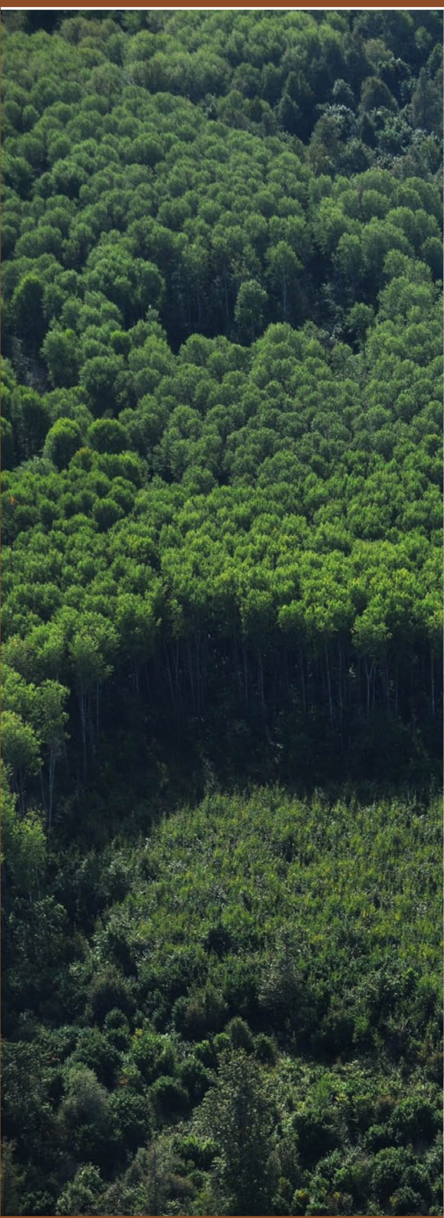
Food and Agriculture
Organization of the
United Nations

Global forest sector outlook 2050

Assessing future demand and sources of timber for a sustainable economy

PROVISIONAL



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Assessing future demand and sources of timber for a sustainable economy

FAO FORESTRY WORKING PAPER

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Background paper for The State of the World's Forests 2022

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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Cover photograph: From left to right, aerial view of a forest ©FAO/Vasily Maksimov; a worker saws pieces of wood coming from trees belonging to Nyandarua Tree Growers Association using a chainsaw at Waka Sawmill. © FAO/Luis Tato; sawmill and lumber yard of large-scale timber company producing high quality wood for the manufacture of a variety of products in Viet Nam © FAO/Joan Manuel Baliellas.

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Acronyms and abbreviations

CLT	Cross-laminated timber
CO_2eq	Carbon dioxide equivalent
EFI	European Forest Institute
EUJRC	European Union Joint Research Centre
EWP	Engineered wood products
FAO	Food and Agriculture Organization of the United Nations
FLEGT	Forest Law Enforcement, Governance and Trade
FLR	Forest Landscape Restoration
FRA	Forest Resources Assessment
FTE	Full-time equivalent
GDP	Gross domestic product
GFPM	Global Forest Products Model
GHG	Greenhouse gas
Glulam	Glue-laminated timber
IEA	International Energy Agency
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
IRW	Industrial roundwood

ITTO	International Tropical Timber Organization
LKTS	Lesser-known timber species
MAI	Mean annual increment
MMCF	Manmade cellulose fibre
MPP	Mass plywood panel
NDC	Nationally determined contribution
NLT	Nail-laminated timber
NZE	Net zero emissions
OECD	Organisation for Economic Co-operation and Development
RWE	Roundwood equivalents
SDG	Sustainable Development Goals
SME	Small and medium enterprise
SSP	Shared socioeconomic pathways
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture

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The authors would also like to thank the many researchers who work on basic research and innovative topics to advance the role of timber as a sustainable material, while highlighting the need to bring together the environmental and societal requirements of modern silviculture and wood industries.

Finally, special thanks are due to Tuukka Castrén from the World Bank and Jana Korhonen of the United States Department of Agriculture (USDA) for their peer review of this work and for providing valuable comments that have improved this study.

Executive summary

This report combines the results of a long-term outlook for the forest sector to 2050 with a complementary assessment of wood demand in a sustainable economic environment. It aims at identifying potential supply gaps and needs in forest industries in terms of roundwood production, industry investments and employment.

The baseline outlook data for primary processed wood products in this study derives from the Global Forest Products Model (GFPM) where projections depend on the historical patterns of wood products production and trade, which was derived from the Food and Agriculture Organization of the United Nations (FAO) data and their interaction with exogenous factors such as gross domestic product (GDP), population, trade policies or forest area change (Nepal *et al*., 2021b). The basic settings of the simulation (World 500) as used for this study have not been altered by the authors.

The global threats to climate, biodiversity and a healthy environment are mainly caused by the excessive use of non-renewable materials. This has led to political interventions to accelerate the decarbonization of economies and to introduce a circular bioeconomy. In several countries such initiatives and programmes are planned or already implemented (Verkerk, 2021; FAO-UNECE, 2022).

Hence, the forest sector outlook in this study will vary as to the function of the effectiveness of these measures and their impact on availability and prices for competing non-wood materials. The most promising wood products for large scale substitution of non-renewable materials uses are mass timber and engineered wood products in construction, man-made cellulose fibre (MMCF) for textile production and wood for energy (Verkerk, 2021). Thus, this study focuses on these products to illustrate the potential impact and challenges of enhanced demand for wood in a sustainable economic context.

The results are derived from the authors' calculations outside the GFPM model. Other studies, drawing on different assumptions and development pathways (see UNECE and FAO, 2021), suggest higher demand growth for these and other innovative wood products. The results of this study may be seen as a conservative approximation of future trends, considering the high levels of uncertainty in this dynamic field.

The wood fuel outlook for 2050 presents trajectories of future wood fuel demand as suggested by the GFPM, the International Energy Agency (IEA) in IEA (2021b) and the Intergovernmental Panel on Climate Change (IPCC) in IPCC (2018). The study, however, does not suggest a baseline outlook for wood fuel due to the wide variation of trajectories.

The last few decades have shown that the consumption of wood products has been influenced by economic shocks and international crises (as happened in the aftermath of the political change in European communist countries in the 1990s, the global financial crisis in 2008, the COVID-19 pandemic that began in 2020 and the ongoing war in Ukraine). Hence, the outlook data presented in this study should be read with due caution.

KEY RESULTS OF THE PRIMARY PROCESSED WOOD PRODUCTS OUTLOOK 2050

The GFPM outlook for a primary processed wood products consumption of 3.1 billion m^3 roundwood equivalents (RWE) in 2050 reflects an increase of 37 percent compared to 2020. The additional demand for wood products to substitute non-renewable materials (mass timber and man-made cellulose fibre) may increase by up to 272 million m^3 (Table 1).

Depending on the use intensity of wood industry residues, the resulting industrial roundwood (IRW) demand may grow between 0.5 billion to 0.9 billion m^3 by 2050 compared to IRW in 2020. In addition, up to 199 million m^3 would be required to substitute for non-renewable materials (Table 2).

Scenarios of future wood fuel consumption trajectories to 2050 show a wide amplitude. Most scenarios indicate that the global consumption volumes of wood from forests in energy uses range between 2.1 billion and 2.7 billion m^3, compared to 1.9 billion m^3 in 2020 (Table 3).

TABLE 1.
Primary processed wood products outlook, 2050

Products in million m^3 (RWE)	2020	2050	Percentage increase 2020–2050
GFPM outlook primary processed wood products*	2 286	3 124	37
Non-renewable material substitution: Mass timber in construction	4	41 to 123	5 to 12
Non-renewable material substitution: MMCF	39	57 to 149	8 to 23

Sources: Authors' own elaboration based on FAOSTAT Forestry 1990 and 2020, GFPM 2050 simulation, United Nations World Population Prospects 2019. Medium fertility variant, 2020–2100; United Nations World Urbanization Prospects: The 2018 Revision, and Textile Exchange. 2021. Preferred Fiber & Materials – Market Report. Textile Exchange.
*Including sawnwood, veneer/plywood, particle and fibre board, and wood pulp.

TABLE 2.
Industrial roundwood demand outlook, 2050

Industrial roundwood in million m³ (RWE)	2020	2050	Percentage increase 2020–2050
IRW (basic outlook)	1 983	2 500 to 2 900*	25 to 45
IRW demand for non-renewable material substitution***	n/a**	45 to 199	n/a

Sources: Authors' own elaboration based on FAOSTAT Forestry for IRW 2020, GFPM 2050 simulation, and additional volumes due to the substitution of renewables for non-renewables as detailed in chapter 2.4

*Max wood industry residues in 2050: 876 m³. Varying wood industry residues use intensities of 30, 50, 70 percent.

**How much actual MMCF production is based on wood residues or pulp logs is unknown.

***Assumes use of 50 percent of sawnlog residues from mass timber production to be used in MMCF production.

TABLE 3.
Wood energy outlook, 2050

Wood fuel consumption	2020 (billion m³)	2050 (billion m³)	Percentage change 2020–2050
Medium outlook pathways (based on IEA, IPCC and GFPM)		2.1 – 2.7	+11 to 42
High outlook (based on IPCC)	1.9	7.7	+400
Low outlook (based on IPCC)		1.6	-19

Source: Authors' own elaboration based on IEA. 2021a. *Net Zero by 2050. A Roadmap for the Global Energy Sector.* IEA, Paris.

KEY RESULTS OF ROUNDWOOD SUPPLY TO MEET DEMAND OUTLOOK 2050

Industrial roundwood

This study does not identify a global IRW supply gap to meet basic outlook demand in 2050. However, IRW shortage in Asian sub-regions will induce increasing trade flows of industrial roundwood and primary processed wood products (chapter 3.3).

Further, a potential demand increase to substitute for non-renewable materials and an increasing use of wood for energy in the future renewable energy mix will require additional efforts to increase roundwood production (Table 2).

Future IRW supply is prone to uncertainties resulting from climate change driven policy interventions in naturally regenerated production forests and the productivity and expansion of planted forests. In case IRW availability from naturally regenerated forests is reduced, it will be necessary to increase substantially the productivity of existing planted forests and establish new areas to meet future demand.

In 2020, naturally regenerated temperate and boreal forests provided about 44 percent of global IRW production (chapter 3.5.1). In a continuation of historical trends, outlook studies by other authors (see UNECE and FAO, 2021) project an annually increasing stock in naturally regenerated temperate and boreal forests, suggesting potential for increasing the supply of IRW. However, significant uncertainties remain regarding the influence of forest management and conservation policies on harvesting volumes.

Planted forests contributed around 46 percent to the global IRW supply in 2020 (chapter 3.5.2). However, the actual productivity of planted forests (at global average) is low. The study exemplifies how supplying future demand may be achieved by a combination of production of naturally regenerated temperate and boreal forests and of planted forests (increasingly in the Global South).

It concludes that at least 33 million ha of additional highly productive plantation forest would need to be established to supply the basic IRW demand increase up to 2050, if naturally regenerated forest production remains stable. This estimate is roughly in line with other studies that estimate plantation area growth between 20 million and 40 million ha by 2050 (chapter 3.5.2).

If productivity in naturally regenerated temperate and boreal forests remained stable at 2020 production (0.4 m^3/ha), the productivity in existing planted tropical/sub-tropical forests needs to increase from actual average production of 2.7 m^3/ha/a to 7.2 m^3/ha/a to meet the basic demand outlook in 2050 (chapter 3.5.3).

More restrictive policies for extractive forest use in the EU-27 would lead to a decrease of IRW production in naturally regenerated temperate and boreal forests. To compensate for this reduction, the global average production of planted tropical and sub-tropical forests would need to increase to 8.3 m^3/ha/a to meet the basic demand outlook in 2050 (chapter 3.5.3).

Additional IRW and fuelwood could be sourced from agroforestry systems and tree crop plantations. However, there is no comprehensive data available on the current contribution of these systems to global wood supply. Nonetheless, existing areas are substantial (45 million ha agroforestry and 7 million ha rubber plantations) and can be further increased during agricultural expansion for food production. Further, more than 200 million ha of Forest Landscape Restoration (FLR) pledges suggests that there is potential for establishing planted forests for multiple purposes including roundwood production (chapter 3.5.2).

Wood energy

Actual data on sources of wood energy is fragmented and does not allow for establishing a baseline supply outlook disaggregated for forest categories. Nonetheless, meeting future demand without compromising the sustainability of forest ecosystems will require pro-active management of the related resources.

Future wood energy consumption by 2050 will be shaped by two major trends: (1) the traditional use of fuelwood in the two most rapidly growing world regions of sub-Saharan Africa and Southern Asia; and (2) the envisaged role of modern biomass in renewable energy generation.

In view of the expectation of growing demand in emerging economies, this study sees opportunities for area expansion of fuelwood woodlots and agroforestry systems, aligned with forest landscape restoration initiatives (chapter 4.2.2). Meeting additional fuelwood requirements in sub-Saharan Africa would require a mix of agroforestry and energy woodlots with a total area of 21 million to 31 million ha. However, most fuelwood would still be sourced from naturally regenerated resources (forests and woodlands).

Wood fuel sourcing in industrialized world regions that are predominately located in temperate and boreal zones with naturally regenerated forest resources may increasingly draw on planted forests and wood residues that cannot be utilized elsewhere in wood industries (chapter 4.2.1). This study demonstrates the requirements of a prominent role of wood in the future energy mix, drawing on IEA´s assumptions for a net zero emission scenario (NZE) in 2050. The required volumes and production areas would trigger significant competition with industrial roundwood production and processing industries.

KEY RESULTS OF FOREST SECTOR EMPLOYMENT AND INVESTMENT REQUIREMENTS

Total employment in the forest sector in 2019 was estimated to be 33.3 million formal and informal employees. Historical trends have shown decreasing employment numbers.

The outlook for forest sector employment in 2050 considers varying trajectories of increasing labour productivity. The medium estimate suggests 2050 employment being in the range of 2019 figures. The workforce may increase between 1 percent and 4 percent to meet production for substituting selected non-renewable materials (mass timber in construction and MMCF) (Table 4).

For the production of future primary processed wood products in the basic GFPM outlook for 2050 (Table 1), the required investments to set up new production units and modernize existing industries may amount to USD 25 billion per annum. The investments required to provide industrial roundwood to meet 2050 demand (Table 2) are estimated at USD 40 billion per annum, of which USD 24 billion will be allocated to naturally regenerated production forests and USD 16 billion to establish and replant forest plantations (Table 5).

The additional investments required to produce mass timber and MMCF to substitute non-renewable materials may be between USD 0.6 billion and USD 2.5 billion per annum. Providing the related industrial roundwood supply from forest plantations would require another USD 1.4 billion to 4.5 billion investments per annum (Table 5).

TABLE 4.
Forest sector employment requirements, 2050

Sub-sector	Employment 2019 (in millions)	Employment 2050 (in millions; medium estimate in basic outlook)	Change in basic outlook 2019–2050 (percent)	Employment requirements for non-renewables substitution 2050 (in thousands; lower and upper estimate)	Increase compared to basic outlook 2050 (percent)
Forestry and logging	8 085	7 781	-4	70 to 224	1 to 3
Wood industry	19 400	19 043	-2	185 to 595	1 to 3
Pulp and paper	5 854	6 382	9	72 to 441	1 to 7
Total	33 339	33 206	0	327 to 1 260	1 to 4

Sources: Authors' own elaboration based on FAOSTAT Forestry for roundwood production, and for employment on Lippe, R.S., Cui, S. & Schweinle. (forthcoming). *Contribution of the forest sector to total employment in national economies*. Rome, FAO, and chapter 3.2 for IRW demand and fuelwood consumption of about 2.5 billion m³.

TABLE 5.
Forest sector investment requirements, 2050

Forest category	Annual investment requirements 2020–2050 (USD billions)		Increase in investments due to non-renewables substitution (percent)
	... to meet basic IRW outlook demand	...for non-renewable materials substitution (lower and upper estimate)	
Natural regenerated forests	24	-	0
Plantation forests	16	1.4 to 4.5	9 to 28
Wood processing industries	25	0.6 to 2.5	2 to 10
Total	66	4.5 to 7	7 to 11

Sources: Authors' own elaboration based on forest area (FAO. 2020. Global Forest Resources Assessment 2020: Main report. FAO, Rome) and investment requirements (Austin, K., Baker, J.S., Sohngen. B.L., Wade, C.M., Daigneault, A., Ohrel, S.B., Ragnauth, S. & Bean.A. 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nature Communications*).

CONCLUSIONS

Balancing policy targets and enhancing forest productivity necessary to meet future demand for industrial roundwood

The basic outlook for a primary processed wood products consumption of 3.1 billion m^3 (RWE) in 2050 indicates an increase of 37 percent compared to 2020 (Table 2). The corresponding industrial roundwood requirements will be 2.5 billion to 2.9 billion m^3 (Table 2).

The additional demand for substituting non-renewable materials wood products as analysed in this study (mass timber and man-made cellulose fibre) may increase by 272 million m^3. Other studies suggest even higher additional demand (UNECE and FAO, 2021).

The study suggests that supplying future demand may be achieved by a combination of increased production in naturally regenerated temperate and boreal forests and in planted forests (increasingly in the Global South) (chapter 3.5). However, estimates of the concrete contribution of forest categories and regions to global timber supply in 2050 are highly uncertain. Forest management and conservation policies, market mechanisms, investment decisions and environmental factors will define where IRW production growth will occur.

- Production increases in naturally regenerated boreal and temperate forests rely on the political decisions taken to mitigate and adapt to climate change. Comprehensive policies that balance carbon sequestration, biodiversity and IRW production should be elaborated further to ensure planning security for forest industries (Dieter, Weimar and Iost, 2020; Knauf *et al*., 2015).
- The area of planted forests in the tropics and sub-tropics can be increased by better integrating commercial timber production in forest landscape restoration approaches and agroforestry practices and by engaging large industries as well as smallholders and communities as producers in commercial timber value chains (Stanturf *et al*., 2019; Ange, Finegan and Sist, eds., 2021).
- Increasing productivity in planted forests depends strongly on a well-designed enabling environment that offers sound technical support (e.g. applied research and practical training facilities) to improve seed and seedling quality, and increase silvicultural knowledge. It also requires adequate finances to intensify management (Castrén, Katila and Lehtonen, 2014; McEwan *et al*., 2019) and depends on adhering to environmental and social safeguards.

Meeting the future demand for wood products will require increasing capital allocation in emerging world regions and a well-trained work force

This study estimates that investments required to maintain and expand industrial roundwood production may require about USD 40 billion per annum by 2050. To meet the expected growth in wood products consumption in 2050, another USD 25 billion per annum investment in modernization and in establishing industries may be required. In case of increasing demand for materials to substitute for non-renewable materials, annual investment requirements in forestry and related industries may increase by another USD 4.5 billion to 7 billion (Table 5).

Increasing productivity in forestry and forest-based industries might result in a moderate increase in employment, but employment might even decline. However, the increasing demand for materials that can substitute for non-renewable materials may lead to increasing employment (Table 4). The labour requirements of future wood industries will be more sophisticated, and ensuring a sufficient number of well-trained personnel will require solid education and training. Most forest sectors in emerging economies already lack sufficiently qualified workforces, and the forest sector must compete with other industries for talent at the management and production levels (UNECE, 2020b).

Since future demand is expected to grow and to be highest in emerging markets (chapter 2.3) and the potential for roundwood production is significant in tropical and sub-tropical regions (chapter 3.5), it seems likely that forest industry investments will be made in these regions.

The investments in expanding and modernizing forest industries and their workforces will require the joint effort of the public and private sectors.

- The forest sectors of emerging economies will need public and private investments to overcome common challenges. Public investment could help to raise private investments at scale and help stimulate sustainable growth. The forest sectors need to develop competitive small and medium enterprise (SME) segments by providing access to capital and business development support (Castrén *et al.*, 2014; ITTO, 2021).
- Emerging regions frequently receive low rankings when it comes to the ease of doing business, resulting in substantial risk for investors. In the highly informal space that exists in emerging world regions, domestic and international investors compete with informal investors. Transaction costs are high. Emerging economies will have to work on improving their investment enabling environments and on their forest sector governance (Castrén, Katila and Lehtonen, 2014; Held, Solymosi, Davis and Alonso, 2019).
- In future, the forest industries will need to employ specialists in mechanical harvesting, digital design, automated processing and information technology. Realizing the employment potential will first require investments in education, particularly in vocational training, and on-the-job capacity building (UNECE, 2020a; ITTO, 2021).

Meeting the future demand for wood fuel will require optimized resources allocation and a clear political vision of the contribution of wood energy to the renewable energy mix in 2050

The outlook of wood fuel in the future energy mix is subject to high levels of uncertainty. The trajectory of wood fuel use will be shaped by 1) its future role in the renewables energy mix, which is controversial, under discussion and may result in a substantial increase in demand, and 2) the subsistence needs of growing populations in emerging economies, which vary in function of income growth and energy infrastructure expansion. By the end of 2020 there were still 2.3 billion people relying on wood fuel as their primary source of energy for cooking and heating (IEA, 2021a).

Only minor changes in the relevant factors cause substantial deviations in the long-term consumption outlook. The global wood fuel outlooks for 2050 provided by relevant institutions (IEA, IPCC) suggest a wide variation of scenarios ranging from a 19 percent decrease to a 400 percent increase in consumption compared to 2020 levels. These variations are caused by the underlying assumptions for the drivers influencing the future modern and traditional use of wood fuel (chapter 4.2.1).

Regardless of the volumes that will be required, resources allocation for wood fuel production must be optimized without compromising the sustainability of ecosystems. In view of expected growing demand in emerging economies, this study sees opportunities for expanding the area of fuelwood woodlots and expanding agroforestry systems that may be aligned with forest landscape restoration initiatives. Wood fuel sourcing in industrialized world regions that are predominately located in temperate and boreal zones with naturally regenerated forest resources may increasingly draw on planted forests and industry residues that cannot be utilized elsewhere in wood industries (Norton, 2019).

The challenges to sustainably supplying future wood fuel to meet demand are mainly posed by political factors in industrialized and socioeconomic development in emerging world regions:

- Wood fuel will remain the main energy source for many households in emerging economies. Ensuring access to sustainable wood fuel to private consumers who rely on this source due to economic reasons is a public task comparable to supplying electricity or water. This should be considered in strategic national planning and endowed with reliable budgeting and resources, i.e. in the context of agricultural expansion and FLR (UNEP, 2019; FAO, 2017b).
- Renewable energy policies in industrialized world regions must clearly elaborate on the role of wood fuel in the envisaged energy mix. This helps encourage investments that will allow forest sector actors to meet the growth in demand by increasing wood fuel production, supply chain logistics, and avoids market distortions and resource shortages for solid wood product value chains (IEA, 2021b; Nepal *et al*., 2018).

1. Outline and general methodology

1.1. OUTLINE

This report combines the results of long-term outlooks for the forest sector up to 2050 with a complementary assessment of potentially increased demand for wood in a sustainable economic environment (see Box 1). It aims at identifying potential supply gaps and needs in forest industries in terms of roundwood production, industry investments and employment.

The report takes a demand driven perspective starting with the baseline outlook for the consumption of primary processed wood products under baseline assumptions and for possible increases in the demand for selected products to substitute non-renewable materials (i.e. in construction, textile fibres – see Box 1).

Consequently, it discusses the actual forest resource base and production needs to supply future demand by factoring in the use of wood residues and enhanced productivity in forest industries.

The report is divided into four main chapters:

The chapter **Outlook of demand for primary processed wood products in 2050** reviews historical trends (based on FAOSTAT data) and presents a baseline outlook of the consumption of primary wood products based on the GFPM World 500 simulation of 2017, updated in 2020.[1]

Subsequently, the chapter **Outlook of industrial roundwood demand and supply 2050** discusses the future provision of industrial roundwood. The future demand for primary processed wood products is discussed in contrast with the actual supply situation with industrial roundwood along major forest categories and indicates requirements to expand production.

[1] GFPM version 2017; October 2020 (WORLD 500 simulation). Published by the Department of Forest and Wildlife Ecology of the University of Wisconsin-Madison. The model, actual output data and model explanations can be found at https://onedrive.live.com/?authkey=%21AEF7RY7oAPlrDPk&id=93BC28B749A1DFB6%21118&cid=93BC28B749A1DFB6. See Annex for explanation of main assumption and explanations of the model. The simulation presented draws on middle-of-the-road GDP and population forecasts as detailed by the Shared Socioeconomic Pathway 2 scenario (SSP2) of the International Institute for Applied System Analysis (IIASA), which is also used by the Intergovernmental Panel on Climate Change (IPCC). The data can be found at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10. See Annex for explanations and links to raw data and methodologies.

The chapter **Outlook of wood energy 2050** focusses on global trends and the outlook of wood fuel consumption in 2050. It takes a closer look at the traditional use of wood fuel in sub-Saharan Africa, providing estimates on future supply gaps and related mitigation options.

The chapter **Outlook of employment and investment in requirements in forest industries 2050** estimates the investment requirements in forests and industries and describes the potential impacts on employment with a view to increasing labour productivity. Further, the chapter presents estimations of investment requirements to secure timber supply and to expand and modernize wood processing capacities to deliver on the growing demand as detailed in the previous chapters.

General methodology

This study summarizes the status of wood and wood products consumption in 2020 and presents projected future developments in wood supply and demand to 2050. In doing so, a set of statistical sources, model calculations and secondary literature was consulted.

Analytics and results in this report are presented for the following products (see glossary in Annex) (FAO, 2022).

Forest products

- industrial roundwood (12)
- wood fuel (11)
- sawnwood (05)
- wood-based panels
  - » veneer (06)
  - » plywood (071)
  - » particle board (072/073)
  - » fibre board (074)
- wood pulp (08)

Selected products to substitute for non-renewables

- timber in construction (represented by mass timber / cross laminated timber) (13)
- MMCF from dissolving wood pulp (084)
- wood fuel in bioenergy (11)

Note: Number in brackets shows product section according to FAO. 2022. *Classification of Forest Products*. Rome, FAO.

To enable a better understanding of supply-demand dynamics, the wood products volumes were converted to roundwood equivalents (RWE), indicating the amount of solid wood fibre contained in a wood product (see Annex 8.4 for conversion factors). The conversion represents global averages. Note that conversion factors vary widely in function of species and processing technologies.

The presentation of analysis results applies the regional aggregates and forest categories as used in FAO (2020).

Box 1
Wood products in a sustainable economy

Over the coming decades, the world will see increased competition for limited and finite natural resources. Economic development and population growth will further drive global material consumption. Even though technical and structural changes will further reduce material intensity, the driving forces prevail. The global demand for goods and services and related resources may climb to 200 percent of today´s level or more by 2050 (UNEP and IRP, 2016; OECD, 2018), putting the thresholds of planetary boundaries at risk (UNEP and IRP, 2016).

Increasing global material demand and related resource exploitation are major causes of biodiversity loss, eco-systems degradation and social inequality among other negative externalities. Projections indicate that by 2060 the toxic effects on humans and ecosystems related to the extraction and processing of metals alone will double (OECD, 2018).

The concept of a sustainable economy aims at staying within the limits of the planet's resources, reducing the negative social and environmental externalities of resources extraction and processing, and keeping global warming well below a 2 °C threshold (FAO and UNECE, 2022; EU, 2022) by transitioning towards a more efficient and sustainable use of renewable biological resources. A sustainable economy is built on a bioeconomy that produces and processes the requirements of a growing world population (food, housing, clothing, etc.) based on biobased materials while using fewer inputs, reducing environmental impacts and reducing greenhouse gas emissions. The latter is closely related to the concept of a circular economy, which aims at minimizing waste and making the most of natural resources (FAO and UNECE, 2022).

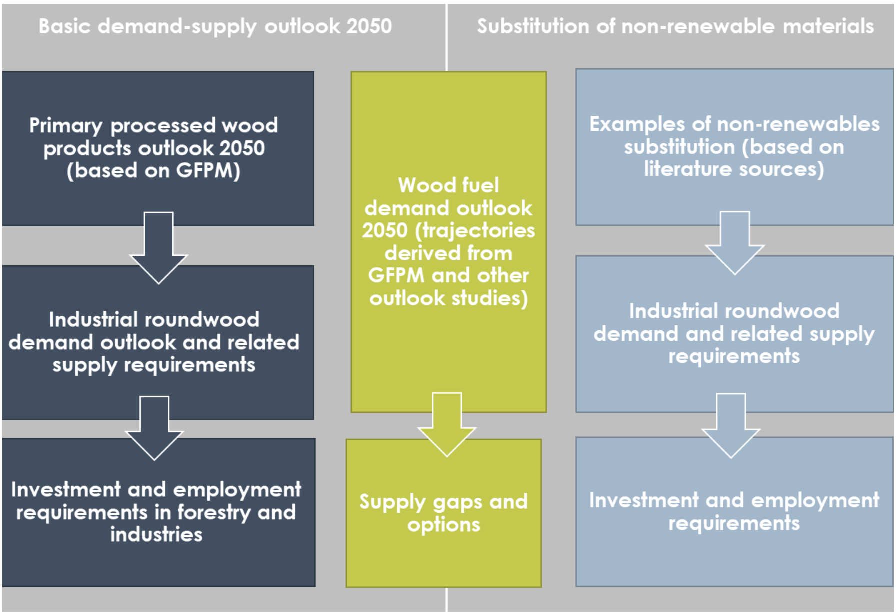
FAO's working definition of bioeconomy from the 2018 Global Bioeconomy Summit: "Bioeconomy is the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy" (GBS, 2018).

Wood is one the world´s most important renewable raw materials. Wood-based products are used in new markets in wood construction, in the chemical industry and in textiles. Industry boundaries are expected to fade, meaning that forest industries will adopt new value chains and other industries may increasingly use wood resources as primary raw material (Hurmekoski, 2019).

However, most wood products that could be suitable for the bioeconomy market are still in the early stages of development. Among these early-stage products are wood foam, glycols, bioplastics (both from tall oil and wood sugars), lignin-based adhesives and wood-based composites, which all have the potential to enter the market in the next 20 years. The products that are most likely to increase in market size are cross laminated timber and wood-based textile fibres (Hassegawa *et al.*, 2022: Verkerk, 2021).

The study followed the workflow as illustrated in Figure 1.

