTIARY	0.5	0.75

Availability of secondary residues

The theoretical availability of secondary residues could also be estimated following the same approach as for primary residues (by applying a residue generation factor and a recoverability fraction to industrial roundwood production). However, direct estimates can also be found in the FAOSTAT forestry production and trade statistics. These values are directly used to avoid uncertainties created by data computation. Values for the "wood residues" and "wood chips and particles" production categories were summed; annual averages for the 2010–2020 period were used.

Energy generation potential

The energy generation potential from residues (in exajoules) was calculated assuming 0.09 m^3 of solid wood volume per gigajoule for residues (FAO, ITTO and United Nations, 2020) and an energy conversion efficiency of 50 percent.

Appendix C: Application of the conceptual framework for the analysis of the mobilization and deployment of modern bioenergy from wood residues in regions of the world

Table C1: Regional and subregional conceptual framework for analysis of potential use of wood residues for energy

Region/subregion	Indicators				
	Access to energy, to renewable energy and to bioenergy	**Production of woodfuel relative to roundwood and wood material use**	**Potential of wood residues for transition from traditional to modern bioenergy**	**Competition for secondary residues used for materials**	**Availability and relative contribution of primary, secondary and tertiary wood residues**
Northern America	High energy access; moderate share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; large share of material products from industrial roundwood	High availability of residues relative to current production of woodfuel	Large share of pulp and panel production that can use secondary residues as feedstock	Similar potentials from primary, secondary and tertiary residues
Central America + Caribbean	Low energy access; moderate to large share of energy consumption met by renewable energy and bioenergy	Large share of roundwood going to woodfuel; moderate share of material products from industrial roundwood	Low availability of residues relative to current production of woodfuel	Small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from tertiary residues
South America	High energy access; moderate to large share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; moderate share of material products from industrial roundwood	Moderate availability of residues relative to current production of woodfuel	Moderate share of pulp and panel production that can use secondary residues as feedstock	Largest potential from secondary residues
Northern Africa	Low energy access; small share of energy consumption met by renewable energy and bioenergy	Large share of roundwood going to woodfuel; small share of material products from industrial roundwood	Low availability of residues relative to current production of woodfuel	Small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from tertiary residues
Eastern Africa	Low energy access; large share of energy consumption met by renewable energy and bioenergy	Large share of roundwood going to woodfuel; small share of material products from industrial roundwood	Low availability of residues relative to current production of woodfuel	Small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from primary residues
Middle Africa	Low energy access; large share of energy consumption met by modern renewable energy, but no bioenergy	Large share of roundwood going to woodfuel; small share of material products from industrial roundwood	Low availability of residues relative to current production of woodfuel	Small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from primary residues

Southern Africa	Low energy access; small share of energy consumption met by renewable energy and bioenergy	Moderate share of roundwood going to woodfuel; moderate share of material products from industrial roundwood	Moderate availability of residues relative to current production of woodfuel	Large share of pulp and panel production that can use secondary residues as feedstock	Largest potential from primary and secondary residues
Western Africa	Low energy access; small share of energy consumption met by renewable energy and bioenergy	Large share of roundwood going to woodfuel; small share of material products from industrial roundwood	Low availability of residues relative to current production of woodfuel	Small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from primary residues
Eastern Asia	High energy access; moderate share of energy consumption met by renewable energy and	Moderate share of roundwood going to woodfuel; large share of material products from	High availability of residues relative to current production of	Large share of pulp and panel production that can use secondary residues as	Largest potential from secondary and tertiary residues
South-Eastern Asia	High energy access; small share of energy consumption met by renewable energy and bioenergy	Moderate share of roundwood going to woodfuel; moderate share of material products processed from industrial roundwood	Moderate availability of residues relative to current production of woodfuel	Moderate share of pulp and panel production that can use secondary residues as feedstock	Largest potential from secondary residues
Central Asia	High energy access; small share of energy consumption met by renewable energy and bioenergy	Large share of roundwood going to woodfuel; large share of material products from industrial roundwood	High availability of residues relative to current production of woodfuel	Moderate to small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from tertiary residues
Southern Asia	Low energy access; small share of energy consumption met by renewable energy and bioenergy	Large share of roundwood going to woodfuel; small share of material products from industrial roundwood	Low availability of residues relative to current production of woodfuel	Moderate to small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from tertiary residues
Western Asia	High energy access; small share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; large share of material products from industrial roundwood	High availability of residues relative to current production of woodfuel	Moderate share of pulp and panel production that can use secondary residues as feedstock	Largest potential from tertiary residues
Northern Europe	High energy access; large share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; large share of material products from industrial roundwood	High availability of residues relative to current production of woodfuel	Large share of pulp and panel production that can use secondary residues as feedstock	Largest potential from secondary residues
Eastern Europe	High energy access; small share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; large share of material products from industrial roundwood	High availability of residues relative to current production of woodfuel	Moderate share of pulp and panel production that can use secondary residues as feedstock	Largest potential from primary residues
Southern Europe	High energy access; large share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; moderate share of material products from industrial roundwood	High availability of residues relative to current production of woodfuel	Large share of pulp and panel production that can use secondary residues as feedstock	Largest potential from tertiary residues

