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Dynamic material flow analysis of wood in Germany from 1991 to 2020

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ABSTRACT

Severe climate change and urgent climate action have raised concerns about wood. Overharvesting and increased wood waste are putting immense pressure on sustainable forest management and the global carbon budget. In Germany, a vital wood supplier and user in Europe, the wood supply chain's production, consumption, trade, and recycling have been insufficiently investigated. To tackle this challenge, we conducted a comprehensive dynamic wood flow analysis from 1991 to 2020. Approximately 2143 million cubic meters of standing timber were felled in German forests over the past three decades, with 80% used for materials and 20% for energy purposes. Wood flow patterns were susceptible to market demand and forest disturbances like drought, storms, and insect infestations. The storm in 2007 left a notable impact, leading to the highest figures ever recorded for various wood products. Notably, the net forest carbon sink, carbon storage in forest products, and energy substitution effect (replacing fossil energy with wood) reached 160, 332, and 343 million tons of carbon, respectively. However, the transition to renewable energy, wooden buildings, and wood and paper packaging demands further strains the wood supply chain. To promote sustainable forest management and achieve climate neutrality, we propose potential strategies for consideration.

1. Introduction

Observable global temperature rise, increasing occurrences of extreme weather events such as storms, floods, heatwaves, heavy rainfall, droughts, and even shifts in climate zones are unequivocal manifestations of current climate change. These changes not only harm regional ecosystems and biodiversity but also pose significant risks to human health and survival (Abbass et al., 2022). To address this critical issue, international agreements such as the Paris Agreement, Sustainable Development Goals, and Climate Action Plan 2050 (BMUB, 2016) have integrated climate change measures into national policies and strategies. Among the leading causes of climate change is the use of fossil fuels and products since the Industrial Revolution, which accelerates greenhouse gas (GHG) emissions. Consequently, transitioning to renewable energy and non-fossil-based products is crucial to combat climate change (Rahmstorf and Markle, 2019).

Wood, as a significant and versatile natural resource, holds vital importance for human civilization and the environment. It is extensively used in construction, furniture, and paper production, serves as a traditional and sustainable energy source, and holds historical, cultural, leisure, and aesthetic values. Additionally, it provides ecological benefits such as soil conservation and carbon storage. In the digital age, paper consumption in Germany has decreased, but the usage of wood-based products has shown a steady increase, particularly in the packaging sector, where both paper and wooden packaging are on the rise. Since the Russia-Ukraine conflict, the uncertainty in the energy market and sharp increases in fossil fuel costs have driven the demand for firewood and energy wood in Germany, leading to regional competition with other material consumers, including industrial and waste wood. However, the increased wood harvesting and forest decrement are raising concerns about sustainable forest management practices. To ensure a well-planned approach to forest logging and wood products production, a retrospective and prospective analysis become essential decision analysis methods.

Material Flow Analysis (MFA) is commonly employed to assess the sustainability and efficiency of material utilization, identify potential environmental impacts, and support decision-making regarding resource management and waste reduction, particularly in the context of an increasing global population and growing resource constraints (Brunner and Rechberger, 2016). Examples of common subjects of MFA studies include metal (Muller et al., 2014), construction materials (Augiseau and Barles, 2017), construction and demolition waste (Guo and Huang, 2019), and electronic waste (Islam and Huda, 2019). Additionally, various studies specific to wood, the finite resource, have

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already been conducted to gather data and insights at the global (Bais et al., 2015), regional (Mantau, 2015; Saal et al., 2022), national (e.g., Germany (Schweinle et al., 2020; Szichta et al., 2022), Austria (Kalcher et al., 2017; Kalt, 2015), Switzerland (Bergeron, 2014; Suter et al., 2017), and Japan (Furubayashi et al., 2017; Kayo et al., 2018)), and city (Nissing and Blottnitz, 2007; Taskhiri et al., 2016) levels.