Figure 1. Workflow



The baseline outlook data for primary processed wood products derives from GFPM. In GFPM, the projections depend on the historical patterns of wood products production and trade derived from FAO data and their interaction with exogenous factors regarding macro changes, such as gross domestic product (GDP), population, trade policies or forest area change (Nepal *et al.*, 2021a). It simulates the market equilibrium solution in each projected year, drawing on assumptions about the future development of these exogenous macro factors.

The basic settings of the simulation (World 500) used for this study have not been altered by the authors (Annex 8.2). They reflect moderate development paths and consider foreseeable megatrends (generally in line with the SSP 2, Shared Socio Economic Pathway 2).[2] It does not include policy or technology induced disruptive changes, such as climate change mitigation strategies.

For the model simulations of the presented GFPM (World 500) the following two aspects are most relevant:

- global population growth is moderate and levels off in the second half of the century; and
- income inequality persists or only improves slowly, and challenges to reducing vulnerability to societal and environmental changes remain.

The demand for wood products (sawnwood, panels, pulp) in the GFPM simulation changes from one year to the next due to changes in GDP (though

[2] SSPs are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies. The scenarios have been used to produce the IPCC Assessment Reports on climate change (see Annex 8.3).

the model enables hosting up to six exogenous demand shift factors). Thus, the GFPM simulation in this study presents a baseline forecast with reduced complexity.

As the GFPM model is based on historical data and structures, it is very limited in foreseeing impacts of new products and structural changes (Hurmekoski and Hetemäki, 2013). To assess the implications of a potentially increasing use of primary processed wood products to substitute for non-renewable materials, separate cases for timber in construction and manmade cellulose fibre (MMCF) are presented. Within each of the cases, scenarios were calculated. The results have been derived by the authors' calculations outsides the GFPM model as explained in the tables that follow.

The wood fuel outlook for 2050 presents trajectories of future wood fuel demand as suggested by the GFPM, the International Energy Agency (IEA) in IEA (2021b) and the Intergovernmental Panel on Climate Change in IPCC (2018). This study does not suggest a "baseline" outlook for wood energy due to the wide variation of trajectories.

The following tables detail the data used and the way they have been processed to arrive at the results presented in this report. The related data and results are presented in the Annexes.

TABLE 6.
Data and approaches used to calculate the demand for basic wood products outlook, 2050

	Item	Consumption to 2020	Basic demand outlook for 2050
1	Industrial roundwood	FAOSTAT Forestry (converted to RWE)	Own elaboration based on GFPM simulation (converted to RWE), adjusted for use rates of wood industry residues (see lines 2 and 3 in this table).
2	Sawnwood, wood-based panels, wood pulp	FAOSTAT Forestry (converted to RWE)	GFPM simulation (converted to RWE)
3	Wood industry residues	FAOSTAT Forestry (converted to RWE): Balance of primary processed wood products production and industrial roundwood production	Based on GFPM simulation (converted to RWE) Wood residues availability = 50% of production volumes of sawnwood and veneer/plywood in 2050
6	Wood fuel	FAOSTAT Forestry	Comparison of several trajectories from GFPM, (IEA, 2021b) and (IPCC, 2018)
7	Wood fuel sub-Saharan Africa	FAOSTAT Forestry	Comparison of several trajectories from GFPM, (IEA, 2019), (UNEP, 2019a), (Pappis, 2019)
8	Wood fuel gap sub-Saharan Africa	Assumes that agricultural area expansion will occur on wooded land/forest that supplies fuelwood Productivity increases in agriculture to 2050 may reduce the required area expansion	Agricultural area expansion estimate 2050 (Alexandratos and Bruinsma, 2012) Mean annual increment (MAI) Miombo (Marzoli, 2007) Medium wood fuel consumption outlooks (see line 7 in this table)

TABLE 7.

Data and approaches used for non-renewables substitution examples, 2050

	Item	Consumption to 2020	Non-renewables substitution 2050
1	Mass timber (exemplified as cross-laminated timber [CLT])	Estimate of production volume 2020 from (Muszynski *et al.*, 2020). Included in FAOSTAT data on sawnwood, veneer and plywood (see Table 6, line 2)	3 scenarios of varying shares of timber construction in urban housing demand based on United Nations population prospects for 2100 (mid-fertility) Demand growth reduced by growth implied in baseline outlook (see Table 6, line 2)
2	MMCF	Estimate of production volume 2020 from (Textile Exchange, 2021 Included in FAOSTAT data dissolving wood pulp volumes included in wood pulp (see Table 6, line 2)	2 scenarios of varying shares of MMCF in textile fibre consumption Demand growth reduced by growth implied in baseline outlook (see Table 6, line 2)
5	Wood fuel in bioenergy	FAOSTAT Forestry	Volumes as suggested by IEA net zero emission scenario to achieve 1.5 °C target (IEA, 2021b). IEA scenario volumes converted from Exajoule to m³ Demand growth reduced by growth implied in baseline outlook (see Table 6, line 6)

TABLE 8.

Data and approaches used to obtain industrial roundwood and related area requirements, 2050

	Item	Targeted IRW production	Area requirements
1	Area requirements of planted forest to produce IRW demand growth 2020–2050	Global demand growth of industrial roundwood in baseline outlook (see Table 7, line 1) in function of wood residue use intensities (see Table 6, line 3)	Based on global average mean annual increment of plantation forests; adjusted values (Payn *et al.*, 2015; Juergensen, 2014) Assuming a varying increase of productivity in plantations and likely productivity reduction in natural regenerated temperate and boreal forests (Dieter, Weimar and Lost, 2020) It is acknowledged that MAIs may vary widely according to region, species and production purpose
2	Area requirements for agroforestry to fill wood fuel gap in sub-Saharan Africa 2020–2050	Volumes as derived in Table 6, line 8	Average mean annual increment based on Iiyama (2014) and Marzoli (2007) It is acknowledged that MAIs may vary widely according to region, species and production purpose

TABLE 9.
Data and approaches used to obtain actual industrial roundwood production by forest category, 2020

<table>
<tr><th></th><th>Item</th><th>Targeted output</th><th>Explanation</th></tr>
<tr><td>1</td><td>Industrial roundwood volumes produced in planted forests</td><td>Production share of planted forests in total IRW production in 2020 based on Nepal et al. (2019)</td><td rowspan="2">The cited study considered all planted forest area reported in FAO FRA 2015
Nepal et al. (2019) estimate areas based on estimated area productivities of forest types in different vegetation zones and geographies. Sources of the relevant data are from Payn et al., 2015, plantation production datasets in top 20 countries with planted forest cover, and Jürgensen, Kollert and Lebedys (2014) compilation of planted species growth for FAO in 2014</td></tr>
<tr><td>2</td><td>Industrial roundwood volumes produced in naturally regenerated forests</td><td>Based on line 1 of this table: IRW production in natural regenerated forests = total IRW production - IRW production in planted forests</td></tr>
</table>

TABLE 10.
Data and approaches used for employment requirements, 2050

	Item	Actual figures in 2019	Outlook 2050
1	Employment requirements in wood industries and wood pulp	Actual employment data from (Lippe, Cui and Schweinle, forthcoming) Employment factor derived from regional production volumes (FAOSTAT Forestry) and related employment	Employment factor applied on GFPM wood products outlook volumes 2050 (see Table 6), considering increasing productivity (benchmark: employment factor in industrialized world regions)
2	Employment requirement forestry and logging	Actual employment data from (Lippe, Cui and Schweinle, forthcoming) Employment factor derived from regional roundwood production volumes (FAOSTAT Forestry) and related employment	Employment factor applied on roundwood products outlook volumes 2050 (see Table 6), considering increasing productivity (benchmark: employment factor in industrialized world regions)

TABLE 11.
Data and approaches used for investment requirements, 2050

	Item	Investment factors	Outlook 2050
5	Investment requirements in wood industries and wood pulp	Factor measured in USD/m³ intake capacity, investment factor derived from consulting work for wood and pulp industries and published investment data and factors include equipment, set-up and buildings Global average: It is acknowledged that investment volumes may substantially vary according to layout, regional set-up cost and technology Production volumes as reported in FAOSTAT Forestry for 2020	GFPM based wood products production growth by GFPM 2020–2050 (see Table 6) x USD/m³ intake Production volumes 2020 as reported in FAOSTAT Forestry
6	Modernization requirements in wood industry and wood pulp	Factor measured in USD/m³ intake capacity Corresponds to complete re-investment for existing capacities in 2020 and in 30 years in 2050 with the same investment factors as for new investments (see line 5)	Existing production volumes x USD/m³ intake capacity Production volumes 2020 as reported in FAOSTAT Forestry
7	Investment requirements in new planted forests	Factor measured in USD/ha planted Factor derived from consulting work for forestry companies and factors do not include cost of land Global average: It is acknowledged that investment volumes may vary substantially according to species, regional factor cost and mechanization level	Area requirement (ha) x USD/ha x n rotations Area requirement based on Table 6 and Table 8
8	Maintenance requirements of existing forest plantations	Measured in USD/ha Refers to replanting of existing areas after harvest (end of rotation), value corresponds to investment in new plantations (see line 7) Assumes average rotation across all plantation forests and assumption results in about 2.5 rotations from 2020 to 2050	Existing and new plantation forest area 2020 x USD/ha x n rotations, considering values in line 7
9	Investment requirements in naturally regenerated forests (temperate and boreal)	Measured in USD/ha naturally regenerated production forest Monetary value obtained from (Austin *et al.*, 2020) for Europe and Northern America for a scenario considering highest efforts to combine carbon-biodiversity-timber management Naturally regenerated production forest area from (FAO, 2020)	Area of naturally regenerated production forest in temperate and boreal regions multiplied by investment factor No production area expansion assumed until 2050

2. Outlook of demand for primary processed wood products in 2050

2.1. KEY RESULTS OF PRIMARY PROCESSED WOOD PRODUCTS OUTLOOK 2050

- The outlook for primary wood products consumption based on GFPM shows an increase of 0.8 billion m^3 (+37 percent) RWE from 2.3 billion m^3 RWE in 2020 to 3.1 billion m^3 RWE in 2050.

Wood-based panels may see the strongest increase in future consumption (+102 percent for veneer/plywood and +72 percent for particle/fibre board). Further, the outlook shows an increase of 30 percent in consumption of sawnwood and a moderate 5 percent increase for wood pulp.

- The substitution of non-renewable materials in construction and production of MMCF may trigger additional consumption between 98 million and 272 million m^3 in 2050; an increase of 8 percent to 23 percent compared to the basic GFPM outlook.
- Assuming higher adaption of mass timber products in the construction sector, the additional primary processed timber demand could be between 41 million and 123 million m^3 RWE in 2050.

Dissolving wood pulp based MMCF for textile production consumption may increase from 57 million to 149 million m^3 in 2050.

TABLE 12.
Summary table of key results for primary processed wood products outlook, 2050

Primary processed wood products basic outlook 2050	Volume 2020 (million m^3)	Volume 2050 (million m^3)	Percentage change 2020–2050	Wood products selected to replace non-renewables	Volume 2050 (million m^3; lower and upper estimate)	Volume change on basic outlook (percent)
Sawnwood	929	1 205	3	Sawnwood in mass timber / CLT	41–123	3–10
Veneer/ plywood	267	539	102	Not considered		-
Particle/ fibreboard	345	593	72	-		
Wood pulp*	745	786	5	Wood pulp for MMCF	57–149	5–12
Total	2 286	3 123	37		98–272	8–23

Sources: Authors' own elaboration based on FAOSTAT Forestry 1990 and 2020, GFPM 2050 simulation, United Nations World Population Prospects 2019. Medium fertility variant, 2020–2100; United Nations World Urbanization Prospects: The 2018 Revision, and Textile Exchange. 2021. Preferred Fiber & Materials – Market Report. Textile Exchange.

*According to GFPM, paper consumption will increase by 40 percent by 2050. Raw material will be increasingly wastepaper, which is estimated to grow by 66 percent (Annex 8.6).

2.2. HISTORICAL TRENDS IN PRIMARY PROCESSED WOOD PRODUCTS CONSUMPTION

Since 1990, the global consumption of primary processed wood products has increased from 1.8 billion m^3 RWE[3] to 2.3 billion m^3 RWE. This increase has been driven by a substantial expansion of wood-based panel production (Figure 2).

Sawnwood production has recovered from its massive decline in the post-1990 period and production drop in the aftermath of the 2008 financial crisis and reached pre-crises production levels in 2020 (Figure 2). The demand for sawnwood shows increasing tendencies because of innovative applications in the construction sector (i.e. engineered wood products [EWP])[4] and the generally accelerating pace of construction in emerging economies, which are trying to address the looming housing deficit for growing populations. Still, the vast majority of sawnwood is used as standard boards for conventional use in construction.

[3] RWE: Amount of solid wood fibre contained in a wood product. It is the roundwood equivalent volume (green volume prior to any shrinkage) needed to produce the product when there are no losses or wood residues.

[4] EWPs include I-beams (also called I-joists), finger-jointed sawnwood, glulam (sawnwood glued into beams), laminated veneer lumber and mass timber panels, including cross-laminated timber (CLT) (UNECE and FAO, 2020).

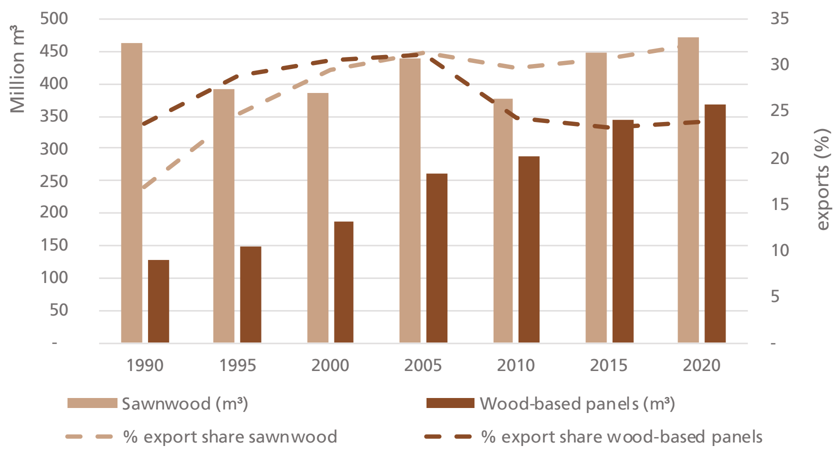
The demand for wood-based panels (plywood, particle and fibre board) from construction, packaging and furniture has grown constantly over the past decades and has been less vulnerable to economic shocks than sawnwood consumption. Due to their higher versatility, wood-based panels have substituted for sawnwood in multiple applications such as furniture, construction and packaging, and this partly explains the slow recovery process of sawnwood production since 1990.

The consumption of wood pulp has only moderately increased since 2000. The increasing availability and use of recovered fibre from waste paper[5] has increasingly substituted for virgin pulp.

Trade has become increasingly important for wood pulp and sawn wood producers. Around 37 percent of global wood pulp production and 32 percent of global sawnwood production has been exported in 2020. Europe, Northern America, Latin America and the Caribbean, and South-eastern Asia are the most important net-exporting regions (Figure 5), while Eastern Asia is the major net-importing region.

The relevance of exports has declined for wood-based panels, for which the export share has decreased from 31 percent in 2000 to 24 percent in 2020, indicating that panels are increasingly used by secondary processing industries within the regions.

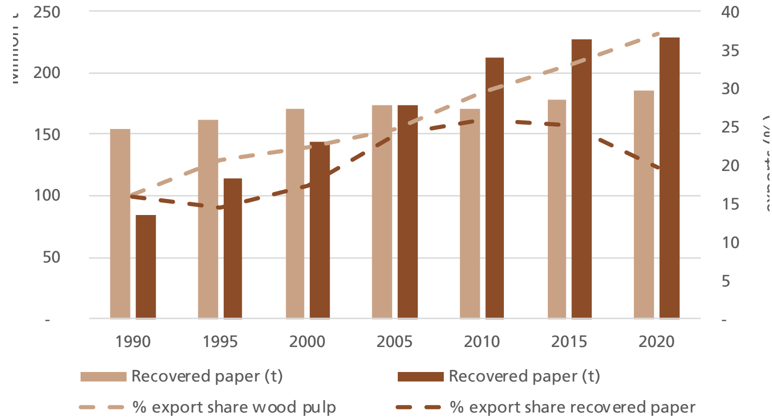
Figure 2. Global production volumes and export rates of sawnwood and wood-based panels, 1990 to 2020



Source: FAOSTAT Forestry

[5] Paper recycling rates in key economies in 2018 ranged from 45 percent in China to 85 percent in Australia (EPN, 2018).

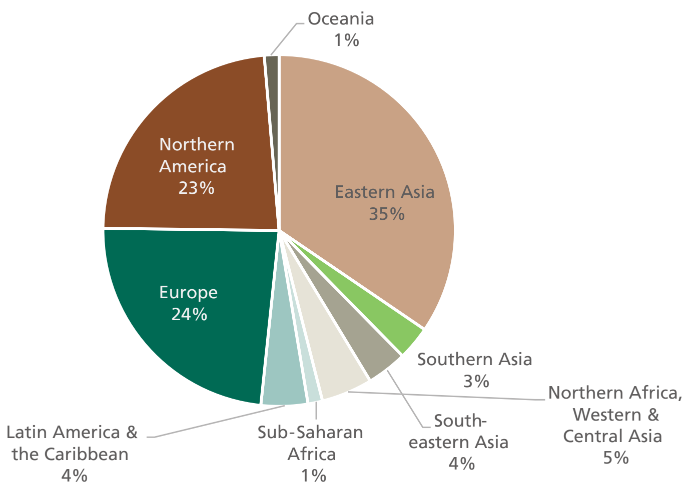
Figure 3. Global production volumes and export rates of wood pulp and recovered paper, 1990 to 2020



Source: FAOSTAT Forestry

The main primary wood product consuming regions in 2020 have been Eastern Asia, Europe[6] and Northern America. These three regions accounted for 82 percent of global consumption (Figure 4), while hosting only 36 percent of the world population. Chapter 2.3 provides more detailed information on consumption patterns by regions and primary processed wood products.

Figure 4. Regional participation in global primary processed wood products consumption, 2020

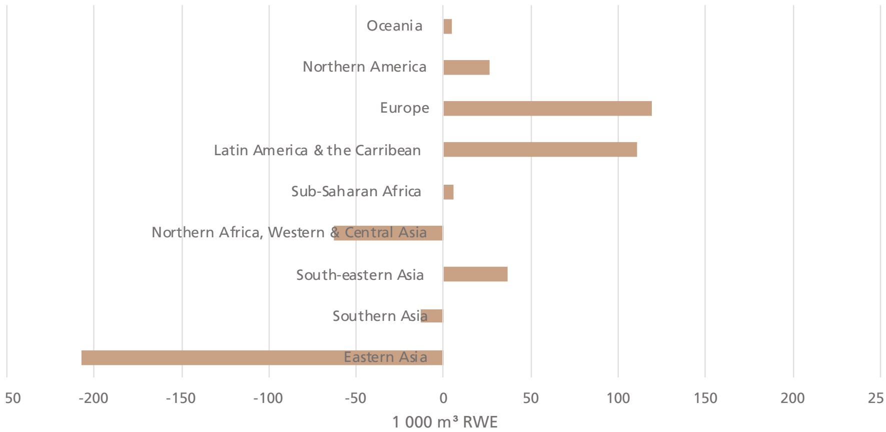


Source: FAOSTAT Forestry
Note: Total primary wood products consumption volume of 2.3 billion m³ RWE.

[6] Within Europe, the Russian Federation represents about 22 percent of primary processed wood products production and 12 percent of European consumption (FAOSTAT Forestry).

Eastern Asia sources a substantial share of its consumption volumes from imports, i.e. from Europe,[7] Latin America and the Caribbean, Northern America, and South-eastern Asia. The reliance on imported wood products is likely to continue due to the continued logging bans and poor productivity of China´s massive plantation estate (Hoffmann, Jaeger and Shiurong, 2018). Other regions with significant trade deficits of primary processed wood products are Southern Asia and the regional aggregate of Northern Africa and Western and Central Asia (Figure 5).

Figure 5. Regional trade balances of primary processed wood products, 2020



Source: FAOSTAT Forestry

Note: Trade balance computed as exports less imports for sawnwood, wood-based panels and wood pulp converted to m³ RWE.

2.3. OUTLOOK OF GLOBAL PRIMARY PROCESSED WOOD PRODUCTS CONSUMPTION IN 2050

The demand projections of primary-processed wood products in this chapter are based on a GFPM simulation updated in October 2020.[8] In the GFPM, the projections depend on the historical patterns of wood products production and trade derived from FAO data and their interaction with exogenous factors regarding macro changes such as GDP, population, trade policies or forest area change (Nepal *et al.*, 2021). It simulates the market equilibrium solution in each projected year, drawing on assumptions about the future development of these exogenous macro factors.

[7] Within Europe, the Russian Federation represented about 24 percent of exports in 2020 (FAOSTAT Forestry).

[8] GFPM version 2017, October 2020 (WORLD 500 simulation). Published by the Department of Forest and Wildlife Ecology of the University of Wisconsin-Madison. See Annex for explanation of main assumption and explanations of the model. The simulation presented draws on middle-of-the-road GDP and population forecasts as detailed by the SSP2 scenario of the IIASA, which is also used by the IPCC.

The settings of the simulation reflect moderate development paths and consider foreseeable megatrends. It does not include policy or technology induced disruptive changes, such as climate change mitigation strategies, nor climate change impacts on forest production.

The demand for wood products (sawnwood, panels, pulp) in the used GFPM simulation changes from one year to the next due to changes in GDP (though the model enables hosting up to six exogenous demand shift factors). Thus, the GFPM simulation in this chapter presents a baseline forecast with reduced complexity. The implications of additional use of wood to substitute non-renewable materials in construction and textiles are discussed in chapter 2.4 (for primary processed wood products).

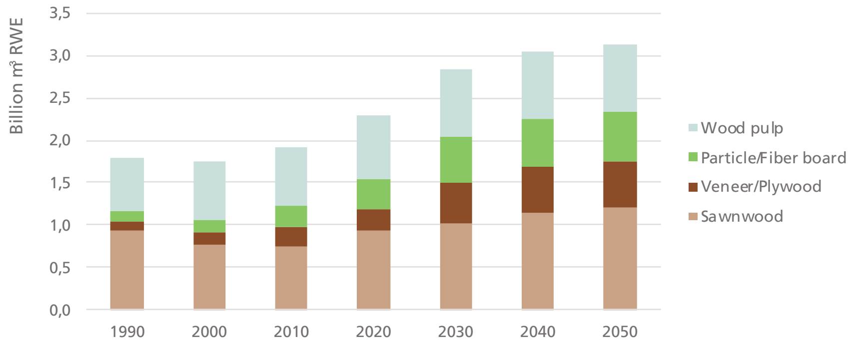
The GFPM simulations for 2050 indicate a strong increase in the consumption of primary processed wood products over the period 2020 to 2040. The consumption growth rates will slow down after 2040. This is mainly because of the slowdown of growth in Asia from 2040 onwards, resulting in reduced wood products demand. The population and income growth rates in sub-Saharan Africa will not compensate for these decreasing consumption growth rates, as GDP levels according to SSP2 projections are lagging behind and historical correlation of wood products demand with GDP in sub-Saharan Africa has been weak.

According to the simulation for 2050, the total volume of primary processed wood products consumption may increase by 0.8 billion m^3 RWE from 2.3 billion m^3 RWE in 2020 to 3.1 billion m^3 RWE in 2050 (Figure 6).[9] Wood-based panels will see the strongest increase in future consumption (+102 percent for veneer/plywood and +72 percent for particle/fibre board). Further, the simulation indicates an increase of 30 percent in consumption of sawnwood and 5 percent in wood pulp.

Eastern Asia will expand its leading role, consuming 41 percent of the world´s primary processed wood products. Europe and Northern America will lose shares in global consumption compared to 2020. The share of wood products consumption in other world regions remain rather stable (Figure 7).

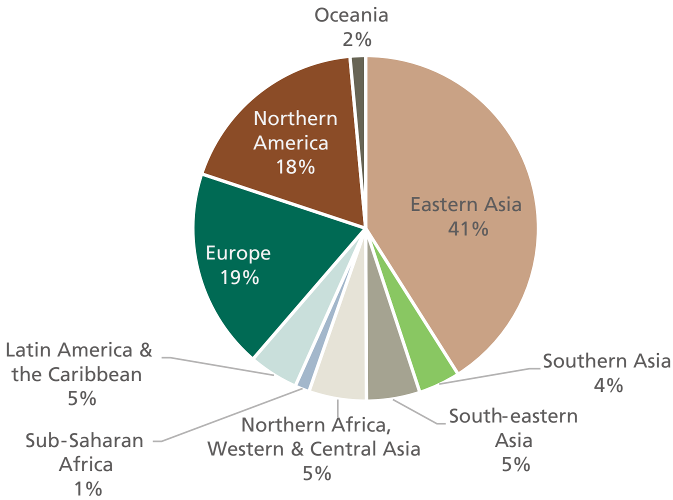
9 The simulated consumption volumes in 2050 refers to “traditional” primary processed wood products (sawnwood, wood-based panels and wood pulp) feeding into further value adding in secondary processing industries and construction. These volumes, expressed in RWE, include double-counting effects, since residues from primary processing (i.e. from sawmilling and veneer production) are used as intake in the production of particle board, fibre board and wood pulp (see chapter 3.5 on sources of industrial roundwood).

Figure 6. Global historical and projected consumption of wood products, 1990 to 2050



Sources: FAOSTAT Forestry 1990 to 2020, and GFPM simulation 2030 to 2050 (Annex 8.5).

Figure 7. Regional participation in global primary processed wood products consumption, 2050



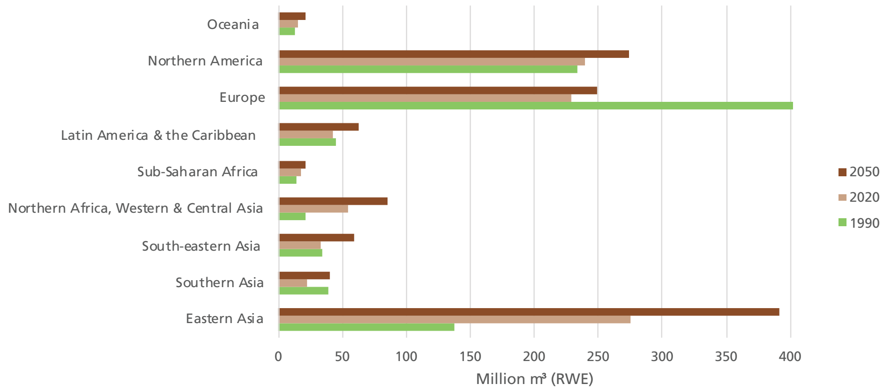
Source: GFPM data (Annex 8.5)

Note: Total primary wood products consumption volume of 3.1 billion m³ RWE.

Uncertainties exist regarding the detailed disaggregation according to wood product groups due to multiple mutual substitution possibilities of sawnwood, plywood and other wood based panels. Hence, the presentation of simulated wood products consumption by region should be read with reservations.

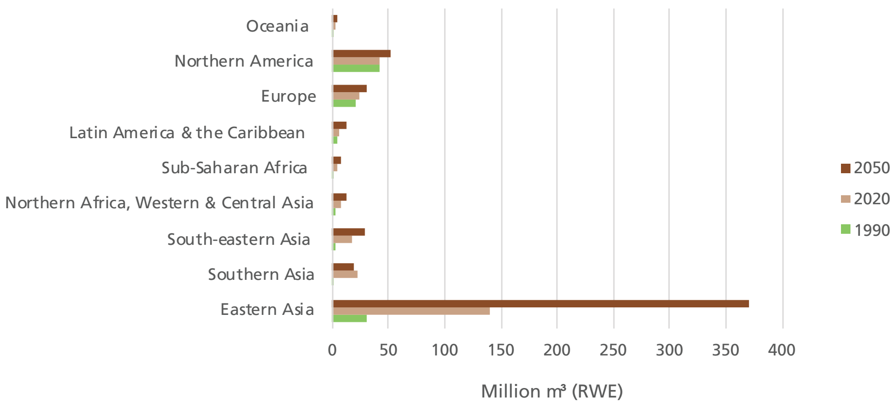
The consumption of sawnwood (Figure 8) and wood-based panels (Figure 9 and Figure 10) are simulated to increase across all world regions. Growth will be drivep in Eastern Asia, Europe and Northern America, and to a certain extent in other Asian sub-regions. The situation for wood pulp consumption looks different with substantially decreasing consumption volumes in Europe and Northern America (Figure 11). This reduction is compensated for by consumption increases in other world regions, especially in Asian sub-regions. Across all world regions, GFPM simulates the growing consumption of recycled paper, further explaining the moderate outlook for wood pulp consumption.[10]

Figure 8. Historical and projected sawnwood consumption by world regions, 1990, 2020 and 2050



Sources: FAOSTAT Forestry 1990 and 2020, and GFPM simulation 2050 (Annex 8.5).

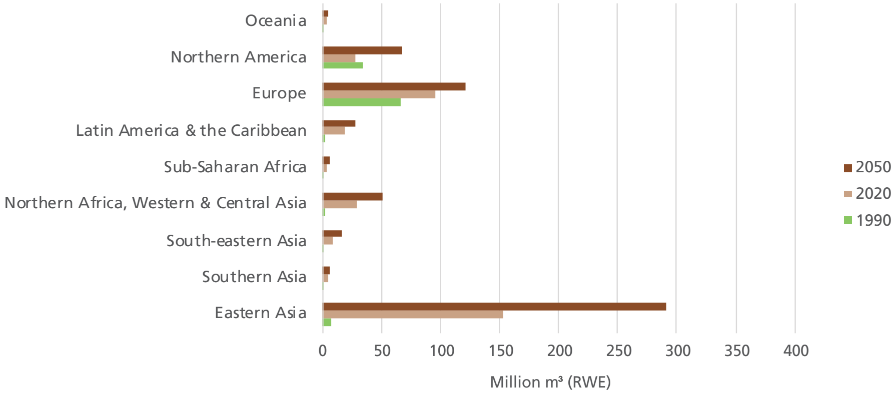
Figure 9. Historical and projected veneer and plywood consumption by world regions, 1990, 2020 and 2050



Sources: FAOSTAT Forestry 1990 and 2020, and GFPM simulation 2050 (Annex 8.5).