Western Europe	High energy access; large share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; large share of material products industrial from roundwood	High availability of residues relative to current production of woodfuel	Moderate to small share of pulp and panel production that can use secondary residues as feedstock	Largest potential from secondary residues
Oceania	High energy access; large share of energy consumption met by renewable energy and bioenergy	Small share of roundwood going to woodfuel; large share of material products industrial from roundwood	High availability of residues relative to current production of woodfuel	Moderate share of pulp and panel production that can use secondary residues as feedstock	Largest potential from secondary residues

Source: Authors' own elaboration.

Appendix D: Values of statistics used to rate indicators for regions and world averages

Table D1: Primary energy consumption (including all energy sources) and proportion of renewable energy, by subregion

REGION/SUBREGION	PRIMARY CONSUMPTION OF ENERGY IN 2020 (GJ PER CAPITA)	PROPORTION OF PRIMARY ENERGY CONSUMPTION MET BY RENEWABLE ENERGY IN 2020 (%)	PROPORTION OF PRIMARY ENERGY CONSUMPTION MET BY MODERN BIOENERGY AND RENEWABLES OTHER THAN HYDRO, WIND AND SOLAR IN 2020 (%)
WORLD AVERAGE	71.39	13	1
NORTHERN AMERICA	292.51	12	1
CENTRAL AMERICA + CARIBBEAN	12.82	15	4
SOUTH AMERICA	54.16	11	3
NORTHERN AFRICA	32.15	4	0
EASTERN AFRICA	4.76	35	3
MIDDLE AFRICA	4.73	32	0
SOUTHERN AFRICA	75.53	3	0
WESTERN AFRICA	6.48	8	0
EASTERN ASIA	107.28	12	1
SOUTH-EASTERN ASIA	39.18	8	1
CENTRAL ASIA	96.85	8	0
SOUTHERN ASIA	25.46	7	1
WESTERN ASIA	112.02	4	0
NORTHERN EUROPE	132.79	35	5
EASTERN EUROPE	142.56	7	0
SOUTHERN EUROPE	89.13	18	2
OCEANIA	156.54	17	2
WORLD	226.27	16	1

Note: The definition and data sources for statistics are presented in Sections 3.1 to 3.4.
Source of data: BP 2022. Statistical review of world energy 2022. 71st edition. London, UK. Cited 10 October 2022 www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
Note: Country composition of world regions are based on the FAOSTAT classification.