Many studies have emphasized that official statistics underestimate the usage of timber, and one way to obtain accurate data is through wood flow analysis (Augustsson et al., 2017; Mantau, 2015). The supply of roundwood and waste treatment are major concerns, especially wood waste, which involves cascading use, energy recovery, and environmental impacts. Compared to the high recycling rates of paper, the cascading utilization of post-consumer wood and processing residues remains relatively low (Mantau, 2015; Parobek et al., 2014). However, wood cascading can contribute to climate change mitigation and improve resource efficiency. Short-term wood cascading leads to less wood extraction from forests and has less GHG emissions reduction than the wood substitution effect (Suter et al., 2017). Moreover, the long-term demand for wood can be expected to increase, and long-term wood cascading contributes to more significant GHG emissions reduction than growing forest harvesting (Bergeron, 2016). Wood substitution effects, replacing non-wood materials or energies, were three times higher than the natural carbon sink effect for wood products (Werner et al., 2010). Unfortunately, this aspect has not yet been recorded in official statistics.

Dynamic Material Flow Analysis extends traditional material flow analysis by considering the dynamic nature of material cycles, capturing how material stocks and flows evolve and interact over longer time frames. However, most studies either focus on static analyses for specific years or only cover limited portions of the supply chain, particularly waste wood management (Bergeron, 2014, 2016; Cote et al., 2015; Džubur and Laner, 2018; Kalcher et al., 2017; Mehr et al., 2018; Szichta et al., 2022) and carbon storage (Bais et al., 2015; Kayo et al., 2018). Research on dynamic material flow analysis of wood in Germany, the largest wood producer and consumer in the EU27, is scarce, let alone studies that cover the entire wood supply chain.

Since Germany's reunification in 1990, national statistical data has been comprehensively recorded, and wood consumption has increased yearly. Egenolf et al. (2021) used Exiobase 3.4 to outline Germany's wood footprint in final consumption from 1995 to 2015, observing fluctuating trends due to severe storm events (like "Lothar" and "Kyrill"). During this period, Germany heavily relied on imported roundwood, with a self-sufficiency rate of only 76% in 2015. According to the predictive model by Szichta et al. (2022), the construction sector remains the main consumer of finished wood products, accounting for about two-thirds of the total. The major sources of waste wood in Germany are construction, furniture, and packaging, with construction and demolition waste wood expected to show significant growth over the next 30 years. Cote et al. (2015) conducted a dynamic material flow analysis on paper and paper products, revealing increased carbon stocks generated by Germany's pulp and paper industry. Much of this carbon storage comes from long-lived products, confirming that per capita consumption and product lifetimes are essential variables influencing carbon stock building.

This paper aims to provide a comprehensive and dynamic flow analysis of wood in Germany from 1991 to 2020, covering the supply chain ranging from forests, sawmills, pulp mills, buildings, energy, and waste. Furniture, packaging and other sectors are not examined. The study data is primarily from the Eurostat Database and extensive study reports from the Thünen Institute. In section two, the system boundary and calculation method for dynamic wood flows are elaborated in detail. Additionally, conversion factors for wood and wood products are defined and streamlined for easy comparison. The research findings are subsequently presented in the third part, examining the inflows, outflows, stocks, waste, and environmental impact of wood resources over time. Data uncertainty analysis of wood flow, anomalies in historical trends, future demand projections, and strategies for sustainable development will be discussed in section four. The paper concludes with a summary of key findings.

2. Methods and data

2.1. System Definition (dynamic wood flow modeling)

In line with static wood flow analysis and based on material conservation and cascading cycles, we constructed a detailed dynamic wood flow model to elucidate the flow and stock of wood in Germany, as depicted in Fig. 1. The framework comprises five components: raw material supply (mainly from domestic forests), paper products production, wood products production, energy use, consumer usage and recycling. Transportation and international trade of raw materials and products occur at nearly every stage of the wood flow.

The entire wood industry chain relies on raw materials from different origins, including roundwood and residues from forests, recovered wood and paper, wood from outside the forest, and waste generated during the processing stages. These materials form the basis for producing wood, paper, and energy products.