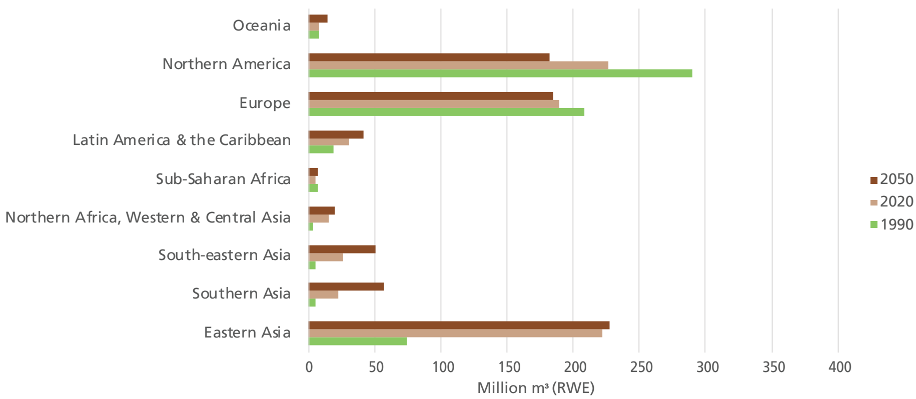
[10] According to FAOSTAT Forestry, recycled paper production increased by 71 percent between 1990 and 2020. GFPM simulates an increase of 66 percent from 2020 to 2050 (Annex 8.6).

Figure 10. Historical and projected particle and fibre board consumption by world regions, 1990, 2020 and 2050



Sources: FAOSTAT Forestry 1990 and 2020, and GFPM simulation 2050 (Annex 8.5).

Figure 11. Historical and projected wood pulp consumption by world regions, 1990, 2020 and 2050



Sources: FAOSTAT Forestry 1990 and 2020, and GFPM simulation 2050 (Annex 8.5).

2.4. CONSUMPTION OF PRIMARY PROCESSED WOOD PRODUCTS USED IN PLACE OF NON-RENEWABLE MATERIALS

2.4.1 Timber in construction

The construction sector is the main consumer of sawnwood and wood-based panels. WBCSD (2020) estimates that around 1.2 billion m^3 RWE of wood products were directly used by the global construction sector in 2018,[11] representing 75 percent of the global production of sawnwood and wood-based panels.

Wood in construction is traditionally accepted and widespread across Europe and Northern America. In recent years, national and international building codes have been revised and now provide the guidelines for using timber in modern high-rise construction (Nepal *et al.*, 2021). Timber construction is promoted by national policies in the context of greenhouse gas (GHG) emissions reduction, aiming at the reduction of environmental impacts of conventional construction materials (embodied energy, water, waste, etc.) and at promoting local forest-based value chains (UNECE and FAO, 2016). In China, more than 40 percent of primary wood products consumption (excluding wood pulp) is used in the construction sector (EFI, 2020a), and since 2015 China has been promoting timber as a viable alternative to conventional steel and concrete construction in high-rise buildings.[12]

Future economic pathways indicate that residential construction will become more urban, more formal and of a higher standard. The total demand for new residential housing in urban areas (mostly multistorey buildings) is estimated at around 460 million units between 2020 and 2050 (Figure 12). Besides the construction of new residential housing in urban areas for a growing population, existing sub-standard housing will need to be modernized across all world regions. Further, a growing middle-class will increase the demand for high-standard housing in suburban areas (Gresham House, 2020).

However, in emerging economies where the largest share of new and improved housing is required, conventional construction materials (bricks, concrete, steel) dominate the building activities (IFC, 2021). Wood is used mainly in traditional construction in rural areas as roof trusses or as auxiliary construction materials for scaffolding or for shuttering concrete. Despite the pressing need to deliver affordable housing for growing populations, the use of timber is not yet widely promoted because barriers are still high. Among those barriers are a lack of industries capable of delivering standardized primary wood products, a lack of experienced project developers, a lack of construction companies able to implement timber construction projects, as well as more formal barriers such as building codes, among others (World Bank, 2017).

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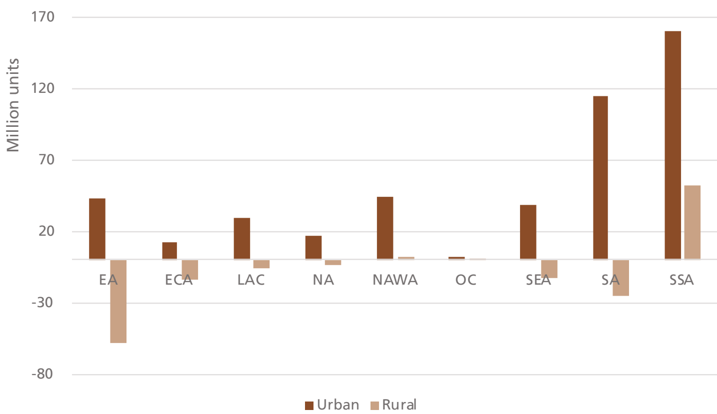
[11] WBCSD (2020) estimates a volume of 362 million tonnes of forest-derived biomass use in construction, which converts to a weight of 0.5 tonnes/m^3 to 0.7 billion m^3 wood products. A disaggregation of this volume is not available. Assuming a mixed RWE conversion factor 1.7 m^3 (mix of sawnwood and panels) results in 1.2 billion m^3 RWE. The production volume of sawnwood and wood-based panels in 2018 was around 1.6 billion m^3 (converted from FAOSTAT Forestry data).

[12] Set out in a directive by the Ministry of Housing and Urban-Rural Development in 2015.

The construction sector is one of the most energy-intensive and emission-heavy sectors of all. Globally, 36 percent of final energy use and 39 percent of energy and process-related CO_2 emissions resulted from the sector in 2018 (GlobalABC, IEA and UNEP, 2019). On the road toward the United Nations Sustainable Development Goals (SDG) and the European Green Deal, it will be essential to decarbonizing the building and construction sector. Furthermore, the construction sector relies heavily upon sand and gravel, which cannot likely be extracted sustainably to supply future demand (UNEP, 2014; UNEP, 2019a).

Replacing main construction elements like sub-floors made of concrete and wall elements (brick) with mass timber products and engineered wood products (EWP) can at least halve GHG emissions (from extraction, manufacturing, transport, construction, maintenance and disposal) (Ximenes *et al.*, 2012). At the same time, it provides an opportunity to produce higher value-added products from timber of poorer quality (ITTO, 2021).

Figure 12. Global rural and urban housing demand, 2015–2050



Sources: Authors' calculations based on United Nations World Population Prospects 2019. Medium fertility variant, 2020–2100; United Nations. World Urbanization Prospects: The 2018 Revision. Average five persons per unit (Annex 8.10).

Figure 13 shows three demand scenarios for market shares of 10 percent, 20 percent and 30 percent mass timber construction in global urban buildings in 2050.[13] The required mass timber/EWP production volumes range between 41 million m^3 and around 123 million m^3 RWE,[14] which presents a substantial increment compared to 2020 production of 4 million m^3 RWE.

The impact of enhanced use of mass timber in the construction sector has also been assessed by UNECE (2021). The study estimates that a substantial

[13] Assuming that 100 percent of urban residential buildings are multistorey. Only new housing units are considered, without refurbishments or re-building activities.

[14] Nepal *et al.* (2021) estimates the future additional production of CLT and glulam beams on top of a business as usual trajectory conservatively projected at 17 million m^3 RWE, optimistically at 47 million m^3 RWE, and very optimistically at 105 million m^3 RWE in the year 2060 (volumes converted at 50 percent recovery rate).

increase of wood construction in Europe and China may trigger an additional consumption of wood products of 90 million m³ RWE and 270 million m³ RWE, respectively.

Box 2

Where do engineered wood products sit within FAO statistics and Global Forest Products Model simulations?

Use of timber in modern urban multistorey construction draws on a blend of wood products, commonly referred to as engineered wood products (EWPs) or mass timber. These products include cross-laminated timber (CLT), nail-laminated timber (NLT), glue-laminated timber (glulam), dowel-laminated timber (DLT), mass plywood panel (MPP), post and beam and heavy timber decking. These are typically produced from sawnwood, veneers and plywood or sometimes a combination of all three. The products with the highest versatility and use in multistorey construction are CLT and glulam beams (Nepal *et al.*, 2021).

Actual production volumes are estimated to be negligible compared to the standard products. In 2020, CLT reached a production volume of about 4 million m³ RWE (Muszynski *et al.*, 2020). The market demand was unforeseen, even for major market actors.*, ** For the United States of America, the Softwood Lumber Board indicates a potential mass timber demand of about 9 million m³ by 2035 (SLB, 2021).

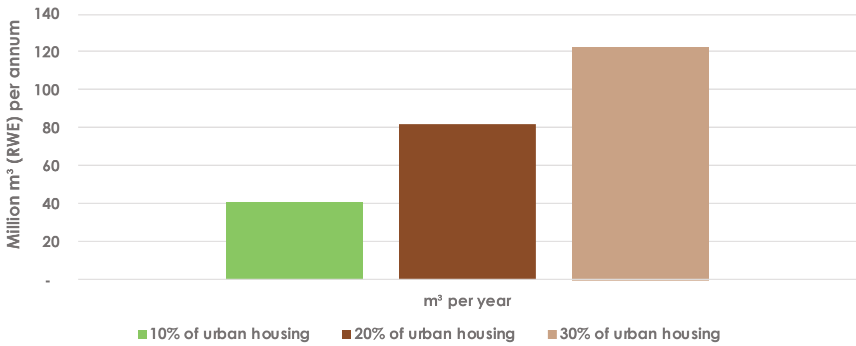
In general, production volumes of EWPs are not recorded as separate products in national and international statistics. Consumption growth due to the increased demand for substitutions for non-renewable materials would be reflected in the FAO product groups sawnwood, veneer and plywood.

The GFPM configuration used for the baseline projections in chapter 2.3 does not consider the end use specific differentiation of primary wood products but is instead based on econometric modelling of market equilibriums. It draws on historical (conventional) consumption patterns of wood products in the function of GDP and prices. This includes already minor shares of EWPs. Further, EWPs are partly used to substitute for other wood products in construction (e.g. panels for concrete shuttering or panels in light frame housing systems). Hence, the GFPM simulations for 2050 indirectly cover an unknown share of EWP consumption growth, though it is certainly far below the magnitudes suggested by actual and projected market growth.

* See www.imarcgroup.com/cross-laminated-timber-manufacturing-plant and www.globenewswire.com/news-release/2021/12/16/2353618/0/en/Global-Cross-Laminated-Timber-CLT-Market-is-Projected-to-Grow-at-a-CAGR-of-15-0-Over-the-Forecast-Period-from-2021-to-2030-Quince-Market-Insights.html and https://carbonremoval.economist.com/mass-timber for examples.

** See Stora Enso (2017). Best-case scenario in the report estimated 1.2 million m³.

Figure 13. Scenarios of global mass timber demand for urban housing, 2050



Sources: Authors' own calculations based on United Nations World Population Prospects 2019. Medium fertility variant, 2020–2100; United Nations World Urbanization Prospects: The 2018 Revision. Average five persons per unit: 21 m³ RWE per unit (Annex 8.10).

Box 3
The positive greenhouse gas impact of mass timber

The positive climate impact of mass timber substituting for non-renewable construction materials varies in function of the energy mix in the region of construction, the type of building and the material substituted.

Verkerk *et al.* (2022) compared recent studies published on this topic resulting in CO_2 savings of 2tCO_2eq per m³ (all buildings, European energy mix) to 4tCO_2 (mid-rise buildings, global energy mix).

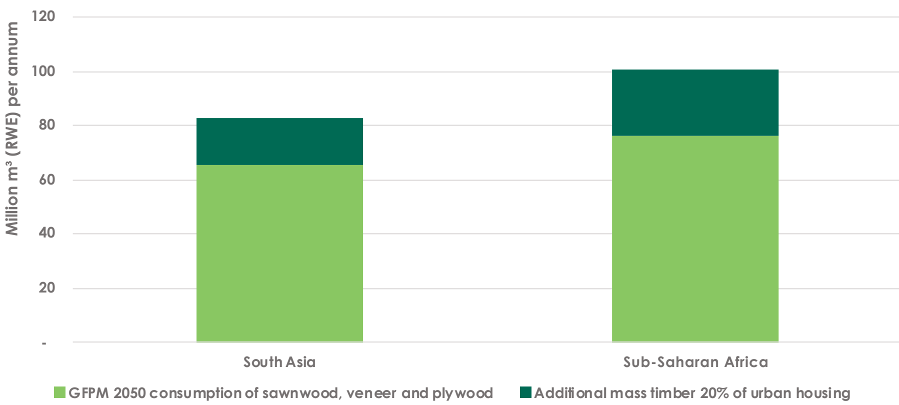
The figures of 40 million m³ to 120 million m³ mass timber substituting for conventional construction presented here suggest that the related annual CO_2 emission savings would be in the range of 80 million tCO_2eq to 480 million tCO_2eq. These volumes are comparable to the GHG emission of Angola and the United Kingdom of Great Britain and Northern Ireland, respectively (for the year 2018).*

The GHG mitigation impact will only materialize if the timber comes from sustainably managed forests.*

*According to the World Bank Indicators Database: Total greenhouse gas emissions (kt of CO2 equivalent).

The most substantial increase in urban housing requirements up to 2050 will occur in Southern Asia and sub-Saharan Africa (Figure 14). Mass timber construction in these regions is basically non-existent. Assuming a 20 percent share of mass timber construction in new urban housing in 2050 would increase the simulated GFPM consumption volumes of sawnwood, plywood and veneer by about 26 percent in Southern Asia and 32 percent in sub-Saharan Africa.

Figure 14. Mass timber requirements to substitute for non-renewable construction materials in Southern Asia and sub-Saharan Africa, 2050



Sources: Mass timber: Authors' own calculations based on United Nations World Population Prospects 2019. Medium fertility variant, 2020–2100; United Nations World Urbanization Prospects: The 2018 Revision. Average five persons per unit; 21 m^3 RWE per unit. GFPM 2050 simulation (Annex 8.10).

2.4.2 Manmade cellulose fibre

The consumption of wood pulp for paper, paper board and tissue has slowed down in recent decades, mainly due to decreasing consumption of newsprint, writing and graphics papers. The most important mid-term consumption drivers will be packaging materials and hygienic tissue in Asian, European and Northern American markets (McKinsey, 2019). The most significant market growth is expected to occur in the Asian sub-regions. There, production capacities of wood pulp have increased massively since 2000.[15] These changing market patterns leave the producers and exporters in other world regions with major challenges. In view of stagnating markets for traditional uses of wood pulp, producers increasingly turn to alternative products. These include cellulose fibre/pulp and chemical/by-products as used in textile fibre production, for bio-composites and for substituting plastics (EFI, 2020a). Still, the total volumes are low compared to overall wood pulp consumption.

[15] Asian wood pulp production has increased by 62 percent from 2000 to 2020. In China, production increased by 300 percent (FAOSTAT Forestry).

MMCF for textiles appear to have become one of the main future market opportunities for wood pulp. The textile and clothing industry is increasingly under pressure to improve the sustainability of value chains and product cycles. While social awareness (e.g. regarding workers' rights, health and safety issues) have been raised continually for many years, the focus is increasingly on the environmental impacts of the clothing and textile industry.

The growing global fibre market is dominated by polyester (57 percent) and cotton (26 percent) fibres (Textile Exchange, 2021). MMCF, which are primarily made of wood, only accounted for 6 percent (0.5 million tonnes) of global fibre production in 2020 (Textile Exchange, 2021).

The need to tackle climate change might require an increase in wood-based cellulose fibres in producing textiles. Currently, textile production[16] is estimated to cause 10 percent of GHG emissions that occur during raw material production, fibre processing and manufacturing apparel (European Parliament, 2020; Ellen MacArthur Foundation, 2017). About 0.5 million tonnes of synthetic microfibres from polyester clothes end up in rivers and ultimately in oceans, representing about 35 percent of all primary microplastics released into the environment (European Parliament, 2020). Further impacts relate to the loss of biodiversity, abiotic depletion and toxicity for humans and ecosystems (Ellen MacArthur Foundation, 2017). Leskinen *et al.* (2018) estimates around a 2.7 tCO2eq saving per m^3 roundwood, if wood-based cellulose fibre replaces other textile fibres.

A growing population creates a growing demand for clothes (IEA, 2018), which is strongly catalysed by the so-called fast fashion trend.[17] The global fibre consumption per person is estimated to increase from 14 kg per person in 2020 up to 17.1 kg by 2030 (Textile Exchange, 2021). The consumption of chemical fibres is expected to be the main source for increased demand (OECD and FAO, 2019). By 2050 the demand for crude oil for textiles might more than triple (Ellen MacArthur Foundation, 2017)[18] and so would the intertwined negative externalities.

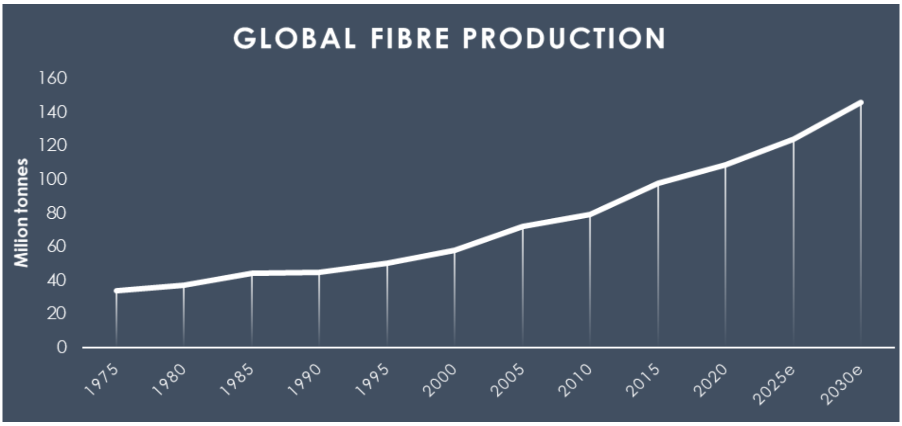
MMCF are increasingly important and have the potential to fulfill some of the future demand for textiles with reduced environmental impacts. Dissolving pulp is a raw material for viscose, lyocell, TENCEL™ and modal – different fabrics that are already used in similar applications. Besides wood as a raw material for dissolving pulp, other ligneous fibres are used (i.e. from bamboo).

[16] Including footwear.

[17] Fast fashion describes the business of producing inexpensive clothing rapidly in response to the latest trends and distributing them through mass-market retailers.

[18] Base year 2015.

Figure 15. Global fibre production – trends and outlook



Source: Textile Exchange. 2021. Preferred Fiber & Materials – Market Report. Textile Exchange.
Note: e=estimated

Figure 17 illustrates two pathways to the future consumption of MMCF in textile industries:

1. The current (2020) share of 6 percent MMCF in total textile fibre production continues (Textile Exchange, 2021). Global values for textile fibre production are based on per capita consumption and population growth figures (Textile Exchange, 2021).
2. Adopted SSP2 scenario based on results from Kallio (2021), with a growing rate of 3.6 percent per annum of MMCF until 2050.[19]

If the participation of MMCF in textile fibre production remained stable at 6 percent until 2050, the consumption of dissolving pulp would increase from around 7 million tonnes in 2020 to around 10 million tonnes in 2050 (Figure 17, converted to RWE with a conversion factor of 5.7 m^3 to 1 tonne). The corresponding roundwood intake would be around 57 million m^3.

The SSP2 scenario in Kallio (2021) results in a substantial increase caused by the study's assumption of MMCF consumption with GDP growth, exceeding the GDP correlation of other textile fibres, which gradually leads to increasing market shares in the total textile fibre market. The participation of MMCF in total textile fibre markets would reach 16 percent in 2050. The corresponding pulp volumes would be 26 million tonnes dissolving wood pulp or 150 million m^3 RWE.

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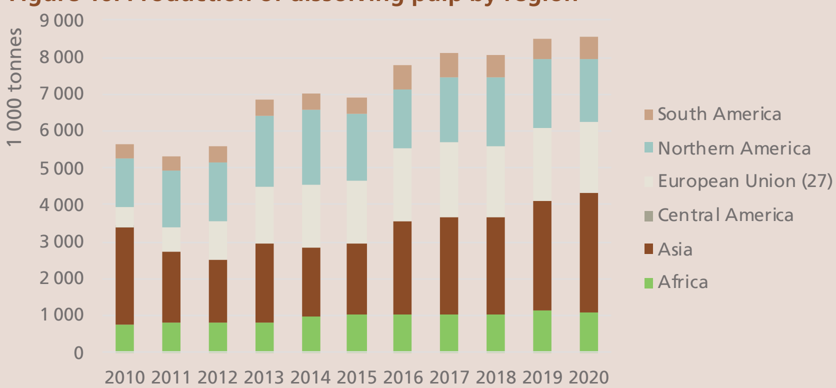
[19] Kallio (2021) simulates future consumption of wood-based MMCF by 2035 under five SSP framed scenarios, with GDP being the major driver of textile fibre consumption. The analysis presented extrapolates this growth up to 2050 for the SSP2 scenario with a GDP elasticity of 1.0.

Box 4
Where does wood-pulp-based manmade cellulose fibre sit within FAO statistics and Global Forest Products Model baseline projections?

MCF is based on dissolving pulp. It is produced in integrated pulp and paper sites with very low, possibly even zero carbon emissions (Huatari, 2019) and superior water footprints. Dissolving pulp production more than tripled between 2000 and 2020, between 2010 and 2020 the industry grew 50 percent (see Figure 16). Still, the production of 8.7 million tonnes in 2020 is small compared to the overall capacities for wood pulp production (187 million tonnes in 2020) (FAOSTAT Forestry). Major growth rates and capacities are shown for Asia and China, respectively. Europe and Northern America also have considerable production capacities.

GFPM does not explicitly simulate dissolving pulp production and does not factor in MMCF demand developments. The GFPM wood pulp consumption projections are based on GDP and wood price induced market equilibriums for paper consumption, which in turn trigger wood pulp production. Since the GFPM wood pulp projection derives from the projected paper demand, factoring in the use of waste paper, the implicit dissolving pulp volumes underestimate the demand growth expressed by the textile industry.

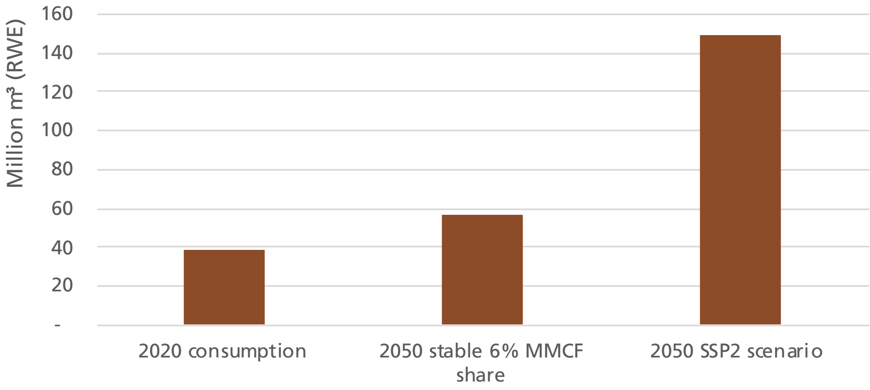
Figure 16. Production of dissolving pulp by region



Source: FAOSTAT Forestry

Note: Total global production in 2020 was 8.7 million tonnes. 157 000 tonnes were produced outside the regions shown in the graph.

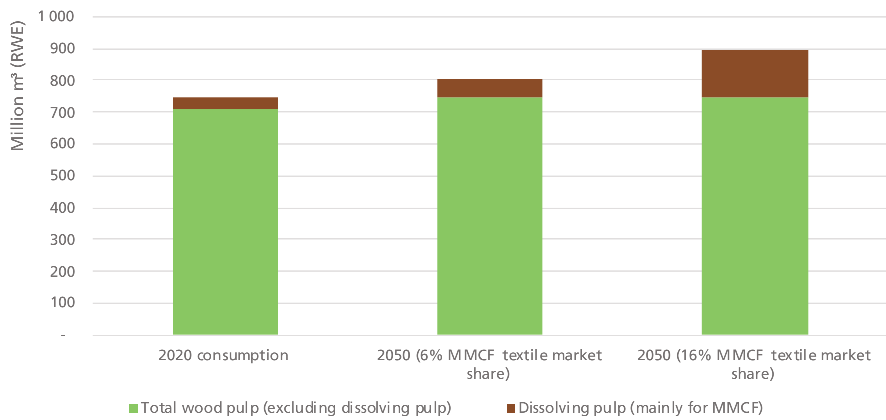
Figure 17. Scenarios of global wood-based manmade fibre demand for textiles, 2050



Sources: 6 percent share based on Textile Exchange. 2021. *Preferred Fibre & Materials – Market Report*. Textile Exchange; RWE conversion factor dissolving pulp 5.68 based on FAO & ITTO. 2020. *Forest products conversion factors.* Rome, FAO; SSP2 based on Kallio. 2021. Wood-based textile fibre market as part of the global forest-based bioeconomy. *Forest Policy and Economics*, 123.

Note: The share of dissolving pulp for MMCF production in total wood pulp production in 2050 would increase from 5 percent in 2020 to 7 percent for stable market shares of MMCF in textile fibres and to 19 percent for growing market shares according to Kallio (2021) (Figure 18; Annex 8.11).

Figure 18. Scenarios of global wood pulp and dissolving pulp consumption, 2050



Sources: 2020 consumption from FAOSTAT Forestry; 2050 wood pulp consumption based on GFPM for wood pulp (Annex 8.5); 6 percent MMCF share based on Textile Exchange. 2021. Preferred Fibre & Materials – Market Report. Textile Exchange; 16 percent MMCF share based on Kallio. 2021. Wood-based textile fibre market as part of the global forest-based bioeconomy. Forest Policy and Economics, 123. RWE conversion factor dissolving pulp 5.68 based on FAO & ITTO. 2020. Forest products conversion factors. Rome, FAO.

3. Outlook for industrial roundwood demand and supply by 2050

3.1. KEY RESULTS OF INDUSTRIAL ROUNDWOOD OUTLOOK FOR 2050

Industrial roundwood demand by 2050

- The production of IRW reached almost 2 billion m³ in 2020, reflecting a 16 percent increase since 1990. Depending on the use intensity of wood industry residues, the further demand increase up to 2050 will be in the range of 27 percent to 44 percent. In absolute terms, IRW demand in 2050 may reach between 2.5 billion and 2.9 billion m³.
- Substituting wood for non-renewable materials in global urban construction at rates between 10 percent and 30 percent could increase IRW demand outlook in the range of 41 million to 123 million m³ RWE in 2050.
- Increasing demand for MMCF in textile production may increase IRW demand from 39 million m³ RWE in 2020 to 57 million to 149 million m³ RWE in 2050.

TABLE 13.
Summary table for industrial roundwood demand derived from primary wood products at varying wood residue use rates

IRW demand 2020 (million m³)	Primary wood products demand 2050 (million m³)	Wood industry residues from sawlogs and veneer logs processing (million m³)	Wood residues use rate (percent)	Residues 2050 (million m³)	IRW demand 2050 (million m³)	Percentage change in IRW demand 2020–2050
1 983	3 123	873	30	262	2 862	44
			50	436	2 688	36
			70	611	2 513	27

Sources: Authors' own elaboration based on FAOSTAT Forestry for IRW 2020, GFPM 2050 simulation, and additional volumes due to the substitution of renewables for non-renewables as detailed in chapter 2.4

TABLE 14.
Summary table for industrial roundwood demand as a substitution for non-renewable materials in urban construction and textile production

Products (volumes in RWE)	Primary wood products demand 2020 (million m³)	Scenario (percent)	IRW demand 2050 (million m³)
Mass timber for urban housing	4	10*	41
		20*	82
		30*	123
MMCF	39	6**	57
		16**	149

Sources: Authors' own elaboration based on FAOSTAT Forestry for IRW 2020, GFPM 2050 simulation, and additional volumes due to the substitution of renewables for non-renewables as detailed in chapter 2.4.
Notes: *of global urban housing built with timber. ** in total global textile production.

Trends in industrial roundwood supply to meet demand 2050

- Future IRW supply will depend on the possibilities for increasing the supply from naturally regenerated and planted forests as well as by expanding areas for production.

In 2020, naturally regenerated temperate and boreal forests provided about 44 percent of global IRW production. Studies project an annually growing stock suggesting the potential for increasing IRW supply. However, significant uncertainties remain regarding the influence of forest management and conservation policies on harvesting volumes.

Forest area losses in naturally regenerated tropical and sub-tropical regions have been substantial and are expected to continue. However, the effect on future IRW supply will be low. Only around 9 percent of global IRW demand comes from these regions. This share has been continuously declining since 1990.

In 2020, planted forests contributed around 46 percent to the global IRW demand. The actual productivity of planted forests (at the global average) is low. High performing plantations produce between six and eight times more IRW than the global average. Enhancing productivity offers possibilities for increasing IRW volumes without area expansion.

Planted forest area expansion offers IRW production possibilities in tropical and sub-tropical regions where plantation areas have grown substantially in recent decades. Small- and large-scale private sector interest and 200 million ha of FLR pledges suggest that this trend will continue and that the supply of IRW from these forests will increase.

This study concludes that 33 million ha of highly productive plantation forest could meet the basic IRW demand increase up to 2050. This estimate is roughly in line with other studies that estimate plantation area growth between 20 million and 40 million ha until 2050.

If IRW availability from naturally regenerated forest is reduced, it will be necessary to enhance substantially the existing planted forests and to expand into new areas to meet future demand.

Additional IRW could be sourced from agroforestry systems and tree crop plantations. However, there is no comprehensive data available on the current contribution of these systems to the global IRW supply. Nonetheless, existing areas are substantial (45 million ha of agroforestry and 7 million ha of rubber plantation) and can be further increased in the course of agricultural expansion for food production.