Table D2: Proportion of woodfuel and other forest products, by subregion

REGION/SUBREGION	PROPORTION OF WOODFUEL RELATIVE TO TOTAL ROUNDWOOD PRODUCTION. AVERAGE 2010–2020 (%)	PROPORTION OF SAWNWOOD, VENEER SHEETS, WOOD-BASED PANELS AND PULP PRODUCED RELATIVE TO TOTAL WOOD PRODUCTS ON A VOLUME BASIS. AVERAGE 2010–2020 (%)
WORLD AVERAGE	50	80
NORTHERN AMERICA	10	95
CENTRAL AMERICA + CARIBBEAN	88	73
SOUTH AMERICA	44	72
NORTHERN AFRICA	96	5
EASTERN AFRICA	94	3
MIDDLE AFRICA	88	11
SOUTHERN AFRICA	52	77
WESTERN AFRICA	91	7
EASTERN ASIA	49	96
SOUTH-EASTERN ASIA	51	75
CENTRAL ASIA	91	99
SOUTHERN ASIA	87	62
WESTERN ASIA	31	94
NORTHERN EUROPE	14	93
EASTERN EUROPE	15	92
SOUTHERN EUROPE	43	85
OCEANIA	38	89
WORLD	14	98

- Source of data: FAOSTAT. 2020. Forestry Production and Trade. Online at www.fao.org/faostat/en/#data/FO

Table D3: Theoretical potential availability of wood residues and other forest products, by subregion

REGION/SUBREGION	TOTAL THEORETICAL AVAILABILITY OF RESIDUES RELATIVE TO PRODUCTION OF WOODFUEL ON A VOLUME BASIS. AVERAGE 2010–2020 (%)	PROPORTION OF WOOD-BASED PANELS AND PULP PRODUCED RELATIVE TO TOTAL WOOD PRODUCTS ON A VOLUME BASIS. AVERAGE 2010–2020 (%)
WORLD AVERAGE	98	55
NORTHERN AMERICA	834	68
CENTRAL AMERICA + CARIBBEAN	16	20
SOUTH AMERICA	72	56
NORTHERN AFRICA	20	4
EASTERN AFRICA	2	1
MIDDLE AFRICA	3	0
SOUTHERN AFRICA	65	63
WESTERN AFRICA	4	1
EASTERN ASIA	275	71
SOUTH-EASTERN ASIA	60	53
CENTRAL ASIA	175	45
SOUTHERN ASIA	11	43
WESTERN ASIA	347	51
NORTHERN EUROPE	593	65
EASTERN EUROPE	283	51
SOUTHERN EUROPE	203	64
OCEANIA	241	47
WORLD	422	57

Source: Authors' own elaboration.

Table D4: Proportion of potential availability of primary, secondary and tertiary wood residues, by subregion

REGION/SUBREGION	PROPORTION OF PRIMARY RESIDUES RELATIVE TO TOTAL THEORETICAL AVAILABILITY OF RESIDUES. AVERAGE 2010–2020 (%)	PROPORTION OF SECONDARY RESIDUES RELATIVE TO TOTAL THEORETICAL AVAILABILITY OF RESIDUES. AVERAGE 2010–2020 (%)	PROPORTION OF TERTIARY RESIDUES RELATIVE TO TOTAL THEORETICAL AVAILABILITY OF RESIDUES. AVERAGE 2010–2020 (%)
WORLD AVERAGE	15	26	59
NORTHERN AMERICA	17	23	60
CENTRAL AMERICA + CARIBBEAN	12	9	79
SOUTH AMERICA	26	35	38
NORTHERN AFRICA	3	4	93
EASTERN AFRICA	55	3	42
MIDDLE AFRICA	73	1	26
SOUTHERN AFRICA	21	22	56
WESTERN AFRICA	42	8	51
EASTERN ASIA	6	29	66
SOUTH-EASTERN ASIA	24	29	47
CENTRAL ASIA	0	0	99
SOUTHERN ASIA	21	0	79
WESTERN ASIA	9	5	86
NORTHERN EUROPE	15	31	54
EASTERN EUROPE	29	25	47
SOUTHERN EUROPE	10	22	68
OCEANIA	10	30	60
WORLD	23	43	35

Source: Authors' own elaboration.

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