Within the paper production cycle, partial pulpwood and sawmill by-products are directed to pulp mills, transforming them into virgin wood pulp and black liquor. Virgin pulp, recovered pulp, non-wood pulp, and non-fiber materials are combined to create primary paper products like graphic paper, household and sanitary paper, packaging paper, and other paper products. After consumption, most paper is recycled and re-enters the next cycle. The average lifespan of paper products is around 2 years (Rüter et al., 2019), and the fiber can be recycled 6-7 times, with some fiber loss during paper and recovered pulp production.

The wood products chain involves primary wood products, such as sawnwood, veneer, plywood, and wood-based panels, processed in sawmills alongside clean sawmill by-products and other industrial waste wood with adhesives and contaminants. Secondary products often require further processing to meet industry-specific requirements, resulting in approximately 10% loss classified as other industrial waste wood (Mantau et al., 2010; Szichta et al., 2022). The timber used in buildings also incurs losses during installation, categorized as construction and demolition waste.

As for energy, wood primarily serves as clean energy for households and wood-based factories, including traditional firewood, industrial waste, recovered wood, pellets, briquettes, and wood charcoal (Szarka et al., 2021). Notably, wood fuels used in factories mostly function as heat sources for product drying, with any surplus electricity and heat sold to the grid and district heating.

Recovered paper is solely used for recovered fiber pulp production, and there is no evidence of its use for energy purposes. However, only a small portion of the recovered wood was used for particle board production (Brunet-Navarro et al., 2018), while the rest is utilized as fuel or compost due to strict regulations in Germany regarding waste wood landfilling.

While forests and wood products act as carbon sinks, they are considered carbon emissions once logs are harvested. Thus, the wood industry chain remains in an emission state during the first three stages. In the installation and use stage, wood in construction and furniture is stored for an extended period, representing carbon storage in wood products. Combusted waste wood is no longer considered carbon stock or emission but a net-zero material, while wood within the material loop should be re-assessed for carbon storage, known as the cascading effect.

2.2. Accounting methods

Dynamic material flow analysis (MFA) of wood in Germany involves examining the inflows, outflows, and stocks of wood resources over time. It provides insights into the production, consumption, and waste generation associated with wood materials within the country. Key