3.2. HISTORICAL TRENDS IN INDUSTRIAL ROUNDWOOD PRODUCTION

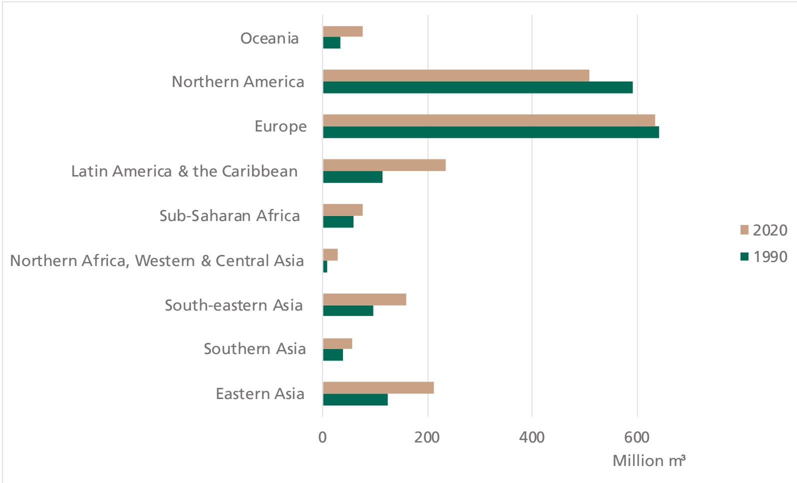
The global production of IRW has increased by 16 percent since 1990, and reached almost 2 billion m^3 in 2020. Since 1990, shares of the main producer regions in Northern America and Europe have declined, while contributions from the southern hemisphere have increased (Figure 19). Still, Europe and Northern America accounted for about 60 percent of global IRW production in 2020.

Looking at the forest category contribution to global IRW production, naturally regenerated forests contributed an estimated 54 percent and planted forests contributed 46 percent to global IRW production in 2020 (based on Nepal, Prestemon and Cubbage, 2019); see also chapter 3.5.2). The most important production regions from naturally regenerated forests are Europe[20] and Northern America (together with around 40 percent of global IRW production, see Figure 25). The most important regions producing IRW from planted forests are Latin America and the Caribbean (12 percent of global IRW production), Northern America (11 percent) and Europe (10 percent) (Figure 27).[21]

[20] Within Europe, the Russian Federation represented around 32 percent of IRW production in 2020 (FAOSTAT Forestry).

[21] FRA 2020 shows around 294 million ha of planted forests. Industrial roundwood production, however, is seen mainly in intensively managed plantation forests, of which there are around 131 million ha (FAO, 2020).

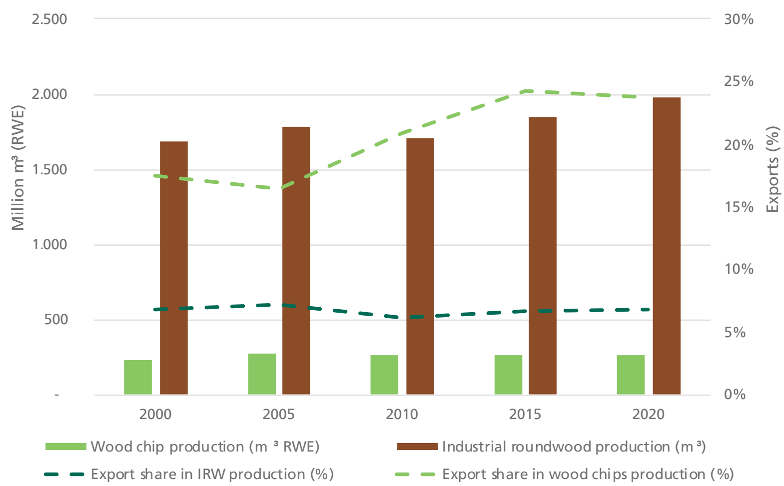
Figure 19. Global industrial roundwood production, 1990 and 2020 by region



Source: FAOSTAT Forestry (Annex 8.7)

Around 15 percent of global IRW production is traded in the form of IRW and wood chips (Figure 20). This share has remained rather stable since 1990, though absolute trade volumes have increased in relation to total production growth. Eastern Asia is the major importer of IRW (i.e. China accounted for 44 percent of global IRW imports in 2020). Oceania, Europe and Northern America are the main exporters. However, most IRW will be processed in the regions of production.

Figure 20. Global production and export shares of industrial roundwood and wood chips, 2000 to 2020

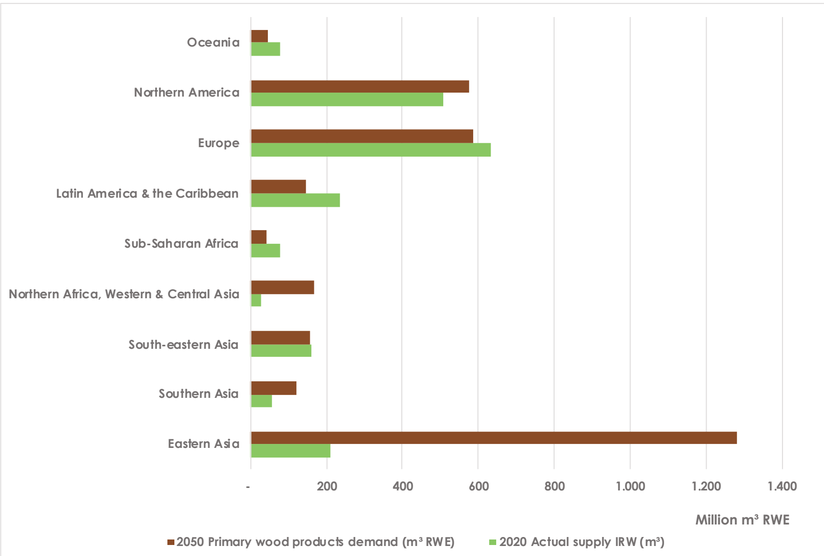


Source: FAOSTAT Forestry

3.3. OUTLOOK FOR INDUSTRIAL ROUNDWOOD DEMAND, 2050

The future supply of IRW will depend upon the availability of resources, wood industry investments and market requirements. The latter will increasingly request standardized raw material to produce wood-based panels, mass timber, engineered wood products and pulp (for traditional and innovative uses). Timber that meets these market requirements will mainly be available from planted forests and naturally regenerated forests of the temperate and boreal zones.

Figure 21. Actual production and projected demand by 2050 of industrial roundwood by world regions



Sources: FAOSTAT Forestry for IRW 2020 (Annex 8.7) and GFPM (Annex 8.5).

Based on primary wood products consumption in 2050 (chapter 2.3), the supply of IRW will have to grow by 1.1 billion million m³ compared to 2020 production volumes. Total demand is estimated at 3.1 billion m³ in 2050.

A significant share of this future wood demand will be met by enhanced use of wood industry residues and waste wood for wood-fibre-based products (panels and pulp).

Wood fibre from wood industry residues and waste wood products have become important raw material sources to meet the supply of IRW. In Europe[22]

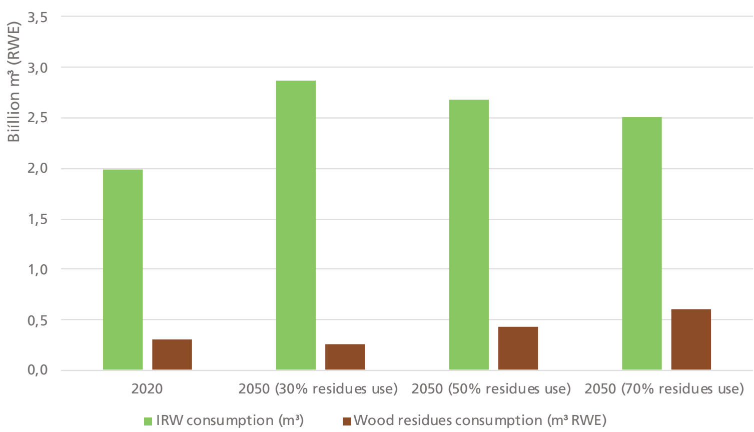
[22] In Germany, around 80 percent of sawmill residues are used for panels and pulp, etc, and the remainder is used to generate energy (pellets, integrated energy for drying, etc.) (Brosowski *et al.*, 2016).

and Northern America,[23] wood residues are contributing substantially to wood industry supply. Also, in wood industry clusters in Eastern Asia and Latin America and the Caribbean, through systematic use, industry residues have become a standard supply chain for wood-based panel and wood pulp producers.

The growing number of large-scale wood industries and the ongoing modernization of forest industries in emerging economies will lead to an increased use of wood industry residues. The actual global contribution of wood residues to the wood industry supply is not known. The indicative wood balance of IRW consumption vs the production of primary processed wood products in 2020 suggests that around 300 million m^3 RWE of wood residues and almost 2 billion m^3 IRW were used to produce about 2.3 billion m^3 RWE primary processed wood products.

Figure 22 illustrates the industrial roundwood demand in 2050 showing three scenarios of wood residue use in industries. If 30 percent (around 260 million m^3 RWE) of the wood residues from sawnwood, veneer and plywood production are used in the production of wood pulp and particle/fibre board, the IRW demand in 2050 would be 2.9 billion m^3. At a wood residue use rate of 70 percent (around 610 million m^3 RWE), the IRW demand in 2050 reduces to 2.5 billion m^3.

Figure 22. Industrial roundwood demand by 2050 as a function of wood residue use in wood industries



Sources: 2020 data elaborated from FAOSTAT Forestry. 2050 data elaborated from GFPM 2050 simulations.

Note: Wood residue considers a recovery rate of 50 percent in sawmilling and veneer/plywood production. For details, see Annex 8.8. Data does not include additional volumes of material substituted for non-renewables in chapter 2.4.

[23] In the southern United States of America, residual chips constitute 20 percent of softwood fibre and 13 percent of hardwood fibre in the fibre consuming industries. In the Pacific Southwest, pulp mills source almost 60 percent of their materials from industry residues (F2M, 2018).

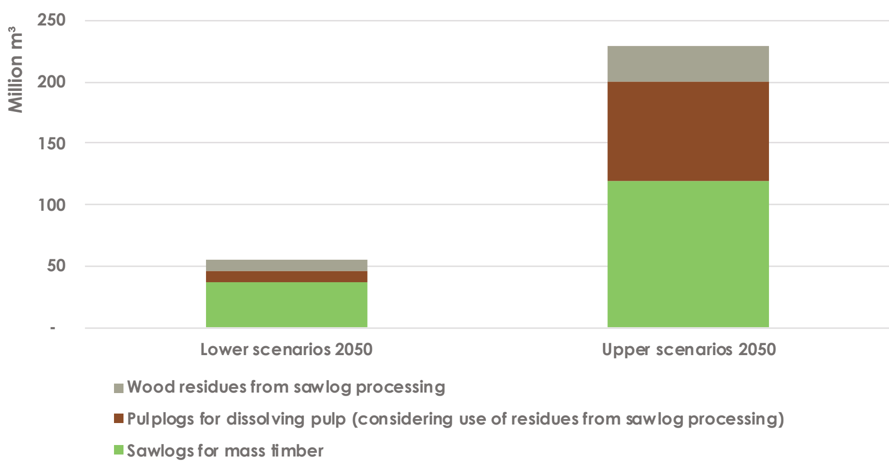
3.4. INDUSTRIAL ROUNDWOOD DEMAND FOR SUBSTITUTION OF NON-RENEWABLE MATERIALS

IRW requirements in 2050 may increase due to the substitution of renewable materials for non-renewable materials in construction and cellulose fibre production (chapter 2.4). The related industrial roundwood requirements may range between 46 million m³ and 149 million m³ in 2050. It includes the 50 percent of wood residues from sawlog processing that will be used for dissolving pulp production.

Mass timber products will require additional primary production in planted or naturally regenerated forests. The potential demand for dissolving pulp to produce MMCF will be partly met through the use of wood residues from processing mass timber sawlogs.

It is difficult to estimate the concrete contribution of forest categories and regions to supply the additional IRW requirements by 2050. Forest management and conservation policies, market mechanisms, investment decisions and environmental factors will finally define where production growth will occur.

Figure 23. Additional industrial roundwood demand by 2050 due to non-renewable material substitution



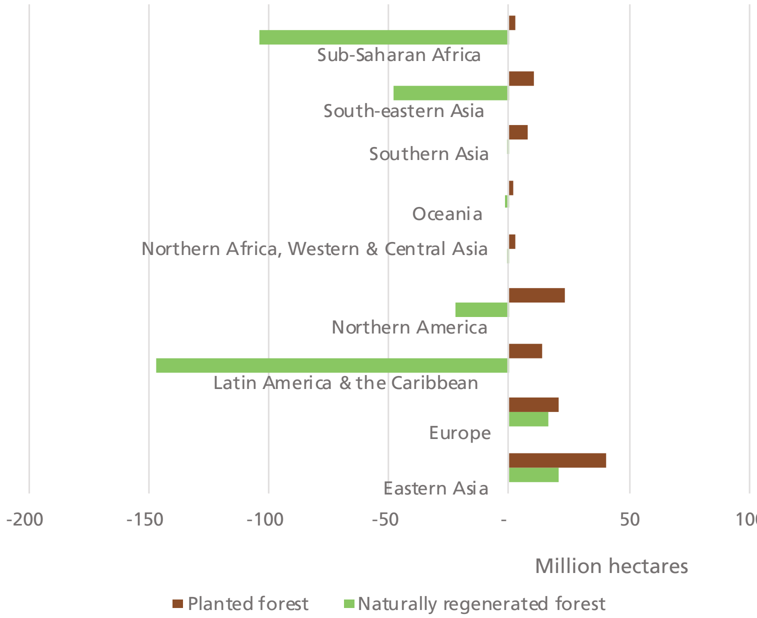
Sources: Additional volumes due to the substitution of renewables for non-renewables as detailed in chapter 2.4 (Annex 8.10 and 8.11).
Note: 50 percent of wood residues from sawlog processing will be used for dissolving pulp production.

3.5. GLOBAL TRENDS FOR INDUSTRIAL ROUNDWOOD SUPPLY

The global forest area has reduced by 4 percent since 1990. Most severe forest area losses have occurred in the tropical and sub-tropical regions of Latin America and the Caribbean, sub-Saharan Africa and South-eastern Asia.

In contrast, planted forest area has increased by more than 70 percent over the same period, especially in Eastern Asia, Northern America and Europe (Figure 24).

Figure 24. Net area change 1990–2020 of naturally regenerated and planted forests by region



Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome.

In view of changing forest area, the future supply of IRW will be subject to: 1) the expansion and productivity of planted forest areas (including agroforestry); and 2) the possibilities for intensifying or expanding the management of naturally regenerated forests. The concrete contribution of forest types and regions to meet IRW requirements in 2050 will be negotiated in the context of forest management and conservation policies, market mechanisms, investment decisions and environmental factors.

To identify the options to meet the IRW demand by 2050, the supply from naturally regenerated and planted forests is discussed in separate sections. Finally, this chapter looks at the interplay of productivity changes in naturally regenerated forest and planted forest to meet the IRW demand in 2050.

The following table summarizes the main trends for IRW production per forest category. Detailed explanations and references are provided in the respective chapters.

TABLE 15.
Summary table of main trends in the industrial roundwood supply by forest category

Forest category	Contribution to IRW production 2020 (percent)	Trends in potential IRW supply 2050
Chapter 3.5.1: Naturally regenerated temperate and boreal forests (Northern America, Europe, Oceania, Eastern Asia)	44	Historical production has continuously increased. Increasing growing stock suggests theoretical potential to increase production. Policies to combat climate change and biodiversity loss may restrict extractive forest uses. Climate change impacts on species composition will restrict availability of commercial species, but the effect is mainly expected after 2050. In total, supply from these forests is expected to increase, though the previously mentioned factors may have significant influence on the concrete volumes.
Chapter 3.5.1: Naturally regenerated tropical and sub-tropical forests (sub-Saharan Africa, Latin America & the Caribbean, South-eastern Asia, Southern Asia)	9	Historically, supply from these forests has been stable. Growing stock in naturally regenerated forests is expected to further decline. Priority is given to conservation and maintenance of ecosystem functions. Suitability of tropical species in modern wood products is limited due to technical specifications and/or costs of production.
Chapter 3.5.2: Planted forests temperate (Northern America, Europe, Oceania)	23	Growing contribution to IRW supply. Most planted areas dedicated to IRW production are already well managed, though improving productivity is possible. Supply from these forests is expected to increase.
Chapter 3.5.2: Planted forests tropical/ subtropical (sub-Saharan Africa, Latin America & the Caribbean, South-eastern Asia, Southern Asia, Eastern Asia)	23	Growing contribution to global IRW supply. Large potential for productivity increases in existing planted forests. Regional FLR pledges of more than 200 million ha offers possibilities to restore areas for IRW production with commercial exotic and indigenous species. Large areas of agroforestry and tree crop plantations (45 million ha) already contribute to IRW supply, though the actual contribution to global IRW (and fuelwood) production is unknown. Agricultural area expansion offers opportunities to enlarge this resource base.

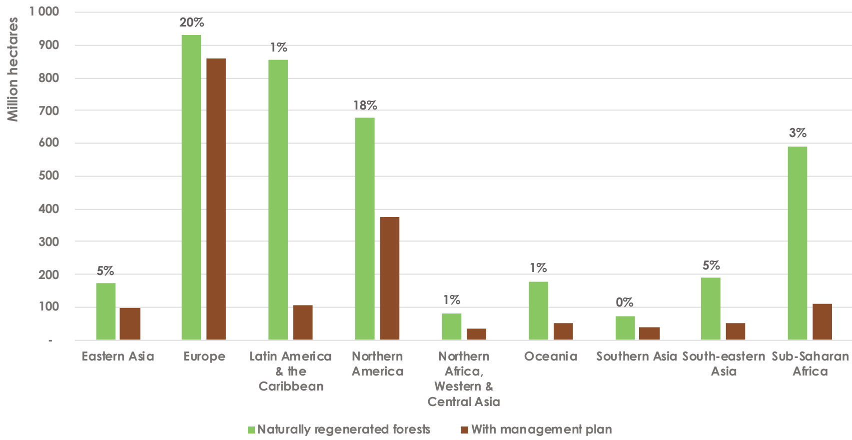
Source: Authors' own elaboration based on chapters 3.5.1 to 3.5.3.

3.5.1 Industrial roundwood supply from naturally regenerated forests

Naturally regenerated temperate and boreal forests

Actual supply from naturally regenerated forests in boreal and temperate zones is estimated at 44 percent of global IRW production[24] (Figure 25). The forest area and growing stock trends in these regions suggest that IRW supply in Europe, Northern America and Eastern Asia will remain stable or even increase in the coming decades (Vauhkonen *et al.*, 2019) (Nepal *et al.*, 2019) (Zhang *et al.*, 2018). However, significant uncertainties remain regarding the influence of forest management and conservation policies on harvesting volumes and the effects of climate change on growth and species composition (see chapter 3.5.3).

Figure 25. Regional area of naturally regenerated forests (total and with management plans) and their contribution to global industrial roundwood production, 2020 (percent)



Sources: Areas from FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome; Contribution to global IRW production in percent is based on 2012 figures published by Payn, T., Carnus, J.-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C. *et al.* 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*; Nepal, P., Prestemon, J.P., Cubbage, F. & Korhonen, J. 2019. Projecting global planted forest area developments and the associated impacts on global forest product markets. *Journal of Environmental Management*.

Note: The actual share of naturally regenerated forests in global production in 2020 is likely to be lower, since planted forest area has increased by between 2012 and 2020 (FAO, 2020). For this analysis, the regional attribution to forest biomes and categories considers Eastern Asian IRW production in naturally regenerated forests originating from temperate forests.

[24] Includes Europe, Northern America and Eastern Asia. It is acknowledged that Eastern Asia and Northern America also include sub-tropical and tropical forests (i.e. in Mexico).

Generally, growing stocks are projected to increase on an average of 0.9 billion m³/a according to the Forest Sector Outlook 2020–2040 study for the UNECE region[25] (UNECE and FAO, 2021).[26] This would allow for an intensified forest management to meet IRW demand growth. Nevertheless, the intensification of forest management in temperate and boreal forests is likely to be restricted by environmental and climate change policies. UNECE (2021) states that forests in Europe and Northern America will face medium to extreme climate impacts and higher disease impacts, therefore the focus is on climate adaptation and forest health management to maintain the status.

Managing forests for carbon storage is complex as it strongly depends on the underlying evaluation period as well as the combination of carbon storage capacity in the forests and in wood products (Pukkala, 2018; Liu & Han, 2009; Knauf *et al.*, 2015). For increased carbon storage benefits in the short-term (next decades), it appears to be better to allow growing stocks to increase and stop harvests as carbon is stored in living biomass, forest soil and deadwood (Pukkala, 2018; Knauf *et al.*, 2015). However, in mid- to long-term evaluations (100 to 300 years) carbon storage in forests could be outperformed by wood usage effects (Knauf *et al.*, 2015). A key question is the longevity of trees and wood products, as well as the decomposition rate of dead trees (Pukkala, 2018).

Furthermore, in the European Union context, the potential immediate impacts of environmental and climate change policies could result in reduced IRW production both due to a reduction of area in favour of increases in protected forest area and a decline of productivity due to higher environmental management requirements. Model projections by Dieter, Weimar and Iost (2020), assessing the potential leakage effects of implementing the European Union-Biodiversity proposal,[27] show a decrease from 473 million m³/a to 324 million m³/a in 2050 in the EU27. This would result in a reduction of 149 million m³/per year, which equals the combined roundwood production of Finland and Germany in 2020 (FAOSTAT Forestry data for 2020).

The outlook for primary wood products consumption by 2050 in Northern America and Europe simulates stable volumes compared to 2020 (chapter 2.3). Production volumes in 2020 of IRW in these regions would be sufficient to meet the regional consumption in 2050 (Figure 21). However, since these regions host major wood products exporting economies (chapter 2.2 and Figure 5), IRW consumption in these regions may be significantly higher than regional consumption volumes suggest. In the end, expanding planted forest area (chapter 3.5.2) and enhancing the productivity of the planted forests (chapter 3.5.3) in tropical and sub-tropical regions will eventually influence the volumes required from natural regenerated forests.

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[25] UNECE partner regions cover basically all temperate and boreal forest areas in Northern America, Europe and Asia.

[26] This figure includes growing stock of planted forests.

[27] See European Commission, Directorate-General for Environment (2021).

Naturally regenerated tropical and sub-tropical forests
Although forest area loss in naturally regenerated tropical and sub-tropical regions have been substantial (Figure 24), its implication for future supply with IRW will be marginal as only around 9 percent of global IRW demand is supplied from naturally regenerated forests in these regions (in 2019; Figure 25).[28] The global consumption of tropical timber from naturally regenerated forests has been rather stable since 1990: oscillating between 150–180 million m^3 (Figure 26). The hotspots of consumption have shifted from Europe and Northern America to Asian regions (FLEGT and IMM, 2019). Given the actual trend towards conserving natural forests and the increasing market preference for plantation timber, future production in tropical and sub-tropical natural forests is not expected to increase substantially.[29] Production volumes from naturally regenerated forests in the tropics and sub-tropics are expected to remain at current levels (ITTO, 2021).

Further deforestation is expected to occur in naturally regenerated tropical and sub-tropical forests. UNECE estimates that the growing stock of natural and planted forests in non-UNECE regions are expected to decrease annually by -0.5 billion m^3 by 2040 (UNECE and FAO, 2021). The decline will mainly occur in emerging world regions with tropical and sub-tropical forest cover, despite the fact that planted forest areas are expected to increase in these regions (chapter 3.5.2).

In the face of declining area and increasing demands on tropical forests for their multiple goods and ecosystem services, tropical forest management must ensure benefits for a wide range of actors, from small to large scale and from communities to industrial players.

Industrial concessions will need to incorporate new business models, moving away from timber-exclusive approaches towards diversified models aimed at producing multiple goods and ecosystem services (Karsenty and Vermeulen, 2016). During the period of this development, new silvicultural strategies and improved approaches addressing land tenure, community inclusion and benefit sharing will need to be explored (Tegegne *et al*., 2018).

Limitations to increasingly using naturally regenerated tropical and sub-tropical forests to meet future wood demand are the ongoing trend of decreasing forest areas and growing stocks, as well as the generally low productivity of commercial timber volumes and long lasting post-logging recovery (Gräfe *et al*., 2020; Bonnell, Reyna-Hurtado and Chapman, 2011).

Expanding the spectrum of commercial species (commonly described as lesser-known timber species [LKTS]) could increase the area of productivity, but markets are slow to accept them (van Dijk *et al*., 2020). On the forest

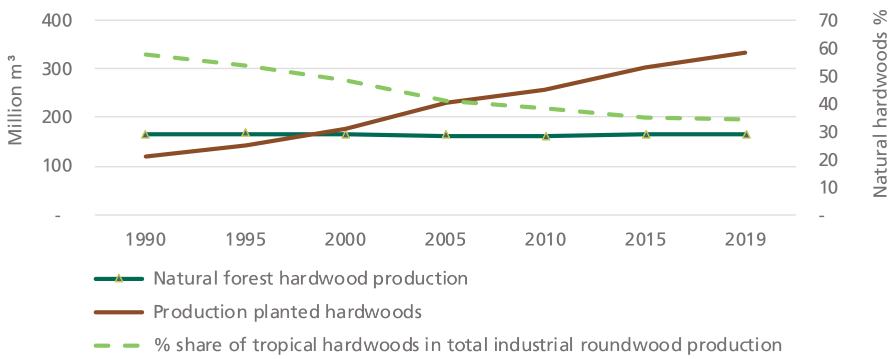
28 This figure considers volumes in Latin America and the Caribbean, sub-Saharan Africa and South-eastern Asia. In these regions there are also temperate forests and other regions host sub-tropical forests (e.g. Eastern Asia).

29 Supply volumes, however, may increase through timber from planned and unplanned large-scale conversion of forest to agriculture. However, these volumes are not sustainable and do not reflect market mechanisms-based demand.

management side, improvement thinning and enrichment plantings aim to gradually increase the amount of marketable tree species and volumes. Scientific confirmation, however, is rare (e.g. Gourlet-Fleury *et al.* [2013]).

A potential for increased production may result from FLR initiatives. The areas under tree cover in tropical and sub-tropical regions may substantially increase. Actual pledges in Latin America and the Caribbean, sub-Saharan Africa and Southern and South-eastern Asia amount to more than 200 million ha (as of March 2022).

Figure 26. Production of non-coniferous industrial roundwood in natural forests and plantations in Africa, Latin America and South-eastern Asia, 1990 to 2019



Source: ITTO. 2021. *Tropical timber 2050: an analysis of the future suply and demand for tropical timber and its contribution to a sustainable economy.* Yokohama, ITTO.
Note: In this analysis, Latin America includes Mexico and Africa includes Northern Africa.

3.5.2 Industrial roundwood supply from planted forests

Planted forests

Generally, the importance of planted forests for global IRW production is increasing (Figure 26). The total area of planted forests is estimated at about 294 million ha (FAO, 2020), although part of this is designated for protection and conservation. Nepal *et al.* (2019) estimates that planted forests produced 46 percent of global IRW supply in 2015. The actual share of planted forests in global production in 2020 was likely higher, due to planted forest area increases between 2015 and 2020 (FAO, 2020).

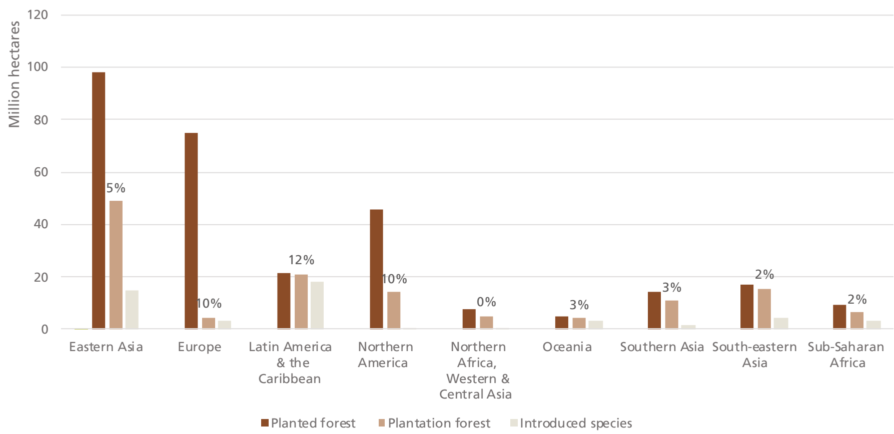
Industrial roundwood production occurs mainly in intensively managed plantation forests, of which there are around 131 million ha (FAO, 2020). Between 2015 and 2020, the plantation forest area increased by more than 6 million ha. The potential productivity of planted forest areas is estimated at 4.6 m³/ha/a (commercial industrial roundwood volume [Payn *et al.*, 2015]). However, real production is estimated to be substantially lower (2.7 m³/ha/a; see chapter 3.5.3). This global average includes planted forest areas for conservation targets and appears low when compared against the productivity of industrial plantations (see chapter 3.5.3). However, forest plantations with dedicated timber production targets frequently perform below industry practice and there is room for improved production without area expansion (as described by Carle and Holmgren [2008]).

The area of planted forests for timber production is expected to increase until 2050. Korhonen *et al.* (2021) estimates a global planted forest area increase of 20 million to 40 million ha by 2050. This figure refers to highly productive plantation forests. However, in some temperate regions with significant planted forest cover (e.g. France, Ireland and the United Kingdom of Great Britain and Northern Ireland) plantations are partly converted to continuous cover management (Mason *et al.*, 2021).

The pace of expansion of planted forest production depends on the enabling environment in forest investments for industrial and small-scale producers, the availability of suitable land in view of competitiveness with agriculture and the increasing cost of land in many countries, and the productivity of plantations as a function of improved planting materials, changing climate conditions and modern management practices (Cossalter and Pye-Smith, 2003).

The expansion of planted forests will require a mix of varying production systems (from small scale to large industrial plantations in pour stand or in agroforestry systems), and related ownership structures and business models that depend on national policies on forest industry development, private capital mobilization, reforestation strategies and overall land use planning. The commercial objectives of private small scale and industrial size actors must be linked to overarching forest sector development targets (e.g. FLR implementation), sustainable growth policies and climate change mitigation and adaptation strategies.

Figure 27. Regional area of planted forests and their contribution to global industrial roundwood production, 2020 (percent)



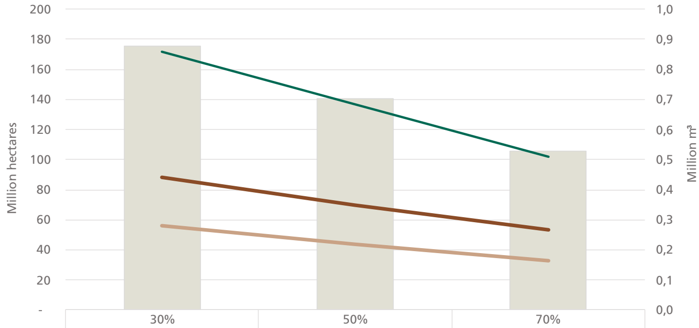
Sources: Areas from FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome; Contribution to global IRW production in percent is based on 2012 figures published by Payn, T., Carnus, J.-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C. *et al*. 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*; Nepal, P., Prestemon, J.P., Cubbage, F. & Korhonen, J. 2019. Projecting global planted forest area developments and the associated impacts on global forest product markets. *Journal of Environmental Management*.

Note: The actual share of natural plantation forests in global production in 2020 is likely to be higher due to planted forest area increases between 2012 and 2020 (FAO, 2020).

Figure 28 illustrates the global additional planted forest area requirements to meet the wood products demand increment from 2020 to 2050 under consideration of varying intensities of using wood industry residues. The required increase in IRW production compared to 2020 IRW production would be around 0.9 billion m^3 to meet 2050 wood industry demand if only 30 percent of wood residues are used. At a wood-industry-residues-use rate of 70 percent, the required IRW production increment would be only 0.5 billion m^3.

The analysis shows that at least 33 million ha of additional commercial plantations could be sufficient to meet 2050 demand growth if: 1) 70 percent of future sawmill and plymill residues were used as virgin wood fibre substitutes; 2) productivity of new plantations is substantially enhanced (average MAI of 15 m^3/ha/a); and 3) production from naturally regenerated forests remains stable at 2020 levels. This figure is comparable to the results of (Korhonen *et al*., 2021), ranging between 20 million ha and 40 million ha.

Figure 28. Hypothetical planted forest area requirements to meet additional industrial roundwood demand in 2050 as a function of productivity and use of wood residues



	30%	50%	70%
IRW demand increase 2020-2050 (1.000 m³)	878.001	703.499	528.997
Actual productivity (5 m ³/ha/a)	172.000	137.000	102.000
Productivity +100% (10 m³/ha/a)	88.000	70.000	53.000
Productivity +300% (15 m³/ha/a)	56.000	44.000	33.000

Percentage of wood industry residues used as fibre

Source: Based on global average commercial volume MAIs of 5 m³/ha/a in planted forests. Payn, T., Carnus, J.-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C. *et al*. 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*.

Notes: Wood residue use will have a recovery rate of 50 percent in sawmilling and veneer/ plywood production in 2050. IRW production requirements based on GFPM wood products outlook 2050 (Annex 8.5). Assumes no production increase from 2020 to 2050 for other forest categories (Annex 8.12). Data does not include additional volumes due to non-renewables substitution in chapter 2.4.

Agroforestry

Timber from agroforestry and silvopastoral systems increasingly contributes to wood industry supplies. Based on FAO (2020) data, a total area of 45.4 million ha of agroforestry was reported, mostly in Asia (31.2 million ha) and Africa (12.8 million ha). Despite this large area, however, the role of agroforestry in IRW production has not been analysed systematically. The wood harvested in agroforestry systems is typically recorded as timber from planted forests. Data from case studies indicate that it could be substantial in some countries and regions. In India, for example, agroforestry and trees outside forests provide more than 90 percent of domestic IRW production (Shrivastava, 2017).

Arguably, most areas under agroforestry provide substantial volumes of wood fuel and timber for subsistence uses in rural construction and in households. However, species composition and management practice would not allow for factoring them in as a reliable supply for modern wood industries.

Modern agroforestry systems designed to produce IRW are capable of supplying quality timber and fibre for large industries as proven in many countries in Latin America and the Caribbean and Asia (Ramachandran and Garrity, 2012). The productivity of agroforestry systems varies largely according to the production targets of the mixed crop/commodity. Case studies indicate that the productivity of eucalyptus silvopastoral systems in Latin America and the Caribbean are almost competitive with pure stands (Macedo Pezzopane *et al.*, 2021). Commercial timber yields from shade coffee production in Central America are in the range of 50 percent to even 100 percent of pure planted stands (Ehrenbergerová *et al.*, 2019).

The timber productivity of agroforestry systems in other world regions is less known. The actual areas of such systems and their contributions to overall timber supply are unknown.

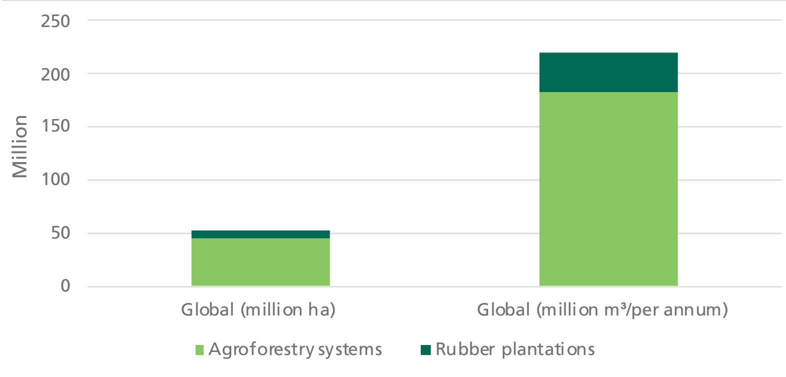
In view of rising competition for agricultural land and increasing land prices, agroforestry and silvopastoril systems have become increasingly interesting for investors, facilitating early positive returns, diversifying revenue streams and approaching more sustainable agricultural practice (Neto *et al.*, 2013) (Reppin *et al.*, 2020).

The potential of tree crop plantations to supply tropical timber markets in the future will depend on improvements in timber quality and increased knowledge of wood properties. Tree-crop plantations (e.g. rubber, oil palm, coconut and horticultural) have significant potential for IRW production in tropical regions.

In South-eastern Asia, rubberwood is already an important source of IRW. In Viet Nam, for example, rubberwood production exceeds 3 million m^3 annually, which is 15 percent of domestic IRW production (Forest Trends, 2018). There are about 7 million ha of rubber plantations globally (FAO, 2020). Because the quality of rubberwood stands vary, the actual volumes entering the wood industries is unknown. Case studies suggest a commercial volume of 50–100 m^3 per ha at the end of the rubber-tapping cycle of 20 to 30 years (ITTO, 2008), which converts to a commercial MAI of 2 to 5 m^3 / ha/a. Assuming a stable rubber plantation area until 2050, the annual supply to the global timber markets could be around 35 million m^3 per annum. This figure, however, is prone to uncertainty. The role of rubberwood to the future supply of IRW remains uncertain. The expansion of areas is subject to global market demand and the prices for rubber.

Figure 29 shows the potential contribution of agroforestry systems and rubber plantations to the global timber supply, assuming conservative production volumes of industrial roundwood.

Figure 29. Areas of agroforestry and rubber plantations and potential roundwood supply, 2020



Source: Areas from FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome.

Notes: Commercial MAI for rubber: 5 m^3/ha per annum; Commercial timber MAI for agroforestry systems: 10 m^3/ha per annum in Latin America and the Caribbean and 5 m^3/ha per annum in other world regions (Source: Expert estimates).

3.5.3 Forest productivity and industrial roundwood production

Besides the expansion of forest area under management to meet future IRW demand, the improved productivity of existing forest areas under management may result in additional IRW supply. Potential productivity gains are assumed mainly to occur in tropical planted forests (chapter 3.5.2). Growing stock trends in naturally regenerated temperate and boreal forests suggest that there are possibilities for intensifying their use, but this may be restricted due to policy and climate change implications (chapter 3.5).

In planted tropical forests, the potential for productivity increases are high since the gap between low and high performing forests is significant. Payn *et al.* (2015) found that the potential average productivity of planted forests in South America were highest with 24 m^3/ha per annum. Between 2014 and 2020, the productivity of eucalyptus and pine in Brazil have been around 35 and 30 m^3/ha per annum (IBÁ, 2021). The high productivity results from improved clonal technology, fertilization, better silviculture, as well as improvements in harvesting and recovery technology.

Nepal *et al.* (2019) estimated the average productivity of planted forests in Africa at 6 m^3/ha per annum. At operational scale, MAIs of well performing eucalyptus and pine plantations in South Africa are between 15 and 25 m/ha per annum respectively (Cossalter and Pye-Smith, 2003). In provenance trials in Ethiopia by MAI of *Eucalyptus grandis* were between 25–41 m^3/ha per annum (Hunde *et al.*, 2003). Varmola *et al.* (2010) report MAI for *Eucalyptus grandis* in the Chinese Guangxi region of 25 m^3/ha per annum, and mill gate productivity of around 21 m^3/ha per annum. These examples show that potentially high growth performances do not translate to high IRW productivity.

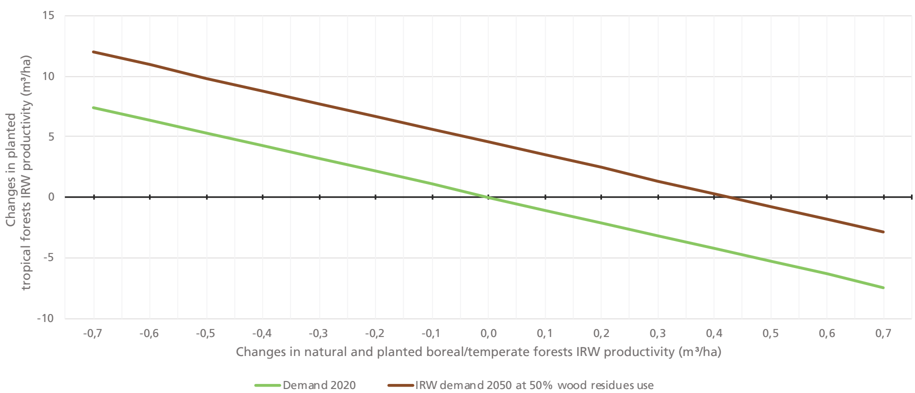
However, the real production from tropical and sub-tropical planted forests is only around 2.7 m^3/ha per annum (Payn, 2015). The productivity for East Asia was even as low as around 1 m^3/ha per annum. Hence, across all planted forest area, there remains potential to increase productivity.

Based on the assumption that productivity in naturally regenerated temperate and boreal forests remains stable at 2020 production levels (0.42 m^3/ha per annum), the productivity in planted tropical/sub-tropical forests needs to increase from 2.7 m^3/ha to 7.22 m^3/ha per annum to meet the projected demand in 2050 at 50 percent wood residue use rate of 1 971.36 million m^3 (see chapter 3.3).

A stronger ecological focus in the EU27 would lead to a considerable decrease of IRW production in natural regenerated temperate and boreal forests as projected by Dieter, Weimar and Iost (2020). This could roughly relate to an estimated reduction of 0.1 m^3/ha.[30] To compensate for this reduction, the productivity of planted tropical and sub-tropical forests would need to increase by 5 to 8.27 m^3/ha.

Hence the increase in existing planted forest productivity could reduce the need to establish new plantations as illustrated in chapter 3.5.2.

Figure 30. Planted and naturally regenerated forest productivity to meet industrial roundwood demand growth, 2050



Sources: Global average productivity of forest categories as in Annex 8.13. Areas from FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome.

Notes: IRW demand from GFPM for 2050 reduced by tropical IRW 170 million m^3 (chapter 3.5.1) and temperate planted IRW 459 million m^3 as both assumed stable; contribution of planted forests to IRW production adapted from (Payn *et al.*, 2015).

[30] Based on Dieter, Weimar and Iost (2020), with an estimated EU27 reduction of 149 million m^3 in 2050, a forest area of 159 million ha (FRA 2020), and a total natural boreal and temperate forest area of 1.785 million ha, the corresponding productivity reduction would be around 0.08 m^3/ha.

4. Outlook for wood energy, 2050

4.1. KEY RESULTS OF WOOD ENERGY OUTLOOK, 2050

- Future wood energy consumption up to 2050 will be shaped by two major trends: 1) the traditional use of fuelwood in the two most rapidly growing world regions of sub-Saharan Africa and Southern Asia; and 2) by the projected role of modern biomass to generate renewable energy.
- Scenarios of future wood energy consumption trajectories up to 2050 show a wide amplitude. Most scenarios indicate that the global consumption volumes of fuelwood from forests in 2050 may be between 2.3 billion and 2.7 billion m^3, compared to 1.9 billion m^3 in 2020.
- More extreme scenarios suggest: 1) a decline in wood demand for energy consumption due to a reduction in traditional fuel wood uses in emerging economies and a reduced energy demand in industrialized regions; or 2) a significant increase due to enhanced use of wood in the future renewable energy mix.
- Regardless of the exact quantification by 2050, fuelwood will continue to be an important energy source for people in emerging economies, and wood will be part of the renewable energy mix in industrialized world regions.
- The efforts to supply future volumes in a sustainable economic environment may consider the enhanced use of wood residues and the establishment of fuel wood plantations in pure or agroforestry production systems.
- Actual data on wood energy sources is fragmented and does not allow for establishing a baseline disaggregated for fuelwood categories. However, model calculations in this chapter indicate that shifting from naturally regenerated fuelwood to residues and planted resources may trigger competition with other land uses by the wood processing industries.

TABLE 16.
Summary table of selected key results for wood energy, 2050

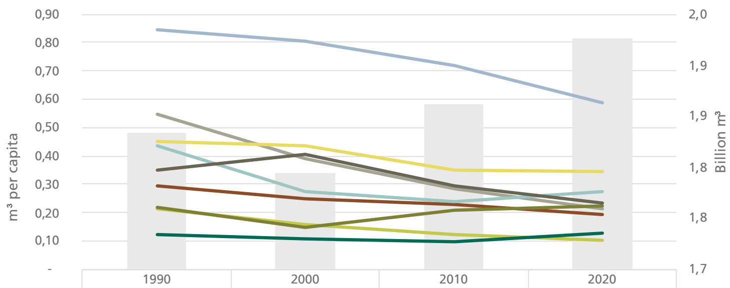
Wood energy consumption sourced from forests	2020 (billion m³)	2050 (billion m³)	Percentage change 2020–2050
Basic outlook (based on IEA, IPCC and GFPM)	1.9	2.3–2.7	+17–42
High outlook (based on IPCC)		7.7	+400
Low outlook (based on IPCC)		1.6	-19

Sources: Author's own elaboration based on chapters 4.2.1 to 4.2.2.

4.2. OUTLOOK FOR GLOBAL WOOD ENERGY CONSUMPTION, 2050

The global consumption of wood fuel has increased by almost 100 million m³ between 1990 and 2020 (Figure 31). Across all world regions, the trend of decreasing per capita consumption has continued and typically ranged between 0.1 and 0.3 m³ per capita and year by 2020. Although per capita consumption has substantially declined in sub-Saharan Africa, the actual per capita consumption of 0.6 m³ per year is far above the global average.

Figure 31. Global wood fuel consumption and per capita consumption by regions, 1990 to 2020



	1990	2000	2010	2020
Woodfuel consumption World (1.000 m ³)	1.833.430	1.793.698	1.862.303	1.925.986
East Asia	0,21	0,16	0,12	0,10
South Asia	0,29	0,25	0,23	0,19
Southeast Asia	0,55	0,39	0,28	0,21
Northern Africa, Western & Central Asia	0,12	0,11	0,10	0,13
Sub-Saharan Africa	0,84	0,80	0,72	0,59
Latin America & Carribean	0,45	0,43	0,35	0,34
Europe	0,22	0,15	0,21	0,23
North America	0,44	0,28	0,24	0,27
Oceania	0,35	0,41	0,29	0,23

Sources: FAOSTAT Forestry and United Nations World Population Database.

The role of wood energy in the future global energy mix will be shaped by the mix of traditional uses for cooking and heating and the modern use of wood fuels in industries, households and for generating electricity.[31]

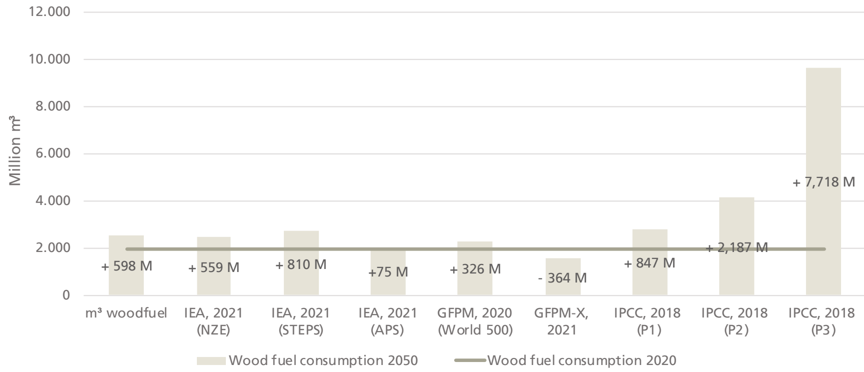
However, long term wood energy consumption trends are difficult to assess, and projections of future demand depend strongly on underlying assumptions. While important factors such as population growth and income development are comparably easy to assess, the effects of energy policies and their implementation are subject to high levels of uncertainty. Further, unforeseeable economic shocks and disruptions at the national and international levels may result in an increasing use of fuelwood (as happened during the COVID-19 pandemic, for example in Kenya (Shupler *et al.*, 2021) and Nepal (Giri, 2021).

During recent years, a series of model simulations and scenarios have been produced that aimed at hedging the wide variety of assumptions and unknowns of future wood fuel consumption. The outlooks emphasized framing the assumptions for traditional use of wood fuel in developing economies (i.e. in sub-Saharan Africa) and the global role of wood fuel in the renewable energy supply. As a function of the underlying assumptions, the global figures of these outlooks vary widely. The following compilation summarizes the results of recent outlooks published by the IEA in 2021 and IPCC in 2018, and the basic GFPM simulations for 2050. For a description of the underlying assumptions of these scenarios, see Annex 8.15.

The scenarios of future wood energy consumption trajectories up to 2050 show a wide amplitude. Most scenarios indicate that the global consumption volumes of fuelwood from forests in 2050 may be between 2.3 billion and 2.7 billion m^3, compared to 1.9 billion m^3 in 2020; the global consumption volumes in 2050 may be around 2.5 billion m^3.

[31] Traditional biomass includes fuelwood, charcoal, agricultural residues, etc. used for cooking and heating. Modern biomass includes organic matter managed sustainably. The technology used to obtain the energy limits or mitigates emissions of flue gases and accounts for ash residue management. The efficiency of conversion to energy is higher than the use of traditional fuels (WEC, 2016).

Figure 32. Outlooks of wood fuel demand growth in global energy mix, 2050



Sources: Elaborated from FAOSTAT Forestry (wood fuel consumption 2020);12 000 volumes from simulations of GFPM (world 500) and GFPM-X; IEA. 2021b. *World Energy Outlook 2021.* Paris, IEA; IPCC. 2018. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways.* Geneva, IPCC.

Notes: IEA 2050 wood fuel volumes used solid biomass growth rate 2020 to 2050 for the respective scenarios: Net Zero Emission (NZW), Announced nationally determined contribution (NDC) pledges (APS) and Stated Energy Policies (STEPS) (Annex 8.15).

4.2.1 Wood fuel in global bioenergy, 2050

In the industrialized economies such as Europe and parts of Eastern Asia, climate change mitigation policies promote the modern use of wood biomass and this has led to increasing use by households and industries (FAO, 2016; EU, 2019). The significant rise in production and trade with wood pellets is an indicator of the growing relevance of wood biomass in the energy mix of industrialized economies in Europe and Asia (UNECE and FAO, 2020).

In Europe, wood biomass is the most important bioenergy source (UNECE and FAO, 2021). The European Commission's long-term vision estimates that, by 2050, the consumption of bioenergy will amount to between 170 and 252 Mtoe (EEA, 2018). Most of this increase, however, shall be met by biogas from agricultural residues and waste.

In major Asian economies, wood biomass for energy has seen growing interest over recent years. The bioenergy policies in China, Japan and the Republic of Korea are pursuing a fuel switch strategy of their coal-fired energy infrastructure drawing on imported biomass (i.e. wood pellets). The bioenergy policies in Malaysia and Indonesia are putting emphasis on agricultural residues and, to a minor extent, on wood biomass (Junginger, Koppejan and Goh, 2020). In general, the future supply of wood biomass in the region will be subject to high levels of uncertainty, including questions about how reliable import streams will be in the long run (e.g. from Northern America) and whether future sourcing areas may shift to other world regions (e.g. Latin America and the Caribbean).

The promotion of forest biomass as a renewable and primary energy source in industrialized economies is increasingly challenged by the scientific community, indicating that the use of forest biomass is only meeting carbon neutrality targets under strict considerations of sustainability, accounting and efficiency criteria (Norton, 2019; Booth, 2018). The general consensus is that forest-based biomass used for energy should be concentrated on residues and post-consumer materials that cannot be utilized elsewhere in wood industries (FAO, 2016).

In view of growing demand for solid wood products and wood fibre, the opportunity cost of using wood for energy increases. For example, wood-fibre-based industries (pulp, particle and fibre board) draw on the same raw material as modern fuelwood (wood residues, small diameter logs). Further, land for forest production is increasingly in competition with suitable land for agriculture and this is limiting the overall production possibilities of wood (for energy and for solid wood products). (Dieste *et al*, 2019) suggests that the value added from one hectare of forest plantation for sawn timber production is four times the value added for electrical energy from wood biomass in Uruguay. Similar observations are made for the downstream employment impact of wood processing in Germany: Based on one m^3 roundwood intake, the employment impact in sawn timber production is about four times the impact of pellet production (FNR, 2015).

The IPCC and IEA scenarios presented in this chapter assume a decreasing use of traditional wood fuel (i.e. in developing world regions, see also chapter 4.2.2) while modern wood fuel uses increase (i.e. in industrialized world regions). It remains unclear, whether society and politics are willing to increase use intensity of naturally regenerated forests in these regions (see also chapter 3.5 on industrial roundwood production). If not, this would trigger massive global trade flows of transportable biomass (chips, pellets) from planted forests in the global South. Arguably, the tradability will be affected by transport cost fluctuations and transport capacity availability.

Box 5 illustrates the volumes and area requirements if virgin fuelwood from naturally regenerated forests was phased out and wood energy demand was being met with residues and planted forests only. The targeted volumes are derived from IEA's NZE scenario to reflect the prominent role of wood energy in climate change mitigation. Both the enhanced use of residues and the substantial expansion of energy plantations will have to consider trade-offs with requirements from competing industries and land uses.

4.2.2 Traditional use of wood fuel, 2050

Since 1990, the growth rates for traditional use of wood fuel have declined or stabilized in several world regions. However, in sub-Saharan Africa and

Box 5
Wood energy supply in the International Energy Agency's net zero emission scenario, 2050

This box illustrates the potential wood energy production and area requirements to meet NZE targets. The total demand for wood energy in this scenario amounts to 4.1 million m³.

The scenario considers a substantial reorganization of wood supply for energy uses, putting emphasis on residue uses and planted forests. The use of fuelwood from naturally regenerated forests is largely eliminated.

The scenario assumes that there will be 1.5 billion m³ supplied from the wood industry and harvesting residues (IEA, 2021a). The scenario, however, does not consider the potential competition for these resources from pulp and wood-based panel production. The potential trade-offs are not considered. There is no comprehensive information for actual use of residues from harvesting and wood processing. The basic outlook for wood products demand (chapter 2.3) indicates that the maximum volume of wood industry residues may amount to 873 million m³ in 2050 (Annex 8.8). While in some countries (i.e, in Europe) these resources are already fully integrated in the existing value chains, untapped potential in many emerging regions remains due to the absence of off-taking consumers or the fragmentation of residues supply. Further, the massive extraction of logging residues from forests comes with negative effects on biodiversity and forest fertility (Ranius *et al.*, 2018).

IEA´s NZE scenario indicates a fuelwood volume 2.6 billion m³ wood fuel from planted forests in 2050 (+0.6 million m³ compared to 2020). This converts to an area of 130 million ha planted forests* dedicated for wood fuel production to be established on marginal lands, pasture and land currently used for less productive bioenergy crops. These substantial area requirements would require close coordination and integration with global pledges for forest landscape restoration, amounting to 200 million ha in 2020.** Competing FLR requirements for conservation, natural forest rehabilitation and industrial roundwood production may restrict implementation of this approach. The financing, ownership and management of these plantations would need to be adapted to local requirements with the participation of communities and industries and the public sector. Expanding agroforestry could be another option to increase the fuelwood supply from planted resources (compare to Box 6).

* Assuming a mean annual increment of 20 m³/ha per annum.
**See www.bonnchallenge.org/pledges

Figure 33. Bioenergy supply from wood resources 2050 under the International Energy Agency's net zero emission scenario

Source: Elaboration based on IEA. 2021a. Net Zero by 2050. A Roadmap for the Global Energy Sector. IEA, Paris.

Notes: Converted from energy supply in Exajoule (EJ) to m^3 (Factor: 1 EJ = 73.1 million m^3). Wood and harvesting residues 20 EJ, short rotation plantations 25 EJ and other planted forest and agroforestry 10 EJ.

Southern Asia, the traditional use of fuelwood[32] has continued to increase. Though per capita consumption has reduced due to sustained economic growth and the expansion of the energy infrastructure (UNEP, 2019a), it has not been enough to halt population growth-driven increases of total consumption volumes. In 2020, around 2.3 billion people relied on wood fuel as their primary source of energy for cooking and heating (IEA, 2021a).

Arguably, the most relevant impacts on traditional wood fuel consumption are the pace of urbanization, expansion of electricity use in rural and urban areas, and affordable access to alternative energy sources (UNEP, 2019a). The urban population´s energy demand is typically higher than that of rural households. If urbanization is not accompanied by access to electricity, demand for fuelwood and charcoal increases. On the other hand, urban migration may substantially reduce the fuelwood and charcoal demand when income levels increase and there is regular and affordable access to electricity and non-wood fuels (Singh *et al.*, 2021).

Across the developing world regions, policies are promoting a household changeover from traditional biomass use to modern combustion. This is being carried out mainly by introducing modern cookstoves and retort-based

[32] Traditional biomass includes fuelwood, charcoal, agricultural residues, etc., used for cooking and heating. Modern biomass includes organic matter managed sustainably. The technology used to obtain the energy limits or mitigates emissions of flue gases and accounts for ash residue management. The efficiency of conversion to energy is higher than the use of traditional fuels (WEC, 2016).

charcoal production technologies. IRENA (2018) estimates that 867 million traditional cook stoves will have to be replaced to completely substitute traditional fuelwood with modern fuelwood consumption up to 2050.

However, studies suggest that improved cooking stoves only mitigate the negative externalities of traditional fuelwood use incrementally. Their contribution to public health, climate change mitigation and other SDGs may be limited (Bailis *et al*., 2017). Other alternatives, such as liquefied petroleum gas, ethanol and biogas can offer greater potential benefits (Rosenthal *et al*., 2018).

Finally, wood fuel availability itself will set limits on consumption. With the expansion of agricultural land due to population growth, the area for collecting fuelwood diminishes and the time required to collect fuelwood increases. The agricultural production area in sub-Saharan Arica is expected to grow by 51 million ha to 2050 (from base year 2012) (Alexandratos and Bruinsma, 2012). Since the area expansion will mainly occur in the vicinity of rural settlements, the availability of fuelwood may reduce by 102 million m^3.[33] A key challenge for the future will be to address this gap by providing a reliable supply until alternative energy sources become available. Box 6 shows the options to supply wood fuel demand growth from woodlots and agroforestry in sub-Saharan Africa.

Fuelwood demand in emerging economies depends on cooking practices and frequency, the caloric values of wood species and the availability of alternative fuels. Fuelwood supply varies according to biological growth conditions and the general condition of the wooded environment. Further, fuelwood is extracted from several sources: forests, trees in agroforestry systems, and other trees outside forests. Further, fuelwood users respond to scarcity by switching to other biofuels or actively increasing their wood supply from woodlots or agroforestry (Bailis *et al*., 2017). With more effort required, people are likely to shift to other energy sources (e.g. from agricultural waste that is expected to grow substantially in the coming decades (DBFZ, 2013).

The complexity presents challenges for assessing future supply gaps, designing mitigating activities and ultimately defining the tipping point of traditional fuelwood transition to modern and alternative energy sources (UNEP, 2019a). Recent outlook studies on sub-Saharan African wood fuel consumption have assessed a variety of scenarios as shown in Figure 34 (description of scenarios in Annex 8.16).

Most of the scenarios project an increase of wood fuel consumption of around 30 percent compared to 2020. On the other hand, IEA's scenario, assuming that African countries will comply with their announced nationally determined contribution (NDC) pledges, would result in a substantial decrease of 64 percent compared to 2020. Assuming that African countries comply with their stated policy commitments, the IEA simulation of 2019 (IEA, 2019) may suggest a realistic, though ambitious, picture of fuelwood consumption in 2050 of 721 million m^3 (+11 percent compared to 2020).

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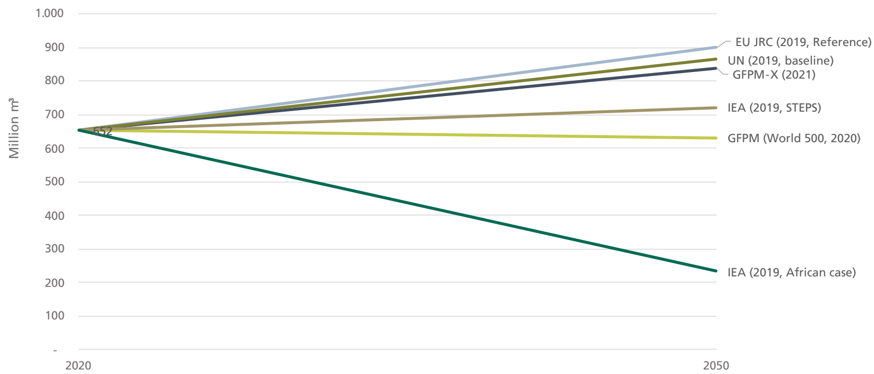
[33] Assuming sustainable fuelwood supply of 2 m^3/ha per annum from African Miombo woodlands (Marzoli, 2007).