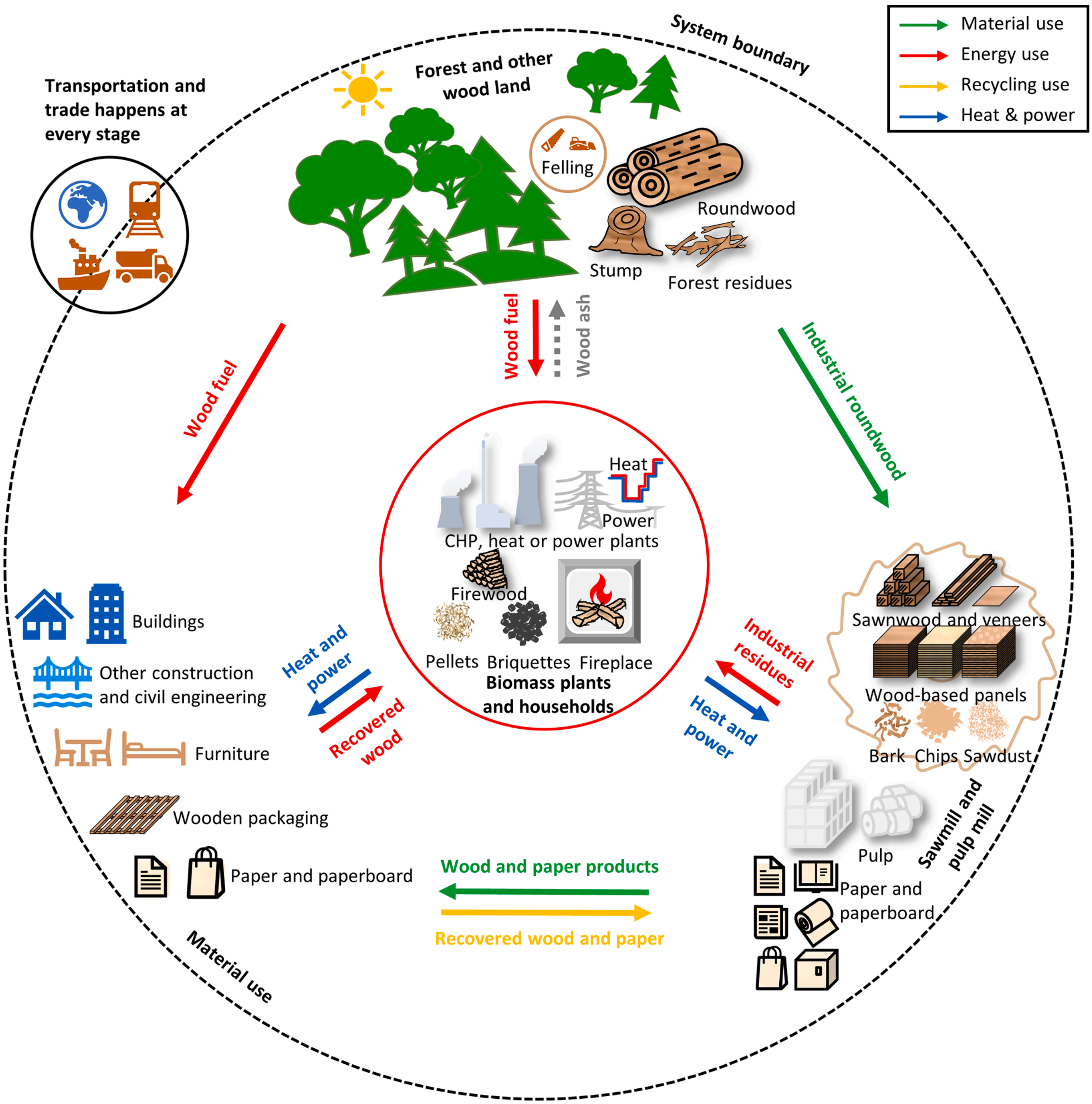

Fig. 1. The framework of wood flow analysis in Germany.

components considered in the dynamic MFA of wood in Germany include: (1) Consumption: Wood consumption in Germany encompasses various sectors, including construction, furniture production, paper manufacturing, and bioenergy. MFA evaluates the quantities of wood consumed by different sectors, identifying trends and patterns over time. (2) Production: This involves roundwood harvesting, wood products from sawmills, paper products from pulp mills, and other energy products from facilities. It examines the annual quantities of wood produced, including roundwood and all wood-based products. (3) Imports and Exports: The analysis tracks the inflows and outflows of wood through international trade, accounting for raw materials and processed goods. (4) Waste and Recycling: Wood waste generated during the production, consumption, and disposal stages is an essential aspect to consider. MFA tracks the quantities of wood waste generated, recycled, and disposed of as landfill or incineration. It also examines the recycling and reutilization rates of wood materials. (5) Stocks and Reserves: MFA assesses the stock of wood resources held within the country at a given time. This includes standing timber in forests, wood products in use, and wood held in inventories. Monitoring stocks helps understand the availability and potential for future wood use. (6) Environmental Impacts: MFA can also incorporate environmental indicators to evaluate the environmental impacts of wood production and consumption, such as carbon emissions and energy consumption.

2.3. Conversion factors

Unlike metal and other materials, the measurement and statistics of wood are usually expressed in multiple volume and weight units (FAO/ITTO/UN, 2020). Therefore, the conversion factor calculation is essential in the material flow analysis of wood. In fact, only the density and carbon content of the same species can be considered constant in wood, determined by genetic characteristics. Both fiber mass and volume units, for wood, paper, and energy products, will see changes in universal conversion factors when the composition of raw materials input varies yearly. Especially with technological advancements, the proportion of recovered fibers is gradually increasing. Nevertheless, this is merely an improvement at the technical level, and how much to use and what raw materials to use are still influenced by factors such as forest supply, disasters, prices, policies, and national strategies. As a result, it is not always possible to obtain a constant universal conversion factor for all wood and wood products. Fixed ratios for single years, such as the results of circular wood flow in 2020, are also not applicable to all years.