Figure 34. Comparison of simulated trajectories of fuelwood consumption in Africa, 2050



Sources: Pappis, I., Howells, M., Sridharan, V., Usher, W., Ramos, E. & Gardumi, F. 2019. *Energy projections for African countries.Technical report.* European Union Joint Research Center; UNEP. 2019a. *Review of Woodfuel Biomass Production and Utilization in Africa: A Desk Study.* Nairobi, UNEP; (IEA 2019. *Africa Energy Outlook 2019.* Paris, IEA.

Notes: GFPM-X and GFPM simulations corrected for missing values. The figure simplifies the fuelwood consumption trajectories (Annex 8.16).

Box 6
Agroforestry and woodlot requirements to meet wood fuel demand growth in sub-Saharan Africa

This box showcases the area required to meet the additional wood fuel demand of 185 million m³ in sub-Saharan Africa by 2050.

Without alternative energy sources to rely on, fuelwood consuming households in sub-Saharan Africa suffer from deforestation and conversion of woodlands to agriculture. In the sub-Saharan African context, the expansion of agricultural land driven by population growth will severely limit the availability of fuelwood.

To enlarge the fuelwood resource base, fuelwood woodlots of fast growing trees have been promoted and were widely planted in many African countries (Bailey *et al.*, 2021) (Toth *et al.*, 2019) (Ndayambaje, 2013). The full extent and supply of wood fuel in these areas is unknown (UNEP, 2019). (Bailey *et al.*, 2021) (Toth *et al.*, 2019).

With growing competition for land in rural areas, there will be many obstacles in the way of establishing new woodlots. Hence, the topic of woodlots for fuelwood production should be a component of the strategies for implementing African FLR pledges.* In view of the looming fuelwood gap, such area expansion should be considered under agroforestry management for wood fuel production. This would reduce the need to set aside areas for pure woodlot management and make more efficient use of the limited suitable land that is available.

Wood fuel production in agroforestry systems can be implemented without major negative trade-offs for agricultural production and may even improve crop performance (Kuyah *et al.*, 2019). Examples from India show that a substantial share of fuelwood demand can be supplied from agroforestry systems (64 percent of national demand (Singh *et al.*, 2021).

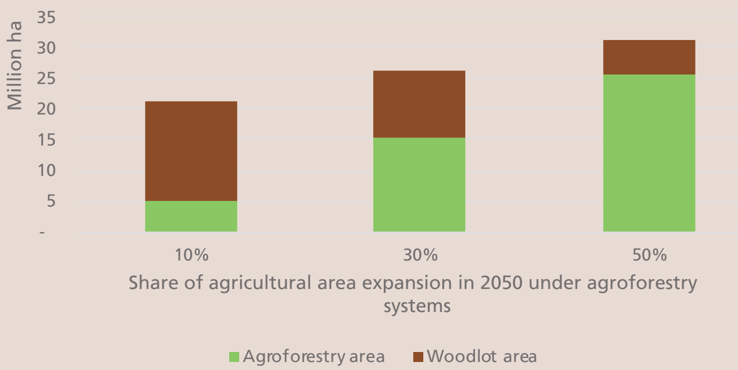
Alexandratos and Bruinsma (2012) estimate an expansion of agriculture area of 51 million ha by 2050 in sub-Saharan Africa. Since the area expansion will mainly occur around rural settlements, the availability of fuelwood may reduce by 102 million m³. In combination with a population driven demand growth of around 83 million m³ ** by 2050, there will be a future wood fuel supply gap of 185 million m³ (Annex 8.17).

However, meeting the looming supply gap of 185 million m³ would require an expansion of dedicated woodlot areas of around 18 million ha.***

With a growing share of agricultural area under agroforestry systems, the share required of additional woodlot area decreases. The total woodlot area requirements would be 6 million ha if 50 percent of agricultural area expansion of 51 million ha is managed under agroforestry fuelwood systems. The woodlot area requirements would increase to 16 million ha in case of 10 percent agroforestry share in agriculture expansion.

* By the end of 2022, African FLR pledges amounted to around 130 million ha (see www.bonnchallenge.org/pledges).
** Based on mean GFPM-X/GFPM increase for sub-Saharan Africa up 2050.
*** Based on a mean annual increment of 10 m³/ha per annum.

Figure 35. Agroforestry and woodlot area requirements to meet additional growth in sub-Saharan Africa



Sources: Based on agricultural area expansion in 2050 of 51 million ha in Alexandratos & Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO; and average annual fuelwood production from Agroforestry (5 m³/ha per annum) in Iliyama, M., Neufeldt, H., Dobie, P., Njenga, M., Ndegwa, G. & Jamnadass, R. 2014. The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Current Opinion in Environmental Sustainability*; and wood lots (10 m³/ha per annum) (Annex 8.18).

5. Outlook of employment and investment requirements in forest industries, 2050

5.1. KEY RESULTS OF EMPLOYMENT AND INVESTMENT REQUIREMENTS OUTLOOK, 2050

Employment requirements, 2050

- Total employment in the forest sector was estimated to be about 33.3 million formal and informal employees in 2019. This number has declined since 2013 from 39.5 million. The reduction is the result of improvements in labour and forest productivity.
- The outlook of forest sector employment in 2050 factors in varying trajectories of increasing labour productivity: the medium estimate (as shown in Table 17) suggests that 2050 employment will be in the range of the 2019 figures.
- The workforce requirements may increase to meet potential production of materials to substitute for selected non-renewable materials between 1 percent and 4 percent.
- The employment requirements to substitute for non-renewable materials considers only selected products. The future requirements may be higher if other innovative wood products expand market shares.

TABLE 17.
Summary table of selected key results for employment requirements, 2050

Sub-sector	Employment 2019 (in millions)	Employment 2050 (in millions) (medium estimate in basic outlook)	Change in basic outlook 2019–2050 (percent)	Employment requirements for substitution of selected non-renewables 2050 (thousands) (lower and upper estimate)	Increase compared to basic outlook 2050 (percent)
Forestry and logging	8 085	7 781	-4	70–224	1–3
Wood industry	19 400	19 043	-2	185–595	1–3
Pulp and paper	5 854	6 382	9	72–441	1–7
Total	33 339	33 206	0	327–1 260	1–4

Sources: Author's own elaboration based on chapters 5.2.1 to 5.2.2.

Investment requirements, 2050

- To produce primary processed wood products to meet the future demand of 3.1 billion m^3 RWE in 2050, the required investments to set up new production units and modernize existing industries may amount to USD 25 billion per annum from 2020 to 2050.
- In view of historical trends of increasing the wood processing capacities in emerging economies and improving IRW availability from plantation forests in these regions, the required investment volumes will be increasingly allocated in emerging world regions.
- The investments required to provide industrial roundwood are estimated at USD 40 billion per annum, of which USD 24 billion will be allocated to naturally regenerated production forests and USD 16 billion to establish and replant forest plantations.
- This estimate is subject to a variety of factors including commercial aspects and the use intensity of wood residues rather than roundwood and policy driven factors supporting or restricting the use and establishment of forest areas.
- The additional investment requirements to produce mass timber and MMCF to substitute for non-renewable materials may be between USD 1.4 billion and USD 2.5 billion per annum.
- Providing the related industrial roundwood supply from forest plantations would require another USD 1.4 billion to 4.5 billion in investments per annum.

TABLE 18.
Summary table of selected key results for investment requirements, 2050

Forest category	Annual investment requirements 2020–2050 (USD billions)		Increase in investment requirements due to substitution of non-renewables (percent)
	... to meet basic IRW outlook demand	...for exemplified substitution of non-renewable materials (lower and upper estimate)	
Natural regenerated forests	24	–	0
Plantation forests	16	1.4–4.5	9–28
Wood processing industries	25	0.6– 2.5	2–10
Total	66	4.5–7.0	7–11

Sources: Author's own elaboration based on chapters 5.3.1 to 5.3.3.

5.2. EMPLOYMENT REQUIREMENTS IN THE FOREST SECTOR, 2050

The employment data presented in the following sections are based on the results of recent studies on employment in the forest sector. The outlook estimates for the year 2050 do not disaggregate for formal and informal employment since the actual knowledge about informality in the forest sector remains weak and would not allow for projecting trends into the future. However, recent studies indicate that informal employment in the forest sector may amount to around 80 percent in Africa and Asia, around 50 percent in the Americas (including Northern and South America) and 23 percent in Europe (Lippe, Cui and Schweinle, forthcoming).

5.2.1 Employment requirements in forestry and logging

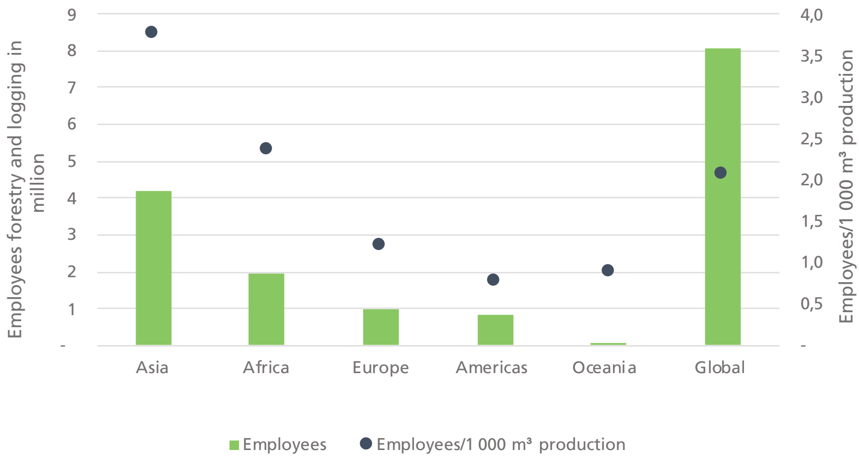
Total employment in forestry and logging was estimated to be about 12.5 million employees in 2015 (FAO, 2020). A forthcoming study indicates that employment in forestry and logging was 8.1 million in 2019 (Lippe, Cui and Schweinle, forthcoming). Most recent ILO data show the highest employment in forestry and logging in Asia (around 6 million) and Africa (around 2 million) (Figure 36).

These figures include formal and informal employment as recorded by the ILO. Informal employment may be substantially higher, i.e. related to fuelwood and charcoal production in Africa and in some Asian countries (Lippe, Cui and Schweinie, 2022).

Since 1990, employment has decreased in all world regions except for South America and Africa. The generally decreasing trend has been explained by declining wood production in some regions, for example in Europe's post-1990 transition economies and in Northern America due to post-2008 market distortions. Further, labour and forest productivity has increased leading to less employment required per roundwood unit. Whereas in Africa and partly in South America, roundwood production increases over-compensated-for productivity increases (FAO, 2020).

Assessing labour productivity on roundwood production remains difficult since statistical data on forestry and logging employment is still weak in many countries, that is informal employment and employment data related to fuelwood production in emerging economies is fragmented (FAO, 2020). Still, generating employment factors based on statistical data supports estimating potential pathways for future developments. Based on roundwood production and employment recorded by the ILO (Lippe, Cui and Schweinie, forthcoming). labour productivity on roundwood production is around 1 employee per 1 000 m^3 roundwood production in regions where mechanized forest operations are wide-spread (Europe, the Americas). On the other hand, the average roundwood employment factor in Asia is 3.8 and 2.4 in Africa per 1 000 m^3 (Annex 8.19).

Figure 36. Regional employment and employment factors in forestry and logging, 2019



Sources: Based on FAOSTAT Forestry for roundwood production, and for employment on Lippe, R.S., Cui, S. & Schweinle, J. (forthcoming). *Contribution of the forest sector to total employment in national economies*. Rome, FAO.
Note: data on employment provided as average for the years 2016 to 2019 (Annex 8.19.)

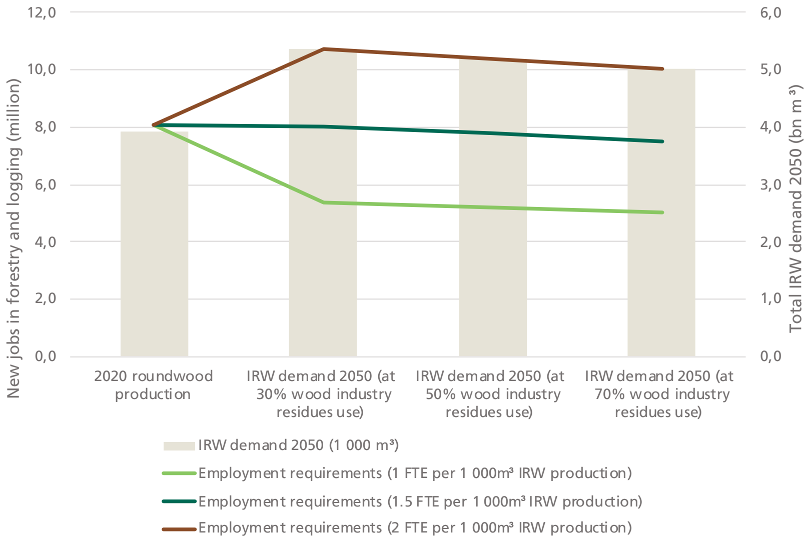
The long-term projection of employment in forestry and logging is subject to several uncertainties such as the total volume of roundwood demand as a function of the use of wood residues substituting for virgin roundwood (see chapter 3.3), and the productivity of forest management and plantations (see chapter 3.5.3).

The following outlook figure illustrates how employment in forestry and logging may evolve considering 1) varying volumes of industrial roundwood production due to enhanced use of wood industry residues, and 2) increase of labour productivity.[34] It considers the total volume of roundwood production in 2050 including industrial roundwood and fuelwood. The authors acknowledge that in 2050 substantial volumes of fuelwood may be collected for subsistence. Thus, the outlook may be distorted.

If IRW demand growth would be produced according to industry best practice (around 1 employee per 1 000 m³ IRW production), employment requirements in forestry and logging would decline to around 5 million. Assuming lower productivities, the employment requirements increase to 10 million.

[34] The productivity of operations combines the productivity of forest growth (due to forest management, and biological growth of species and planting material) and the productivity of the labour force (due to training, mechanization).

Figure 37. Employment in forestry and logging in 2020 and 2050 considering varying intensities of labour productivity increase



Sources: Based on chapter 3.2 for IRW demand and fuelwood consumption of about 2.5 billion m³ (chapter 4.2.1) and (Annex 8.20).
Note: full-time equivalent (FTE).

5.2.2 Employment requirements in wood processing industries

In 2019, there were 25.3 million people formally and informally employed in the wood industries[35] and pulp and paper industries (Figure 38) (Lippe, Cui and Schweinle, forthcoming).[36] Employment has reduced from 29.9 million in 2013.

The computed labour productivity in wood industries and pulp and paper is high in Europe, the Americas[37] and Oceania (<5 employees per 1 000 m³ IRW intake), whereas it is particularly low in Asia and Africa (>20 employees per 1 000 m³ IRW intake) (Figure 39).

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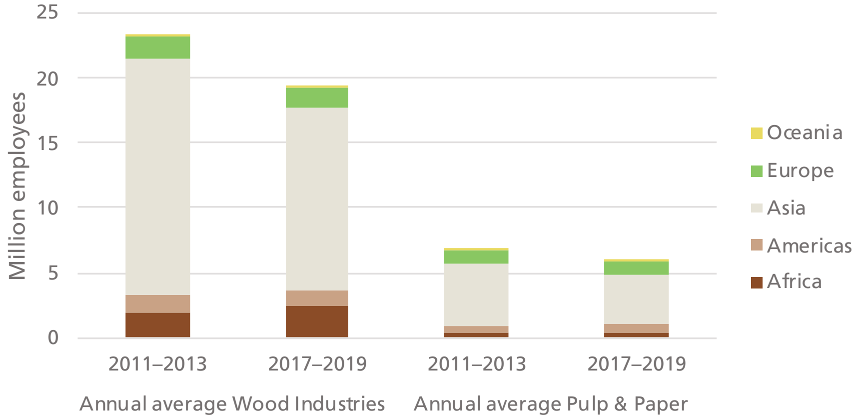
[35] Production of sawnwood and wood-based panels, excluding furniture.

[36] The cited figures do not disaggregate according to formal and informal employment but use an approach to assess the total forest sector related employment. There is no comprehensive analysis available on the scale of informal employment in the forest sector, but estimates suggest it may be up to 80 percent in emerging economies (Cui, Lippe and Schweinie, 2022). Most informal employment is likely to occur in forestry and logging, but also in micro-enterprises and among the self-employed in wood processing enterprises. The essential criteria for distinguishing formal and informal jobs is whether they are subject to labour legislation and income tax or entitled to social protection or not (Hussmanns, 2004).

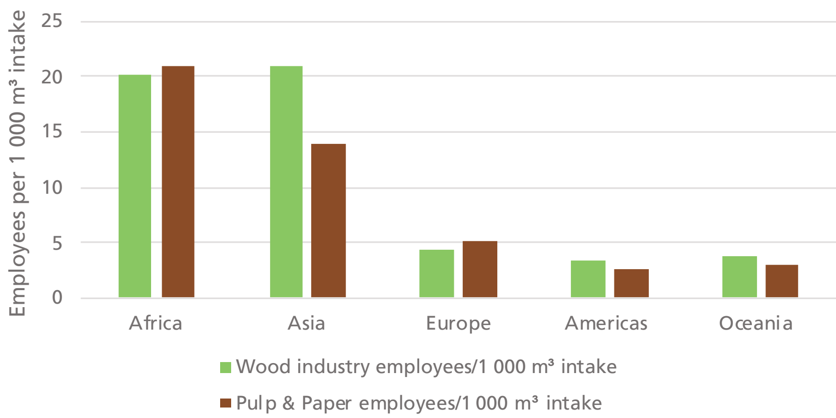
[37] Includes Northern, South and Central America.

Figure 38. Employment in wood industries and pulp and paper, 2019



Source: Based on Lippe, R.S., Cui, S. & Schweinle, J. (forthcoming). *Contribution of the forest sector to total employment in national economies*. Rome, FAO.

Figure 39. Labour productivity in wood industry and pulp and paper, 2019

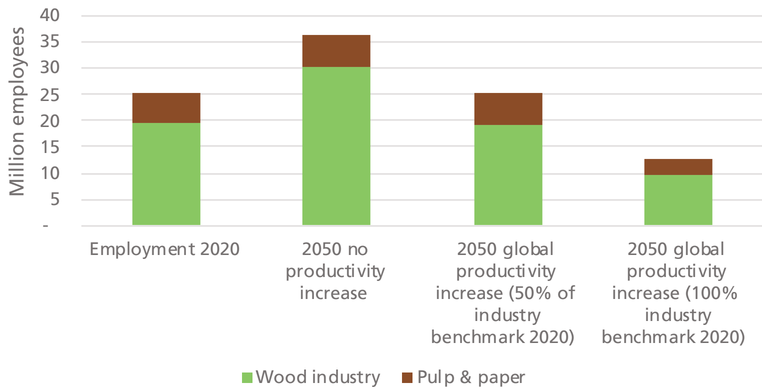


Sources: Based on 2019 production for wood industry (sawnwood and wood-based panels) and wood pulp (FAOSTAT Forestry) and employment data by Lippe, R.S., Cui, S. & Schweinle, J. (forthcoming). Contribution of the forest sector to total employment in national economies. Rome, FAO. (Annex 8.21).

Considering the GFPM simulation results for 2050 (chapter 2.3), the global wood processing industries will have to expand intake capacities by around 0.8 billion m^3 by 2050 (Figure 6). Figure 40 illustrates possible trajectories in the development of employment in wood industries and pulp and paper, drawing on wood products consumption simulations of the GFPM (chapter 2.4).

Assuming no labour productivity increases by 2050, employment would increase by around 11 million jobs (Figure 40). However, productivity gains, changing market requirements and the modernization of the forest industries may lead to a decrease in employment. If the total global labour productivity achieved the productivity levels of industrialized regions by 2050, employment would drop by about 11 million jobs compared to 2020 levels. In a scenario with a medium productivity increase, employment would remain at the 2020 level.

Figure 40. Outlook of employment requirements in wood industries and pulp and paper to 2050 considering varying scenarios of labour productivity



Sources: Based on GFPM, FAOSTAT Forestry, and Lippe, R.S., Cui, S. & Schweinle, J. (forthcoming) *Contribution of the forest sector to total employment in national economies*. Rome, FAO. (Annex 8.22).

5.3. INVESTMENT REQUIREMENTS IN THE FOREST SECTOR, 2050

As noted in previous chapters, there are several factors (mainly enhanced use of wood residues, productivity changes of natural and planted forests, and policy driven use restrictions) that may alter future IRW supply and the contribution shares from naturally regenerated forests and plantations. Thus, the estimation of investment requirements in forestry for future industrial roundwood production draws on the simplified assumptions that the production area in naturally regenerated forests remains stable between 2020 and 2050, while forest plantation areas will grow by about 30 million ha (in line with most conservative estimates in chapter 3.5.2).

The investment requirements outlook in wood industries and pulp and paper are based on industry benchmarks for modern industrialized SMEs. Acknowledging that in 2050 primary wood products will also be produced by less industrialized micro and small enterprises, the outlook figures are subject to inaccuracies. The investment requirements to substitute for non-renewable materials considers only the products as exemplified in the previous chapters. The future requirements may be substantially higher if other innovative wood products expand their market shares.

5.3.1 Investment requirements in naturally regenerated forests for industrial roundwood production

The investment requirements in future timber production from naturally regenerated forests are subject to a variety of factors that include policy driven factors induced by climate change mitigation/adaptation and biodiversity conservation strategies. Publicly owned naturally regenerated forests, which are important sources of timber, will increasingly be managed for enhancing carbon sequestration, biodiversity and social benefits (WEF, 2021).

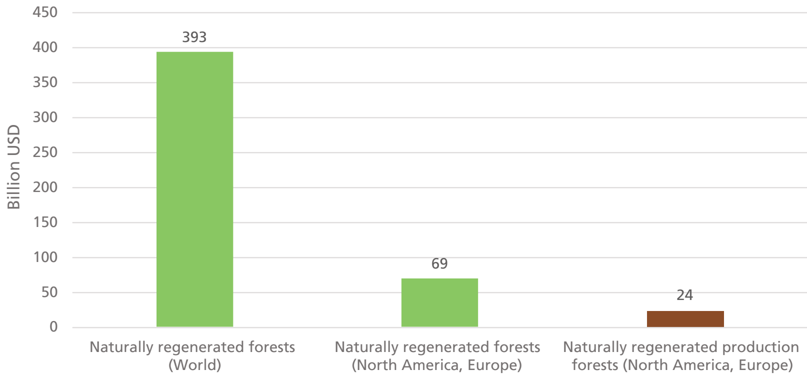
In recent years, several studies were published that estimate the investment volumes required to halt deforestation and maintain the world´s forest ecosystem functions. UNEP (2021) estimates annual investment requirements in forests of USD 403 billion up to 2050 (including re/afforestation, mangrove and peatland restoration, and silvospasture). McKinsey (2021) indicates annual investment requirements of USD 500 billion in the forest sector to meet climate change requirements. However, UNEP and McKinsey do not explicitly consider the impacts on future timber production. Austin *et al.* (2020) estimates the global average annual investment requirements amounting to USD 393 billion up to 2055 in scenarios that gradually optimize carbon sequestration benefits while providing timber to the markets.

In the following, the data of Austin *et al.* (2020) is used to assess the investment requirements in naturally regenerated forests, since it provides a detailed breakdown by global geographies and explicitly addresses timber production as a production target.

The investment volumes provided by Austin *et al.* (2020) include activities to avoid deforestation, to improve sustainable forest management, to increase rotation periods and to restore forest landscapes. Most of these investment requirements (USD 320 billion per annum) would be allocated to emerging world regions (mainly tropical and sub-tropical forest conservation and rehabilitation). Due to the comparatively low contribution of these forests to future global timber production (chapter 3.5.1), the required investments in these geographies are not a direct indicator for commercial timber production investment needs in naturally regenerated forests.

However, the indicated investment requirements of approximately USD 69 billion per annum in Northern American and European forests is a good proxy for the timber production related investment requirements, since these forests will supply substantial roundwood volumes in 2050. Since about 27 percent of the naturally regenerated forest in Northern America and 47 percent in Europe are designated production forests, the relative share of annual investment requirements on naturally regenerated forests producing industrial roundwood amounts to USD 24 billion.

Figure 41. Annual average investment requirements in naturally regenerated forests, 2055



Sources: Authors' own elaboration based on forest area (FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome) and investment requirements (Austin, K., Baker, J.S., Sohngen. B.L., Wade, C.M., Daigneault, A., Ohrel, S.B., Ragnauth, S. & Bean., A. 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nature Communications*) (Annex 8.23).

5.3.2 Investment requirements in plantation forests for industrial roundwood production

The investment requirement etsimates in plantation forests for timber production can draw on industry benchmarks, though variations across regions, species and production systems (small to large) can be substantial.

The global plantation forest area for timber production is likely to increase by at least 30 million ha by 2050 (compare also chapter 3.5.2 on area requirements and Korhonen *et al.* [2021] and Austin *et al.* [2020]).[38] Thus, the total plantation forest area in 2050 may increase to about 161 million ha by 2050.

The establishment costs[39] of the most important plantation species (pines and eucalyptus) range between USD 500 and USD 1 200 per ha (excluding cost for land).[40] Hence, initial investments would amount to USD 240 billion. Assuming an average 12-year rotation period,[41] the average annual investment in plantation forests will be approximately USD 16 billion. This figure considers the total expected plantation forest area of 161 million ha.

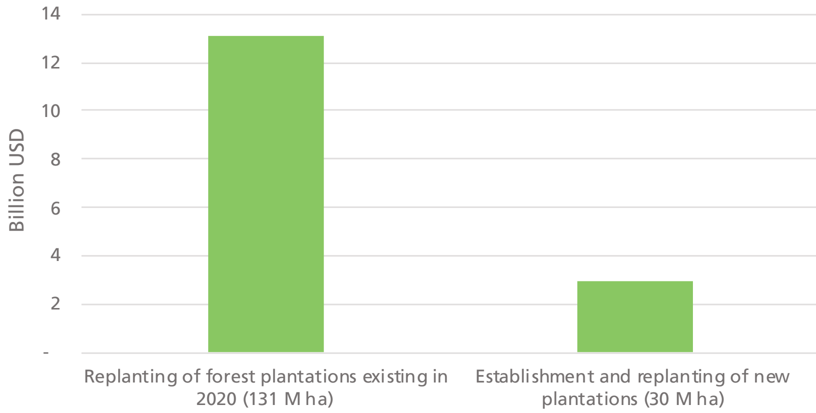
[38] Also Austin *et al.* (2020) calculates a minimum increase of approximately 24 million ha in their model scenario, and the maximum plantation area increase is 82 million ha.

[39] Including all costs until the plantation is secured, and excluding the purchase of land.

[40] In fact, the range of establishment costs can be wider, that is, the establishment in smallholder systems is typically lower, since it is less intense and labour costs are not fully reflected. At the lower end, higher costs may occur in industrial plantations in countries with labour and factor costs.

[41] Acknowledging that rotations for high productive pulp logs may be only 6 years, while sawlog regimes in some regions may last 18 years and more.

Figure 42. Average annual investment requirements in plantation forests, 2020 to 2050



Sources: Based on global plantation forest area and share of naturally regenrated forest area designated for production 2020 from FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome. Estimate for plantation investments based on industry practice (Annex 8.24).

Box 7
Possible additional investment and employment requirements in forestry to supply industrial roundwood in substitution for non-renewable materials

As discussed in chapter 2.4, the additional volumes to substitute for selected non-renewable materials may range between 46 million m³ and 149 million m³ in 2050 (Figure 23).

The investment requirements to meet a potentially increasing demand for substitutes for non-renewable materials will be influenced by a variety of issues: forest management and conservation policies, market mechanisms and factor cost, incentives and environmental factors.

Investment requirements in roundwood production would mainly be triggered by saw/veneer log, while shares of the potential demand for dissolving pulp to produce MMCF could be met through an enhanced use of wood residues.

The required IRW volumes could be sourced from additional primary production in plantations or in naturally regenerated forests. The limitations of enhancing production in naturally regenerated forests are discussed in chapter 3.5.3. At the other extreme, all additional wood for this purpose could be produced from plantations (in this case high yielding and short rotation for pulp log production).

Drawing on the simplified assumption that all IRW required for additional IRW for non-renewable material substitution will be produced in plantations, the annual investment requirements up to 2050 may range between USD 1.4 billion and USD 4.5 billion (see Annex 8.24 for details). The required investments would be an increase of 9 percent to 28 percent compared to the investment requirements in forest plantations under baseline assumptions. Additional employment requirements in plantation forestry may amount to around 200 000 jobs.

* Growth rates in industry plantations for pulp and fibre are > 40 m^3 ha per annum.

5.4. INVESTMENT REQUIREMENTS IN WOOD INDUSTRIES

The investments in wood processing industries up to 2050 will have to consider the expansion of new production capacities and modernization of existing units.

Global intake capacities will increase by approximately 0.8 billion m^3 (RWE) by 2050 (Figure 6). The required investments to set up production expansion to meet consumption growth are estimated at almost USD 200 billion.[42]

In addition, the existing wood processing capacities in 2020 amounted to 2.2 billion m^3 RWE, which will require modernization during the forecast period. The forecast period of 30 years covers two investment cycles (typcially15 years each).[43] Within this time frame the existing industries will undergo complete replacement, modernization and upgrading of the main equipment. The total related investments may accumulate to USD 570 billion.

In total, the investment requirements over the coming three decades will amount to USD 760 billion. This translates to an average annual investment need of USD 25 billion per annum from 2020 to 2050 (Figure 43).

Where expansion and industry investments will be realized remains subject to various factors such as the availability of the raw material, market access and the investment enabling environment. Hence, increases in major wood product consuming regions (e.g. Eastern Asia) may trigger investments and employment within the region, but also abroad.

FAO (2020) indicates that 53 percent of the primary wood products were produced in industrialized world regions. This share has reduced from 74 percent in 1990, due to the strong growth of Asian and Latin American processing capacities. This trend suggests that investments will be increasingly required in emerging economies. This is also supported by trends in industrial

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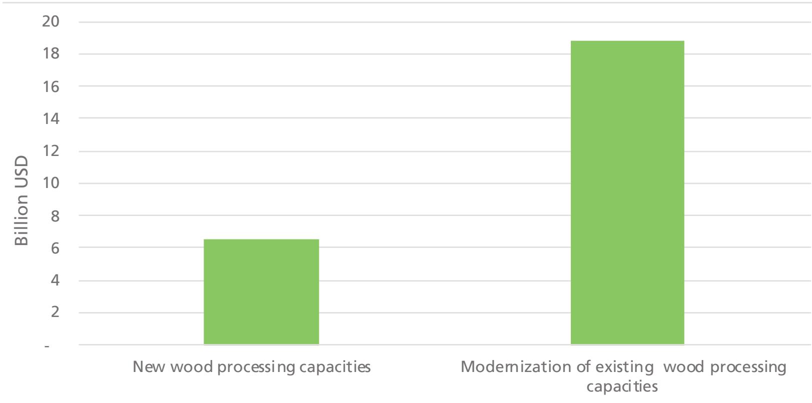
42 Investment requirements in pulp and paper only consider investments related to units that produce wood pulp.

43 Investments in large scale food industries and pulp and paper are typically depreciated over a lifetime of >15 years. Modernization is an ongoing process. However, substantial upgrades or replacements of the main equipment usually takes place towards the end of the depreciation period.

roundwood supply, which will be increasingly met by plantations in emerging world regions (chapter 3.5).

Figure 43. Global investment and modernization requirements in primary wood processing industries, 2020 to 2050



Sources: Calculations based on: Global Forest Products Model consumption simulations for primary processed wood products 2050 and FAOSTAT Forestry for production 2020.
Note: Average Capex per 1 m³ per annum IRW intake for log processing = USD 200. Average Capex per 1 m³ per annum IRW intake for wood-fibre processing = USD 300 (Annex 8.24.)

Box 8
Will the employment and investment requirements for substituting for non-renewable materials differ from conventional wood industry requirements?

Wood product volumes required to substitute for non-renewable materials will trigger additional employment in the forest sector. To a certain extent, these wood products will generate relatively more employment per m³ of industrial roundwood intake than actual wood industry processes. This is especially the case in the production of EWPs and mass timber products.

The following analysis compares actual best practices in medium to large wood industries.

The production of CLT is based on reassembling sawnwood products. The required additional processing lines require between 0.5 to 1 employee per 1 000 m³ RWE intake (based on Quesada, Smith and Berger [2018]). The results in a total employment factor for CLT production of 4.5 to 5 employees per 1 000 m³ RWE intake: approximately 30 percent higher than the actual employment factor of 4 employees per 1 000 m³ RWE intake in wood industries (see Annex 8.19).

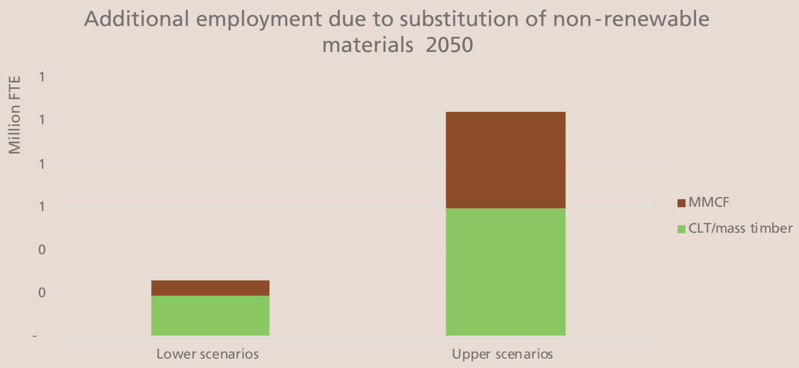
Obviously, investment requirements of CLT production will also be higher. The investment volumes include the sawmilling lines plus secondary processing lines for jointing. The total investment volume is 50 percent to 100 percent of the investment for a pure sawmill. The proxy investment factor for CLT would be around USD 300 to 400 per m³ RWE annual intake (based on a review of CLT producing companies), compared to USD 200 per m³ RWE for pure sawmills (see Annex 8.24).

On the other hand, the production of MMCF for textile production is based on dissolving pulp. Employment and investment requirements are the same as for wood pulp production for paper production: 4 employees per 1 000 m³ RWE intake; USD 300 per m³ RWE annual intake.

The following figures show the employment and investment requirements based on demand growth assumptions explained in chapter 2.4.

Employment impact could be between 0.3 and more than 1 million full time equivalents. The required investments would amount to USD 18 billion to 75 billion.

Figure 44. Additional employment and investment requirements due to substitution of non-renewable materials



Notes: Based on employment factor 5 employees per 1 000 m³ RWE annual intake in CLT mass timber and 4 employees in dissolving pulp. Investment requirements: 350 USD per m³ RWE annual intake in CLT/mass timber and USD 300 in dissolving pulp. Future wood product volumes to substitute for non-renewable materials as explained in chapter 2.4 (Annex 8.25).

6. Conclusions

The global threats to climate, biodiversity and a healthy environment are mainly caused by the excessive use of non-renewable materials. This has led to political interventions to accelerate the decarbonization of economies and to introduce a circular bioeconomy. In several countries such initiatives and programmes are planned or are already in implementation (Verkerk *et al.*, 2022; FAO and UNECE, 2022).

As a result, the forest industries outlook in this study will experience variations as a function of the effectiveness of these measures and their impact on availability and prices for competing non-wood materials. These are mainly oil-based products and mineral and metallic construction materials. The global resources of these raw materials are projected to decrease while prices are expected to increase (OECD, 2018). Further, decarbonization tools like carbon budgets, carbon pricing and carbon taxes will influence the demand for renewable products and products with a low carbon footprint (Howard *et al.*, 2022).

Wood products that may experience substantial increases due to their increasing use as a substitution for non-renewable materials will be used mainly in the construction sector and to substitute for mineral oil-based polymers (such as plastics and polyester fibre). The forest sector has developed and introduced suitable products for these markets, though production capacities are still small and production prices are often not yet competitive.

The most promising wood products for large scale substitution uses are mass timber and engineered wood products in construction and man-made cellulose fibre for textile production (Verkerk *et al.*, 2022). This study focuses on these products to illustrate the potential impact of an enhanced demand for wood in a sustainable economic context.

The demand for these wood products as analysed in this study may increase up to 230 million m^3 per year. This reflects an increase of approximately 8 percent above the basic outlook up to 2050. The related investments in forestry and industries may amount to as much as USD 7 billion per year to 2050. Other studies, drawing on different assumptions and development pathways (such as UNECE and FAO [2021]) suggest even higher demand growth for these and other innovative wood products for the bioeconomy. Thus, the results may be seen as a conservative approximation of future trends, considering the high levels of uncertainties in this dynamic field.

Balancing policy targets and enhancement of forest productivity will be required to meet future demand for industrial roundwood.

The basic outlook for primary processed wood products consumption of 3.1 billion m³ RWE in 2050 indicates an increase of 37 percent compared to 2020. The projected growth is higher than growth observed for the 30-year period 1990 to 2020 (+28 percent). This, despite population growth in the 2020–2050 period (+25 percent) will be lower than during the 1990–2020 period (+46 percent). The disproportional growth of wood products consumption will be driven by higher incomes in emerging world regions resulting in catch-up effects for consumer goods (e.g. paper, packaging, clothing and furniture) and in more construction sector activities.

The demand for substitutions for non-renewable materials as analysed in this study (mass timber and man-made cellulose fibre) may increase by 272 million m³. Other studies suggest even higher growth rates (UNECE and FAO, 2021).

The effort required to meet future demand will be challenging, i.e. providing sustainable roundwood and allocating the required investments in forestry and industries.

The production of IRW has reached almost 2 billion m³ in 2020. Depending on the use intensity of wood industry residues, future IRW demand may grow between 0.5 billion to 0.9 billion m³ by 2050 compared to 2020 IRW consumption.

Although this study has not identified global industrial roundwood supply gaps to meet basic outlook demands, future supply is prone to uncertainties resulting from policy interventions in natural regenerated forests and the productivity of planted forests.

This study shows that supplying future demand may be achieved by a combination of an increase in naturally regenerated temperate and boreal forests and of planted forests (increasingly in the global South).

The forest area and growing stock in temperate and boreal naturally regenerated forests is expected to increase, suggesting the possibility of increasing timber production in these regions (UNECE and FAO, 2021). However, increasing production levels will strongly depend on the political decisions taken to mitigate and adapt to climate change and to stop biodiversity loss. Carbon sequestration and biodiversity targets will most likely restrict increasing timber production. Some scenarios even indicate decreasing production volumes if non-timber benefits are prioritized (Dieter, Weimar and Iost, 2020). Further, climate change itself may cause volatility of IRW availability of species prioritized by markets due to disturbances (wind, fire, diseases) and due to a natural shift in harvest amounts from softwood to hardwood (though it is unlikely within the forecast period) (Knauf *et al.*, 2015).

Potential reduction in naturally regenerated forest supply strengthens the outlook that plantation production will need to increase.

The forest area that contributes to the production of IRW could be substantially increased by proactively integrating commercial timber production in FLR approaches and agroforestry practices in the tropics and sub-tropics. The estimates of this study indicate that the area required for expansion would be at least 33 million ha. Nevertheless, this study emphasizes that expanding planted forests requires substantial efforts and investments (compare the section on investments and employment). Consequently, improving the productivity in existing planted forests offers an opportunity to increase production. This study suggests that the potential for productivity gains can be substantial as the actual gap between low and high performing planted forests is significant. High performing plantations produce six to eight times more IRW compared to the global average production of planted forests at 2.7 m^3 ha per annum (Payn *et al*., 2015).

It will be crucial to improve the enabling environment for forestry to ensure that the overall value chain performance increases. Smallholder producers and communities often require support to start their forestry activities. They often lack access to capital as forestry typically requires its finance in the early phase and has a long pay-back period. Furthermore, weak market linkages and poor access to market information are limiting factors for smallholders. Such constraints can be at least partly offset by assisting producers to form tree grower associations or cooperatives, which can provide technical support to improve production and market information, thereby strengthening their bargaining position (Castrén *et al*., 2014).

Meeting the demand for future wood products will require increasing capital allocation in emerging world regions and a well-trained work force

This study estimates that investments required to maintain existing plantations and establish new ones (around 30 million ha) would require annual investments of USD 16 billion by 2050. The investments related to maintaining timber production in temperate and boreal naturally regenerated production forests, while enhancing carbon storage and biodiversity co-benefits, may require approximately USD 24 billion per annum by 2050.

To meet the growth in wood products consumption, this study estimates that the required industry investments in expansion and modernization are estimated at USD 760 billion or USD 25 billion per annum from 2020 to 2050. In case of increasing demand for materials to substitute for non-renewable materials, annual investment requirements in forestry and industries may increase by another USD 4.5 billion to 7 billion.

Financing for the required annual investment will have to be negotiated between the public and the private sector, depending on the ownership of naturally regenerated production forests.

The investment requirements in future timber production and related forest management are subject to a variety of factors that not only include commercial aspects, but also policy driven factors induced by climate change mitigation/adaptation strategies, for example, publicly owned forests that are important sources of timber from naturally regenerated forests in tropical, temperate and boreal zones, may increasingly be managed for enhancing carbon sequestration, biodiversity and social benefits.

As future demand is projected to be highest in emerging markets and the potential for roundwood production is significant in tropical and sub-tropical regions, it appears likely that forest industry establishment might increasingly occur in these regions.

Obtaining the required investment in modern industries in these regions will have to consider the capitalization of domestic enterprises. A critical mass of technology-driven start-ups and SMEs is required to build future modern companies that can attract larger equity investments. This requires the formalization of enterprises and the creation of investment accelerators. Financing products are needed that meet the specific needs of the forest sector, such as recoverable or convertible grants or subordinated loans. The process of building, formalizing and capitalizing enterprises should be accelerated in existing clusters with structures of raw-material supply and multilevel processing (Castrén *et al*., 2014).

The production in forestry and wood industries to meet future demand will not necessarily result in a significant increase in employment in the sector. This study suggests that productivity gains, changing market requirements and the modernization of forest industries may even lead to decreasing employment in 2050. A mid-case estimate suggests that employment may remain rather stable at the 2020 level (total of about 32 million employees in the forest sector).

Increasing demand for material to substitute for non-renewable material may have reverse effects and may lead to increasing employment figures. The examples calculated in this study indicate additional employment requirements of up to 1 million jobs.

The actual forest sector employment numbers in emerging economies are comparatively higher than in industrialized world regions (Lippe, Cui and Schweinie, 2022). This is caused by lower levels of mechanization in forestry and industry processes, resulting in labour productivities that are 5 to 10 times lower than in industrialized regions. Further, the lower labour costs, poorer access to capital and higher levels of informality, create a low-tech and low-wage environment that is based on a manual workforce rather than on industrial economies of scale (UNECE, 2020a).

In the future, the labour requirements of modern wood industries will be more sophisticated, and ensuring sufficient well-trained personnel will require solid education and training. Most forest sectors in emerging economies already lack sufficient qualified workforces, and the forest sector must compete with other industries for talent at the management and production levels (UNECE, 2020b). The pool of future workers in the wood industries will require skills in information technology for computer-aided design, robotics and e-marketing.

Meeting future wood fuel demand will require efforts in optimized resources allocation and a clear political vision of the contribution of wood fuel to the renewable energy mix in 2050.

The global consumption of wood fuel has increased by almost 100 million m^3 between 1990 and 2020. However, across all world regions, per capita consumption has decreased and typically ranged between 0.1 and 0.3 m^3 per capita and year in 2020. Although per capita consumption has substantially declined in sub-Saharan Africa, the actual per capita consumption of 0.6 m^3 per year is far above the global average. By the end of 2020, 2.3 billion people still relied on wood fuel as their primary source of energy for cooking and heating (IEA, 2021a).

The outlook of wood fuel in the future energy mix is subject to much higher levels of uncertainty than for solid wood products. This is because the trajectory of wood fuel use will be shaped by 1) its future role in the renewables energy mix, which is under discussion, is controversial and may result in a substantial increase in demand, and 2) the subsistence needs of growing populations in emerging economies that vary in function of income growth and energy infrastructure expansion. Only minor changes of the relevant factors cause substantial deviations in the long-term consumption outlook.

The global wood fuel outlooks 2050 provided by relevant institutions (IEA, IPCC) suggest a wide variation of scenarios ranging from a 19 percent decrease to a 400 percent increase in consumption compared to 2020 levels. These variations are caused by the underlying assumptions for the drivers influencing the future modern and traditional use of wood fuel.

In the industrialized economies, such as in Europe and parts of Eastern Asia, the modern use of wood biomass is promoted by climate change mitigation policies and has led to increasing use by households and industries. In Europe, for example, wood biomass is the most important bioenergy source and in major Asian economies like Japan and the Republic of Korea, a fuel switch strategy of their coal-fired energy infrastructure is drawing on imported biomass (Junginger, Koppejan and Goh, 2020).

However. the promotion of forest biomass as a renewable energy source in industrialized economies is increasingly challenged by the scientific community, which indicates that the use of forest biomass is only meeting carbon neutrality targets under strict considerations of sustainability, accounting and efficiency criteria (see Norton [2019]).

Further, the use of virgin wood fuel from natural regenerated and planted forests is facing competition from solid wood products demand, which is offering higher societal economic impacts in terms of generating employment and adding value. Hence, the use of wood biomass in these regions is subject to high levels of uncertainty, including questions about how reliable import streams (e.g. for wood pellets) will be in the long run and whether future sourcing areas may shift to other world regions (e.g. from Northern to Latin America and the Caribbean).

On the other hand, the traditional use of fuelwood is expected to increase in sub-Saharan Africa and Southern Asia (IEA, 2019), (Pappis *et al.*, 2019). Though per capita consumption has reduced due to the sustained economic growth and expansion of energy infrastructure, it has not been sufficient to halt population growth driven increases of total consumption volumes (UNEP, 2019a).

Meeting the future demand of traditional wood fuel use without compromising the sustainability of remaining ecosystems will require the pro-active management of fuelwood resources. This includes improving the governance of fuelwood collection and trade by establishing structural changes and targeted regulatory measures including secure tenure for individuals and communities, enforceable permit systems and management plans, and taxation systems that reward sustainable fuelwood management (UNEP, 2019a).

Regardless of the actual wood fuel volumes that will be required, there is need to optimize resources allocation for wood fuel production. In view of the expected growing demand in emerging economies, this study sees opportunities for expanding the area of fuelwood woodlots, and agroforestry systems will have to be aligned with forest landscape restoration initiatives. Wood fuel sourcing in industrialized world regions that are predominately located in temperate and boreal zones with naturally regenerated forest resources should be concentrated on planted forests and industry residues that cannot be utilized elsewhere in wood industries (Norton, 2019).

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8. Annex

8.1. GLOSSARY OF TERMS

Agroforestry: “Other land with tree cover” with temporary agricultural crops and/or pastures/animals. 1. Includes areas with bamboo and palms provided that land use, height and canopy cover criteria are met. 2. Includes agrisilviculturural, silvopastoral and agrosilvopastoral systems.

Bioeconomy: 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 and enable a transformation to a sustainable economy.

Deforestation: The conversion of forest to other land use independently, whether human-induced or not.

Industrial roundwood: All roundwood except wood fuel. In production statistics, it is an aggregate comprising sawlogs and veneer logs; pulpwood, round and split; and other industrial roundwood.

Planted Forest: Forest predominantly composed of trees established through planting and/or deliberate seeding.

Plantation Forest: Planted Forest that is intensively managed and meets ALL the following criteria at planting and stand maturity: one or two species; even age class; and regular spacing.

Plywood: A panel consisting of an assembly of veneer sheets bonded together with the direction of the grain in alternate plies generally at right angles. The veneer sheets are usually placed symmetrically on both sides of a central ply or core that may itself be made from a veneer sheet or another material.

Roundwood: All roundwood felled or otherwise harvested and removed. It comprises all wood obtained from removals, i.e. the quantities removed from forests and from trees outside the forest, including wood recovered from natural, felling and logging losses during the period, calendar year or forest year. 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

Sawnwood: Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness. It includes planks, beams, joists, boards, rafters, scantlings, laths, boxboards and "lumber", etc. in the following forms: unplaned, planed, end-jointed (for example finger-jointed), etc.

Sustainable Forest Management: A dynamic and evolving concept, [that] is intended to maintain and enhance the economic, social, and environmental value of all types of forests, for the benefit of present and future generations.

Wood-based panels: This product category is an aggregate comprising veneer sheets, plywood, particle board and fibreboard. It is reported in cubic meters solid volume.

Wood fuel: Roundwood that will be used as fuel for purposes such as cooking, heating or to produce power. Wood fuels also include biomass derived from silvicultural activities (thinning, pruning, etc.) and harvesting and logging (tops, roots, branches, etc.), as well as industrial by-products derived from primary and secondary forest industries that are used as fuel. They also include wood fuels derived from ad hoc forest energy plantations. Wood fuels are composed of four main types of commodities: fuelwood (or firewood), charcoal, black liquor and other.

Wood Pulp: Fibrous material prepared from pulpwood, wood chips, particles, or residues by mechanical and/or chemical process for further manufacture into paper, paperboard, fibreboard, or other cellulose products. It is an aggregate comprising mechanical wood pulp, semi-chemical wood pulp, chemical wood pulp and dissolving wood pulp.

Source:
FAO Forest Resources Assessment 2020: Terms and definitions.

8.2. GLOBAL FOREST PRODUCTS MODEL

Key parameter setting World 500 simulation (02 October 2020)

- Base Year 2017
- Calibrated with GFPM-1-29-2017 static with smoothed FAOSTAT data 2016–2017–2018
- GDP and GDP/capita growth as in SSP2
- Forest area and stock and their growth rates, based on FRA2020
- Tariffs based on WTO 2013
- Linear technical change 1993–2010
- Fixed trade base year
- Import and export inertia based on 95 percent upper bound of growth rate 1992–2012
- Freight factors of 2011
- Revised supply other fibre pulp and wastepaper
- Fuelwood from forest=FRA 2010
- Demand elasticities 1992–2016 dynamic model pooled with trend long run
- Supply roundwood elasticities 1992–2016 pooled

The Global Forest Product Model

The outlook of primary wood products consumption in 2050 is based on simulations obtained from the GFPM.

The GFPM is a dynamic economic model of worldwide production, consumption and trade of forest products. It is a general-equilibrium model, which, for every year and country, simulates changes in forest area, stock, production, consumption and trade.

The GFPM's baseline projections for primary-processed wood products reflect moderate development paths and consider foreseeable megatrends (SSP2).

Minor edits were made to the GFPM's generic output numbers, but only when we discovered obvious data bugs, for example, when a country showed zero production or zero consumption (e.g. Nigeria, which was showing zero wood fuel production and consumption) by 2050. Where indicated by plausibility, an average annual growth rate based on historical data was applied.

Like every model, GFPM has its limitations in reflecting real-world dynamics. It should be understood as a strong reduction of a complex reality to envision certain aspects of the future. Developments in emerging markets are especially difficult to anticipate. Nonetheless, the GFPM is currently the only model that enables wood production and consumption projections at the country level while factoring in reciprocal effects of the resource base and market demand and considering global megatrends.

The most recent version (World 500) of the GFPM has been calibrated in October 2020 and draws on historical FAO production and consumption data.

Because this study comes at a time of global economic turmoil due to the COVID-19 pandemic and the war in Ukraine, the forecasts herein need to be contextualized carefully. The model configuration does not integrate 2020 production and consumption data and therefore does not take into account the impacts of the pandemic.

8.3. SHARED SOCIOECONOMIC PATHWAYS

Shared socioeconomic pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies. The scenarios have been used to produce the IPCC Assessment Reports on climate change.

The scenarios are:

- SSP1: Sustainability (Taking the Green Road)
- SSP2: Middle of the Road
- SSP3: Regional Rivalry (A Rocky Road)
- SSP4: Inequality (A Road Divided)
- SSP5: Fossil-fueled Development (Taking the Highway)

The most commonly used SSP2 is described as the "Middle of the Road" Scenario (Riahi, 2017): The world follows a path in which social, economic and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations.

Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and, overall, the intensity of resource and energy use declines.

For the model simulations of the GFPM (World 500) that was presented, the following two aspects are most relevant:

- Global population growth is moderate and levels off in the second half of the century.
- Income inequality persists or improves only slowly and presents a challenge to reducing vulnerability to societal and environmental changes.

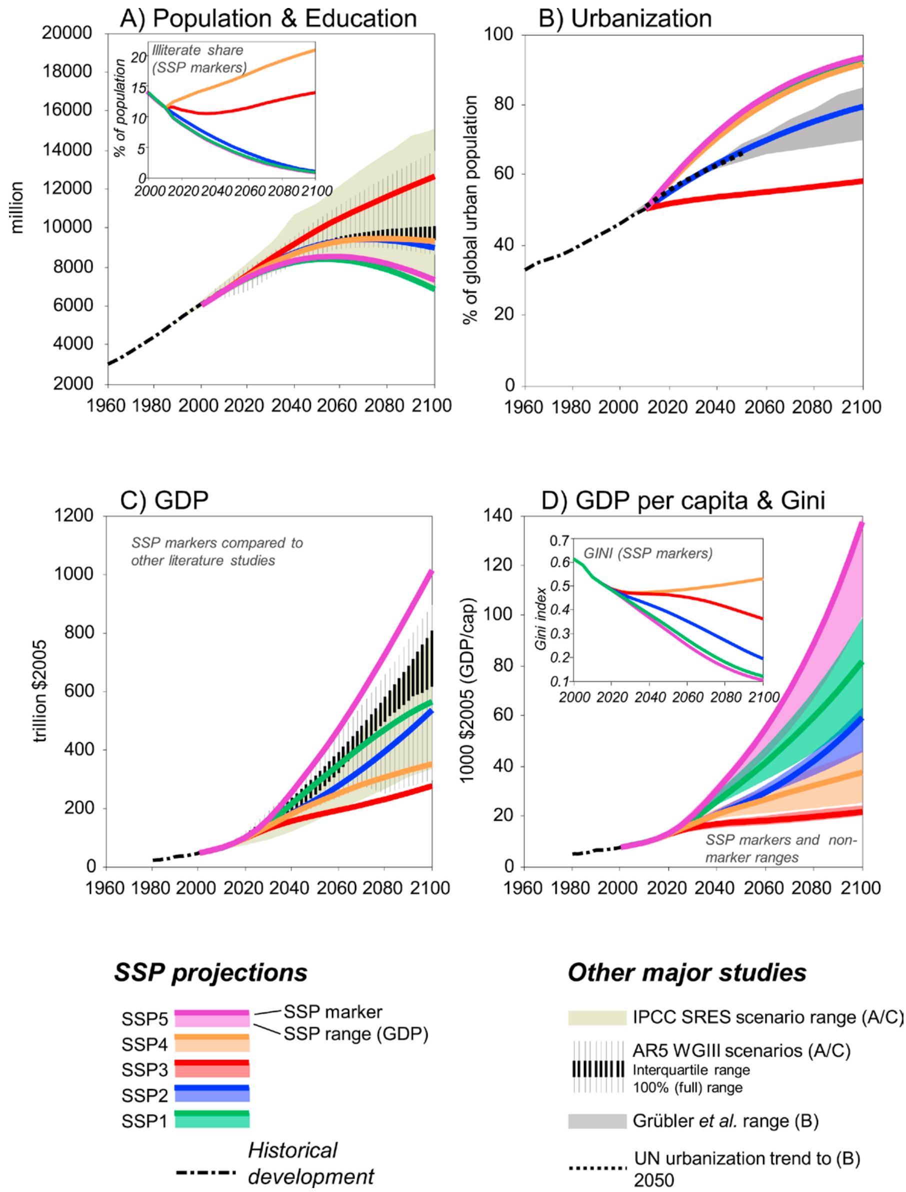
The SSPs provide narratives describing alternative socio-economic developments. These storylines are a qualitative description of logic relating elements of the narratives to each other. In terms of quantitative elements, they provide data accompanying the scenarios on national population, urbanization and GDP (per capita).

Qualitative descriptions, data sources and forecast approaches to be accessed at: https://tntcat.iiasa.ac.at/SspDb/static/download/ssp_suplementary%20text.pdf (Supplementary note for the SSP data sets).

The SSP scenarios and input data used in the presented GFPM simulation of 2020 were published in 2017 and are detailed in the following publications:

- Population: Samir, K.C., Wolfgang, Lutz. 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, 42: 181–192.
- ISSN 0959-3780, DOI:10.1016/j.gloenvcha.2014.06.004
- GDP marker projections by the OECD: Dellink, R. Chateau, J., Lanzi, E. & Magné, B. 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, 42: 200–214,
- ISSN 0959-3780, DOI:10.1016/j.gloenvcha.2015.06.004
- GDP projections by IIASA: Cuaresma, J.C. 2017. Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, 42: 226–236.
- ISSN 0959-3780, DOI:10.1016/j.gloenvcha.2015.02.012
- GDP Projections by PIK: Leimbach, M., Kriegler, E., Roming, N. & Schwanitz, J. 2017. Future growth patterns of world regions – A GDP scenario approach. *Global Environmental Change*, 42: 215–225.
- ISSN 0959-3780, DOI:10.1016/j.gloenvcha.2015.02.005
- Urbanization: Jiang, L. & O'Neill, B.C. 2017. Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, 42: 193–199.
- ISSN 0959-3780, DOI:10.1016/j.gloenvcha.2015.03.008

The following figures illustrate the pathways for the most relevant demographic and economic parameters of the five SSPs.



Sources: Various data sources as compiled in Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S. *et al*. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change.*

8.4. WOOD PRODUCTS CONVERSION FACTORS

Product	M³ RWE conversion
Industrial roundwood (m³)	1
Fibreboard (m³)	1.7
Particle board (m³)	1.51
Veneer sheets (m³)	2
Plywood (m³)	2
Wood pulp for paper (t)	4
Sawnwood (m³)	2
Wood charcoal (t)	5.96
Wood chips and particles (m³)	2.5
Wood-based panels (aggregate) (m³)	1.64

Source: Based on FAO & ITTO. 2020. *Forest products conversion factors.* Rome, FAO.

8.5. FAOSTAT DATA UP TO 2020 AND GFPM OUTPUT TABLES 2050 BY REGION

Sawnwood consumption 1 000 m³ (RWE)	1990	2000	2010	2020	2030	2040	2050
Eastern Asia	137 119	87 737	144 580	274 743	299 008	381 026	391 407
Southern Asia	39 341	19 612	19 662	21 965	31 430	36 516	40 023
South-eastern Asia	33 714	27 610	33 186	33 266	50 322	55 437	59 466
Northern Africa, Western & Central Asia	20 998	27 910	53 589	55 022	60 871	75 055	85 197
Sub-Saharan Africa	14 229	13 055	14 725	17 597	17 534	19 808	21 634
Latin America & the Caribbean	44 486	59 295	56 654	42 080	53 061	58 516	62 390
Europe	402 475	242 148	219 058	228 835	229 562	242 778	249 511
Northern America	233 373	281 061	186 511	239 845	250 900	263 363	274 547
Oceania	12 933	15 201	15 667	15 804	17 607	20 026	21 417
Total World	938 668	773 629	743 632	929 157	1 010 295	1 152 524	1 205 592

Veneer/ Plywood consumption 1 000 m³ (RWE)	1990	2000	2010	2020	2030	2040	2050
Eastern Asia	30 437	48 996	128 190	139 773	354 925	373 237	371 030
Southern Asia	664	395	9 359	22 354	13 573	17 064	19 725
South-eastern Asia	3 076	11 979	12 746	16 807	22 311	25 967	29 202
Northern Africa, Western & Central Asia	2 548	3 223	6 274	7 491	9 399	11 198	12 745
Sub-Saharan Africa	1 162	1 510	3 092	3 943	4 488	5 709	7 193
Latin America & the Caribbean	3 820	5 030	8 574	6 795	10 901	12 114	13 291
Europe	21 179	18 534	20 295	24 491	27 527	29 075	30 168
Northern America	42 260	44 390	33 004	41 479	45 735	49 081	51 953
Oceania	741	1 779	2 644	3 415	3 492	3 837	4 120
Total World	105 887	135 836	224 178	266 548	492 352	527 281	539 427

Particle/ Fibre board consumption 1 000 m³ (RWE)	1990	2000	2010	2020	2030	2040	2050
Eastern Asia	8 101	27 419	98 509	152 585	260 869	285 877	290 769
Southern Asia	290	853	1 876	4 849	3 624	4 701	5 762
South-eastern Asia	947	155	7 338	8 674	11 998	14 423	16 703
Northern Africa, Western & Central Asia	2 010	6 973	19 154	29 819	38 002	44 221	50 514
Sub-Saharan Africa	489	1 112	1 604	3 822	4 102	5 228	6 645
Latin America & the Caribbean	2 993	6 876	16 055	18 511	22 140	24 862	27 843
Europe	66 497	74 752	84 342	95 323	120 801	122 098	121 595
Northern America	34 583	36 030	30 750	28 401	63 035	65 353	67 790
Oceania	1 759	2 802	2 863	3 182	4 299	4 826	5 269
Total World	117 669	156 972	262 491	345 166	528 869	571 590	592 889

Wood pulp consumption 1 000 m³ (RWE)	1990	2000	2010	2020	2030	2040	2050
Eastern Asia	73 896	99 260	142 183	222 153	221 812	228 877	227 749
Southern Asia	5 339	7 229	13 756	22 087	44 990	49 312	56 675
South-eastern Asia	5 037	21 063	27 765	25 973	43 668	48 082	50 928
Northern Africa, Western & Central Asia	3 298	4 656	7 260	14 853	16 056	17 887	20 144
Sub-Saharan Africa	7 030	6 897	6 215	5 137	6 488	6 859	6 982
Latin America & the Caribbean	19 158	27 273	32 728	30 614	41 097	43 369	41 407
Europe	208 886	209 315	203 539	189 466	193 828	192 148	185 277
Northern America	289 874	298 296	238 027	226 288	219 211	203 257	181 848
Oceania	7 684	8 334	9 236	8 461	10 506	12 196	14 524
Total World	620 202	682 323	680 709	745 032	797 656	801 988	785 535

Sources: 1990 to 2020: FAOSTAT Forestry. 2030–2050 GFPM output tables (World 500, updated 2020) converted to RWE as in Annex 8.4.

8.6. GFPM PAPER AND WASTE PAPER OUTPUT TABLES 2050

Production in 1 000 tonnes	Wastepaper				Total Paper			
	2020	2030	2040	2050	2020	2030	2040	2050
Eastern Asia	90 260	123 600	133 813	169 340	160 549	206 616	227 972	246 766
Europe	61 780	71 869	75 540	84 978	107 849	115 984	126 777	136 964
Latin America & the Caribbean	8 796	11 507	12 853	17 385	17 185	20 627	22 876	23 345
Northern America	58 680	69 499	72 508	81 590	89 139	95 857	96 330	93 563
Northern Africa, Western & Central Asia	5 350	7 509	8 458	11 421	7 978	10 188	12 265	14 755
Oceania	3 226	3 683	3 843	4 209	4 097	4 734	5 582	6 837
Southern Asia	4 741	7 961	9 166	13 609	19 648	27 350	31 360	36 975
South-eastern Asia	9 921	14 447	15 819	19 851	22 428	28 558	33 952	39 148
Sub-Saharan Africa	1 383	2 021	2 362	3 362	2 662	3 049	3 454	3 760
Total World	244 137	312 097	334 361	405 746	431 533	512 963	560 567	602 113

Source: GFPM (World 500, updated 2020).

8.7. FAOSTAT INDUSTRIAL ROUNDWOOD PRODUCTION 1990–2020 BY REGION

IRW production 1 000 m³	1990	2000	2010	2020
Eastern Asia	123 074	117 189	184 018	210 808
Southern Asia	39 590	46 559	55 427	56 100
South-eastern Asia	97 086	95 276	121 400	160 110
Northern Africa, Western & Central Asia	9 799	15 094	19 653	28 149
Sub-Saharan Africa	59 932	69 977	70 608	77 078
Latin America & the Caribbean	113 958	151 728	202 398	234 142
Europe	641 527	519 115	532 631	633 228
Northern America	590 738	627 642	479 978	507 256
Oceania	33 802	47 087	57 018	76 818
Total World	1 709 506	1 689 667	1 723 131	1 983 689

Source: FAOSTAT Forestry

8.8. WOOD RESIDUE AVAILABILITY AND INDUSTRIAL ROUND-WOOD DEMAND 2050

The wood residue use rate within the timber industry is a key factor shaping the demand of IRW in 2050. With higher wood residue use rates the demand for IRW reduces. Within the study the wood residue use rate quantifies residues from the production of sawnwood, veneer and plywood, which can be further used to produce particle board and wood pulp. With a generally expected recovery rate of 50 percent the available amount of wood residues in 2050 from sawmilling, veneer and plywood production is 873 million m³. At a wood residue use rate of 30 percent the IRW wood demand in 2050 is projected to be about 2.9 billion m³ and with assumed 70 percent recovery rate it would drop by 12 percent to 2.5 billion m³.

(A) Sawnwood, veneer and plywood demand 2050 (million m³)	50% residues of A (million m³)	Wood residue use rate assumptions (%)	(B) Resulting wood residues volume (million m³)	(C) IRW demand computed from primary wood products (million m³)	IRW demand 2050 (million m³) (C-B)	IRW production 2020 (million m³) (D)	IRW demand growth 2020 to 2050 (million m³) (C-D)
1 745	873	30	0.262	3 123	2 862	1 984	0.878
		50	0.436		2 688		0.703
		70	0.611		2 513		0.529

Sources: (A) GFPM output tables Annex 8.5. (C) Sum of 2050 primary wood products consumption 2050 as in GFPM output tables Annex 8.5. (D) Global IRW production 2020 as in Annex 8.7.

8.9. CROSS-LAMINATED TIMBER AND MANMADE CELLULOSE FIBRE BASELINE OUTLOOK 2050

1 000 m³ (RWE)	Volume 2020 (1 000 m³)	GFPM implied growth rate 2020–2050 (C)	Basic outlook 2050 (1 000 m³)
CLT	4 000 (A)	30% (sawnwood baseline growth 2020–2050)	5 190
Dissolving pulp	39 000 (B)	5% (wood pulp baseline growth 2020–2050)	41 120

Sources: (A) Muszynski, L., Larasatie, P., Guerrero, J. & Hansen, E. 2020. Global CLT industry in 2020: Growth beyond the Alpine Region. *Society of Wood Science Technology (SWT) International convention, July 2020.* (B) Textile Exchange. 2021. *Preferred Fibre & Materials - Market Report.* Textile Exchange. (C) GFPM growth as simulated in Annex 8.5.

8.10. SUBSTITUTION FOR NON-RENEWABLES SCENARIO OF MASS TIMBER USE IN CONSTRUCTION, 2050

Region	Urban population growth 2020–2050 (1 000) (A)	Urban housing unit requirements 2020–2050 (1 000) (B)	Annual urban construction (1 000 units) 2020–2050	Annual timber demand (1 000 m³ RWE) for 10% of units built in timber (C)	Annual timber demand (1 000 m³ RWE) for 20% of units built in timber	Annual timber demand (1 000 m³ RWE) for 30% of units built in timber
Southern Asia	572 184	114 437	381	10 295	20 591	30 886
Sub-Saharan Africa	799 547	159 909	763	14 392	28 786	43 175
World	2 300 762	460 152	1 144	41 007	82 015	123 022

Sources: (A) United Nations 2019 Revision of World Population Prospects 2020 to 2050; mid-fertility variant. (B) Based on five persons per unit (United Nations Database on Household Size and Composition 2019; typical household size for countries in emerging world regions, where most urban construction will be required). (C) 27 m³ RWE per unit, assuming 60 m² floor area per unit (review of construction data on existing mass timber high-rise buildings, for example (Liang, S., Bergman, R., Gu, H. & Kelley, S.S. 2020. Comparative life-cycle assessment of a mass-timber building and concrete alternatives. Wood and Fiber Science, 52.).

8.11. SUBSTITUTION FOR NON-RENEWABLES SCENARIO OF WOOD PULP USE FOR MANMADE CELLULOSE FIBRE, 2050

Global textile fibre market 2020 (approx. 109 million tonnes) (A)	Dissolving pulp demand for MMCF 2020 (1 000 m³ RWE	Total textile fibre market 2050 approx. 167 million tonnes (C) of which MMCF volume 2050 (tonnes)	Dissolving pulp demand for MMCF 2050 (1 000 m³ RWE)	Dissolving pulp demand increase less baseline outlook volumes (Annex 8.9) (1 000 m³ RWE)
6% share wood-based MMCF (A)	39 000 (A)	10 020	56 947	15 827
16% share wood-based MMCF (B)		26 720	149 335	108 215

Sources: (A) Based on (Textile Exchange. 2021. *Preferred Fibre & Materials - Market Report.* Textile Exchange.). (B) 16% increase based on SSP2 scenario (Kallio, A. 2021. Wood-based textile fibre market as part of the global forest-based bioeconomy. *Forest Policy and Economics*, 123.); (C) Based on 2030 market volume in Kallio (2021) trend extrapolated up to 2050. Conversion factor dissolving pulp: 5.7 m³ per tonne.

8.12. PLANTED FOREST AREA REQUIRED FOR PRODUCTIVITY ASSESSMENT

For the following analytics, this study draws on the average productivity of combined tropical and sub-tropical forests of 4 m³/ha as suggested by Payn *et al.*, 2015.

Planted forest area requirements in the tropics and sub-tropics changes as a function of additional IRW supply. This assumes that IRW production from other sources, i.e. naturally regenerated tropical forests and planted forests in all other world regions remain stable to 2050. The targeted production volumes were reduced accordingly.

Since IRW demand will also vary as a function of the wood industry residue use rate, the targeted production is displayed for varying volumes (see the following table).

Planted forest productivity	Forest area requirements (in 1 000 ha) as a function of the wood industry residue use rate				
	Mean annual increment of commercial IRW (m³/ha per annum)	No use of wood residues	Use of 30% wood industry residues	Use of 50% wood industry residues	Use of 70% wood industry residues
Planted forest (global average) (A)	4	281 000	216 000	172 000	129 000
+100% productivity increase (A)	8	142 000	110 000	88 000	66 000
+300% productivity increase (A)	12	69 000	52 000	41 000	30 000

Sources: (A) MAIs: (Nepal, P., Prestemon, J.P., Cubbage, F. & Korhonen, J. 2019, 240 (2019)). Projecting global planted forest area developments and the associated impacts on global forest product markets. *Journal of Environmental Management*); (Payn, T., Carnus, J.-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C. *et al.* 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*), (Jürgensen, C., Kollert, W. & Lebedys, A. 2014. *Assessment of industrial roundwood production from planted forests.* FAO Planted Forests and Trees Working Paper FP/48/E. Rome, FAO.).

8.13. PRODUCTIVITY OF NATURALLY REGENERATED TEMPERATE AND BOREAL FORESTS AND PLANTED FORESTS IN TROPICAL AND SUB-TROPICAL REGIONS

Forest category	Area 2020 (million ha) (A)	IRW production 2020 (million m³) (B)	IRW productivity 2020 (m³/ha) (B/A)
Natural boreal and temperate	1 785.38	758.66	0.42
Planted tropical and sub-tropical	168.11	448.54	2.67
Total	1 953.49	1 207.20	

Sources: (A) (FAO. 2020. *Global Forest Resources Assessment 2020: Main report.* FAO, Rome.); (B) Based on contribution of planted forests to IRW production (adapted from Payn, T., Carnus, J.-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C. *et al*. 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*).

To analyse the interplay of naturally regenerated temperate and boreal forests and planted forest in the tropics and sub-tropics, this assessment looks at simulating production shares of both forest categories to meet future IRW demand.

The IRW productivity of 0.42 m³/ha for naturally regenerated forests in the boreal and temperate biomes appears low since the area includes managed and unmanaged forests. Paquette and Messier (2010) report productivity close to 1 m³/ha per annum for certified natural forests in these regions.

The productivity for planted tropical and sub-tropical forests for 2020 was estimated at 2.67 m³/ha, which is below the numbers reported by Payn *et al*. (2015). They reported productivity for tropical planted forests at 8.4 and sub-tropical at 3.8 m³/ha per annum. The differences are likely due to the increased planted forest area in the tropics and sub-tropics between 2010 and 2020 of approximately 30 million ha, of which only 15 million ha were dedicated plantation forests (FAO, 2020).

8.14. FAOSTAT DATA WOOD FUEL CONSUMPTION BY REGION, 1990–2020

Fuelwood consumption 1 000 m³	1990	2000	2010	2020
Eastern Asia	295 229	236 266	196 179	171 201
Southern Asia	347 635	359 000	388 852	377 385
South-eastern Asia	242 749	203 872	168 557	141 936

Northern Africa, Western & Central Asia	41 235	43 251	48 207	75 860
Sub-Saharan Africa	41 ,248	516 711	606 184	651 890
Latin America & the Caribbean	201 608	227 934	208 006	228 805
Europe	157 303	109 128	154 805	170 453
Northern America	122 659	86 418	82 478	100 715
Oceania	9 415	12 664	10 735	10 018
Total World	1 833 081	1 795 244	1 864 003	1 928 263

Source: FAOSTAT Forestry

8.15. COMPILATION OF GLOBAL WOOD FUEL OUTLOOKS, 2050

The outlook of future use of wood for energy compares the basic GFPM outlook with development scenarios of IEA and IPCC.

IPCC (2018) sees a potentially large role for biomass to play in achieving the <1.5 °C warming targets. In three of IPCC´s four scenarios, the use of biomass for energy in 2050 will increase between 49 percent and 121 percent compared to 2010 levels. This, however, includes all kinds of biomass (wood, agricultural residues and urban waste). Assuming that wood fuel contributions would increase proportionally to other biomass, the corresponding wood volumes in 2050 would be around 0.8 billion m^3 and 2.1 billion m^3 higher than 2020 wood fuel consumption (chapter 4.1). On the other hand, IPCC's P1 scenario assumes a substantial reduction in general energy demand through improved efficiencies and technological innovations, while income levels substantially increase in developing economies. This scenario results in a massive drop of almost 0.4 million m^3 wood fuel compared to 2020.

IEA (2021b) projects increasing solid biomass volumes (roundwood, wood residues, organic waste) between 29 percent and 42 percent. The IEA scenarios assume the compliance of countries with their stated energy policies (STEP scenario), compliance with their announced NDC pledges (AP scenario) and a global net zero emission trajectory (NZE scenario). The IEA scenarios are based on substantially decreasing consumption volumes in traditional wood fuel uses (-29 percent for STEPS and APS and -100 percent for the NZE), while modern uses of solid biomass are projected to increase between 72 percent and 131 percent. Assuming proportional growth rates for all biomass sources, wood fuel volumes would increase between 0.6 million and 0.8 million m^3 by 2050. These volumes include wood industry and harvesting residues.

The GFPM (World 500, based on a market equilibrium model with GDP, population growth and historical consumption trends being the most important exogenous consumption driving factors), results in only slightly increasing consumption (+4 percent compared to 2020) (Figure 32).[44] This low increase is mainly caused by reduced wood fuel demand in sub-Saharan Africa. The model's simulation approach in its basic setting considers a strong negative correlation between GDP growth and wood fuel demand for all countries.

The GFPM-X of 2021 (Global Forest Products Model X; Cobweb Theorem based)[45] simulates stronger wood fuel demand growth than the original GFPM. The model settings consider similar exogenous consumption drivers as the basic GFPM but it is more detailed at the country level, i.e. the African simulations show higher wood fuel consumption volumes. Still, global consumption growth by 2050 (+17 percent) is less than those indicated by IEA and IPCC.

Outlook scenario	2050 (1 000 m³)	Change 2020–2050 (1 000 m³)	Change 2020–2050 (%)
GFPM, 2020 (World 500) (A)	2 003 340	75	4
GFPM-X, 2021 (A)	2 254 338	326	17
IEA, 2021 (NZE) (B)	2 526 025	598	31
IEA, 2021 (STEPS) (B)	2 487 459	559	29
IEA, 2021 (APS) (B)	2 738 133	810	42
IPCC, 2018 (P1) (C)	1 564 335	-364	-19
IPCC, 2018 (P2) (C)	2 774 831	847	44
IPCC, 2018 (P3) (C)	4 115 690	2 187	113
IPCC, 2018 (P4) (C)	9 646 730	7 718	400

Sources: (A) Buongiorno, J., Zhu, S., Zhang, D., Turner, J. & Tomberlin, D. 2022. The Global Forest Products Model. In: *Joseph Buongiorno, Department of Forest and Wildlife Ecology, UW-Madison*. Cited 27 July 2022. https://buongiorno.russell.wisc.edu/gfpm; (B) IEA. 2021b. *World Energy Outlook 2021.* Paris, IEA;
(C) IPCC. 2018. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways.* Geneva, IPCC.

[44] A previous GFPM simulation in 2017 resulted in significant fuelwood consumption reductions, i.e. in Africa (as shown by (ITTO, 2021). This reduction is explained by the positive income trends in most African countries over the period 2010 to 2015 and the related GDP projections for the continent. However, since 2015, income growth has slowed down, and GDP projections were re-framed. Thus, fuelwood consumption volumes in the 2020 GFPM simulation increased.

[45] The model assumes that demand creates its own supply. Consequently, domestic and import demands are the drivers in the evolution of the global forest sector, and global import demand induces export supply. Domestic production fills the net demand (Buongiorno, 2021).

8.16. COMPILATION OF WOOD FUEL OUTLOOK IN SUB-SAHARAN AFRICA, 2050

Recent outlook studies on sub-Saharan African wood fuel consumption have assessed a variety of scenarios:

- IEA (2019) projects moderate fuelwood consumption growth by 2040 (+11 percent) if African states implement their currently stated energy and environmental policies. In a very optimistic scenario (assuming access to electricity for 100 percent of the African population in 2030), traditional biomass use would even drop by 64 percent.
- The European Union Joint Research Centre´s (EUJRC) energy projections for African countries estimates in its reference scenario significantly increasing consumption of biofuel/waste (+38 percent; including biomass from agriculture, waste and fuelwood) (Pappis *et al*., 2019). Notably, EUJRC projections shows even higher uses of (modern) biomass consumption under its 1.5 °C and 2 °C scenarios.
- The United Nations projects African biomass demand for energy generation growing by 32 percent by 2050 (UNEP, 2019).
- The GFPM-X model results in an increase of fuelwood consumption in sub-Saharan Africa of 29 percent in 2050 compared to 2020, while the basic GFPM simulates a slight decrease of -3 percent by 2050.
- The projected fuelwood consumption volumes for Africa in 2050 range from 631 million m^3 (GFPM basic simulation of 2020) to 921 million m^3 (EUJRC simulation of 2019 in Pappis *et al*. [2019]). The cited sources simulate growing fuelwood consumption peaking in the period 2030 to 2040 and stabilizing or decreasing afterwards.

Outlook scenario	2050 (1 000 m^3)	Change 2020–2050 (%)
GFPM (World 500); wood fuel (A)	631 214	-3
GFPM-X; wood fuel (A)	839 390	29
Average GFPM/GFPM-X; wood fuel	735 302	13
GFPM (World 311); wood fuel (B)	351 642	-46
EUJRC (Reference); biofuels/waste Africa (C)	899 194	38
EUJRC (<2 °C); biofuels/waste Africa (C)	921 674	41
UN (baseline); total biomass Africa (D)	863 348	32
IEA (Stated Energy Policies Scenario), total biomass Africa (E)	806 317	24
IEA (Announced NDC pledges scenario), total biomass Africa (E)	360 269	-45

IEA (Stated Energy Policies Scenario), traditional biomass Africa (E)	721 764	11
IEA (Announced NDC pledges scenario), traditional biomass Africa (E)	232 827	-64

Sources: (A) Buongiorno, J., Zhu, S., Zhang, D., Turner, J. & Tomberlin, D. 2022. The Global Forest Products Model. In: *Joseph Buongiorno, Department of Forest and Wildlife Ecology, UW-Madison*. Cited 27 July 2022. https://buongiorno.russell.wisc.edu/gfpm; (B) ITTO. 2021. *Tropical timber 2050: an analysis of the future supply and demand for tropical timber and its contribution to a sustainable economy.* Yokohama, ITTO; (C) EUJRC (Pappis, I., Howells, M., Sridharan, V., Usher, W., Ramos, E. & Gardumi, F. 2019. *Energy projections for African countries.Technical report.* European Union Joint Research Center); (D) UNEP. 2019a. *Review of Woodfuel Biomass Production and Utilization in Africa: A Desk Study.* Nairobi, UNEP; (E) IEA. 2019. *Africa Energy Outlook 2019.* Paris, IEA.

8.17. WOOD FUEL GAP SUB-SAHARAN AFRICA, 2050

Agricultural area expansion 2050 (1 000 ha) (A)	Loss of wood fuel per ha (m³/ha per annum) (B)	Total annual wood fuel loss (1 000 m³) (A x B)	Demand growth sub-Saharan wood fuel outlook (baseline 2020–2050) (1 000 m³) (C)	Total wood fuel gap in 2050 (1 000 m³)
51 000	2	102 000	83 000	185 000

Sources: (A) Alexandratos, N., & Bruinsma, J. 2012. *World agriculture towards 2030/2050: the 2012 revision.* ESA Working paper No. 12–03. Rome, FAO; (B) MAI: (Marzoli, A. 2007. *Inventário florestal nacional. Avaliação florestal integrada de Moçambique.* Ministério da Agricultura Mozambique); (C) reflecting average demand growth of GFPM and GFPM-X simulation (Annex 8.5).

8.18. AGROFORESTRY AND WOODLOT AREAS TO MEET SUB-SAHARAN WOOD FUEL GAP, 2050

Percentage of projected agricultural area expansion in sub-Saharan Africa 2050 (51 million ha) (A)	1 000 ha area requirement for targeted production volumes 185 million m³ (A)	
	Agroforestry MAI: 5 m³/ha per annum (B)	Woodlots MAI: 10 m³/ha per annum (C)
10% Agroforestry	5 100 000	15 988 615
30% Agroforestry	15 300 000	10 888 615
50% Agroforestry	25 500 000	5 788 615

Sources: (A) Annex 8.17. (B) Average annual fuelwood production from Agroforestry based on Iiyama, M., Neufeldt, H., Dobie, P., Njenga, M., Ndegwa, G. & Jamnadass, R. 2014. The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Current Opinion in Environmental Sustainability*; (C) conservative expert estimate.

8.19. EMPLOYMENT FACTORS IN FORESTRY

Region	Employment (1 000) 2020 (A)	Roundwood production (1 000 m³) 2020 (B)	Employment factor 2020 (Employees/1 000 m³)
Africa	1 973	427 018	2.4
Americas	842	105 227	0.8
Asia	4 200	633 228	3.8
Europe	965	741 398	1.2
Oceania	78	76 818	0.9
Global	8 058	1 983 689	2.1

Sources: (A) on Lippe, R.S., Cui, S. & Schweinle. (forthcoming). Contribution of the forest sector to total employment in national economies. Rome, FAO; (B) FAOSTAT Forestry and FAO. 2020. *Classification of forest products.* Rome, FAO.

Note: Africa figures include Western Asia.

8.20. EMPLOYMENT REQUIREMENTS FORESTRY AND LOGGING OUTLOOK, 2050

Employment factor 2050 (A)	If 30% of wood industry residues are used (B)	If 50% of wood industry residues are used (B)	If 70% of wood industry residues are used (B)
1 Employee / 1 000 m³ roundwood production	5 361 690	5 187 188	5 012 686
1.5 Employees / 1 000 m³ roundwood production	8 042 534	7 780 782	7 519 029
2 Employees / 1000 m³ roundwood production	10 723 379	10 374 375	10 025 372

Sources: (A) Factors according to Annex 8.19, with 1 being industry benchmark and 2 global average 2020. (B) Production volumes based on Annex 8.8 for IRW production plus 2.5 billion m³ fuelwood.

8.21. EMPLOYMENT FACTORS IN WOOD PROCESSING INDUSTRIES, 2020

Region	Employees average 2013–2019 (1 000) (A)	Production 2020 (1 000 m³ RWE) (B)	Employment factors 2020 (Employees/1 000 m³)
Wood industry			
Asia	14 104	613 754	20.89
Africa	2 361	70 660	20.06
Europe	1 558	466 962	4.47
Americas	1 292	383 595	3.43
Oceania	85	24 713	3.80
Global	19 400	1 559 684	12.59
Industry practice (C)			3.99
Pulp and Paper			
Asia	3 760	270 213	13.91
Africa	418	19 990	20.92
Europe	962	189 466	5.08
Americas	689	256 902	2.68
Oceania	25	8 461	2.98
Global	5 854	745 032	7.86
Industry practice (C)			4.06

Sources: (A) Employment from Lippe, R.S., Cui, S. & Schweinle (forthcoming). Contribution of the forest sector to total employment in national economies. Rome, FAO; (B) Based on FAOSTAT Forestry production volumes per regions of wood industries (sawnwood, wood based panels) and wood pulp, converted to RWE. (C) Weighed average Europe, Americas, Oceania.
Note: Africa figures include Western Asia.

8.22. EMPLOYMENT REQUIREMENTS WOOD PROCESSING OUTLOOK, 2050

Sector	Employees 2050 at no increase in labour productivity (A)	Employees 2050 if global productivity increases to 50% of industry benchmark 2020 (B)	Employees 2050 if global productivity increases to 100% of industry benchmark 2020 (C)
Wood industries	30 046	19 043	9 522
Pulp and paper	6 175	6 382	3 191
Total	36 221	25 425	12 713

Sources: (A) Global average employment factor 2020 (Annex 8.23) x Total wood products volume 2050 (8.5); (B) (Industry practice employment factor 2020 x 2) x Total wood products volume 2050; (C) Industry practice employment factor 2020 x Total wood products volume 2050.

8.23. INVESTMENT FACTORS IN WOOD INDUSTRIES AND FORESTRY

Sector	Investment (USD/unit)	Investment cycle until complete re-investment/ replanting (years)
Plantations (tropical and sub-tropical)	1 200 / ha (A)	12
Naturally regenerated forests (temperate and boreal)	24 million / 740 billion ha (B)	1
Wood industry (sawmilling, plywood)	200 / m³ RWE intake (C)	30
Wood industry (particle, fibre board)	300 / m³ RWE intake (C)	30
Wood pulp	300 m³ RWE intake (C)	30

Sources: (A) Based on industry benchmarks, though wide variations exist. (B) Naturally regenerated forests based on Austin, K., Baker, J.S., Sohngen. B.L., Wade, C.M., Daigneault, A., Ohrel, S.B., Ragnauth, S. & Bean. A. 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nature Communications*; USD 69 billion per annum for European and Northern American forests of approximately 740 million ha productive forests (FAO. 2020. *Global Forest* Resources *Assessment 2020: Main report.* FAO, Rome), resulting in proportional share of USD 24 billion per annum; (C) Expert data from consulting work for wood industry and pulp investments (company data).

8.24. INVESTMENT REQUIREMENTS OUTLOOK, 2050

Sub-sector	Area or intake capacity	Total investments 2020–2050 USD billion	Investments in USD billion per annum
New forest plantations and replanting	30 million ha (A)	90	3
Replanting forest plantations existing in 2020	131 million ha (B)	393	13
Naturally regenerated temperate and boreal production forests in Europe and Northern America in 2020	740 million ha (C)	720	24
New wood industries	797 million m³ RWE intake (D)	184	6.1
New wood pulp	40 million m³ RWE intake (D)	12	0.4
Existing wood industries modernization	1 540 million m³ RWE intake(E)	343	11.4
Existing wood pulp modernization	745 million m³ RWE intake (E)	224	7.5

Sources: (A) Annex 8.12. (B) and (C) FAO, 2020. *Global Forest* Resources *Assessment 2020: Main report.* FAO, Rome; (D) GFPM simulated increase of sawnwood, veneer and panels (Annex 8.5); (E) Production 2020 FAOSTAT Forestry (Annex 8.5).

8.25. EMPLOYMENT AND INVESTMENT REQUIREMENTS TO SUBSTITUTE FOR NON-RENEWABLE MATERIALS

Product	Factor (A)	Requirement 2050 lower estimate (B)	Requirement 2050 higher estimate (B)
Employment	5 Employees/1 000 RWE intake	185 000	595 000
Investment	4 Employees/1 000 RWE intake	USD 13 billion	USD 42 billion
Employment	USD 350/m³ RWE intake	72 000	441 000
Investment	USD 300/m³ RWE intake	USD 5 billion	USD 75 billion

Sources: (A) Review of existing CLT production capex and employment data and expert interviews (company data); (B) Factor applied on production increase as in Annex 8.10 and 8.11.

8.26. GREENHOUSE GAS SUBSTITUTION FACTORS

Table 2. Market level substitution benefits for three illustrative cases.

Product / functional unit	Sawnwood	Multi-storey wood buildings	Dissolving pulp
Market assumption	Production of sawnwood increases at an annual rate of 1.8% to 2030 (Hildebrandt et al. 2017)	Wood products gain a 1% increase in the annually built floor area of multi-storey residential buildings by 2030	The production of dissolving pulp grows at an annual rate of 3.9% to 2030 (Pöyry 2015)
Substitution case	Around 50% of coniferous sawnwood substituting steel (40%), concrete (40%), and masonry and other (20%) in construction, and around 50% used e.g. in packaging, joinery and carpentry and furniture, substituting various materials	Coniferous sawnwood (50%) and engineered wood products (50%) substituting steel (40%), concrete (40%), and masonry and other (20%) in residential multi-storey construction	Viscose (50%) and Lyocell (50%) replacing polyolefins (75%) and cotton (25%) in apparel
Weighted substitution factor (production stage)	1.11 tC / tC	1.39 tC / tC	1.52 tC / tC
Substitution impact (production stage)	88.7 Mt CO_2eq	4.4 Mt CO_2eq	11.3 Mt CO_2eq
Additional roundwood demand (for the specified end use)	174.8 Mm^3	8.4 Mm^3	31.0 Mm^3

Source: Leskinen P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C. *et al.* 2018. Subsitution effetcs of wood-based products in climate change mitigation. *From Science to Policy 7*. Joensuu, EFI.

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