However, the paper assumes conservative minimum coefficients to observe trends and developments over recent years, provided in Tab. A.1 in Appendix A. According to reports from BMEL (2021a), from 1997 to 2020, the basic density of softwood hovered at 388-404 kg/m^3, while hardwood remained relatively stable at around 563 kg/m^3. The corresponding conversion factors adopted in this paper are 389 kg/m^3 and 563 kg/m^3 on average. For the yield of wood and paper products, solid wood equivalent (SWE) and roundwood equivalent (RWE), we calculated our results based on data from The Food and Agriculture Organization (FAO). RWE refers to the wood volume required to manufacture the wood product before shrinkage and drying, including waste and loss, while SWE does not incorporate these factors, which only assumes the green volume of wood, prior to any shrinkage (FAO/ITTO/UN, 2020; UNECE/FAO, 2010). Between 1987 and 2007, roundwood, on average, provided 60% fiber for pulp, which increased to over 64% in 2010 and fell back to 60.4% in 2020 (Mantau, 2012). Therefore, we assume that in the past 30 years, virgin wood pulp was produced by 61% of industrial roundwood and 39% of sawmill by-products, with an average density of 410 kg/m^3. Similarly, for wood-based panels, except for plywood, the average dependence on industrial roundwood was 40%, and this value has been continuously declining due to technological advancements and waste wood cascades.

Wood energy consumption is measured in terms of primary energy content. Solid biofuels (code: R5100) encompass all wood-based energy, of which approximately 90% is provided by fuelwood, wood residues, and by-products (code: R5110). Official statistics on wood fuel typically include forest roundwood and residues, with the proportion of residues gradually increasing from 20% in the early days to 30% today, averaging 27.7%. Additionally, in this paper, the moisture contents of waste wood and waste paper are assumed to be 20% and 10%, respectively, and the bark content is considered 10%.

2.4. Data source and uncertainty analysis

The wood flow analysis is subject to uncertainty from original data, conversion factors, rounded figures, and other factors. The original data used in this paper mainly comes from Eurostat (2020b), covering a variety of statistical units such as cubic meters (for roundwood), product cubic meters (for primary and secondary wood products), air-dried metric tons (for primary and secondary paper products, waste paper, waste wood), and others. Among them, Import and export data are sourced from customs and are considered to be of the highest credibility level. Although we can convert all wood and paper products from the original units into SWE or RWE for better comparison, this paper still used product cubic meters (m^{3}p) and air-dried metric tons (or million tonnes) as reference units to show changes in wood and paper products without too many conversions. However, roundwood must be compared in cubic meters of volume. The Thünen Institute’s reports provide the raw material input for the corresponding wood products (Döring et al., 2020, 2021; Gieseking et al., 2021; Gieseking et al., 2020; Gieseking and Mantau, 2020). In addition, because of the statistical threshold, official data seriously underestimate the actual consumption, especially industrial roundwood. We calculated the industrial roundwood consumption in Germany based on the proportion of raw material in wood and paper products and processing losses, with the results compared to official statistics and existing research to verify data plausibility.

3. Results

3.1. Overview - cumulative wood flow in Germany from 1991 to 2020

The cumulative material flows of wood in Germany from 1991-2020 are shown in Fig. 2. The results indicate that domestic forests have always been Germany’s main source of wood consumption. In the past three decades, about 76.8% of the net annual increment (NAI) in the forest standing timber, amounting to 2143 million m^3 (Mm^3), has been felled. Felling rates exhibited significant variation, ranging from 51.1% to 104.4% of NAI. It is worth noting that the real removal volume was 1758 Mm^3, as there were harvest losses and unused wood, estimated to be around 18% by Mantau et al. (2016). The average annual harvest was 58.6 Mm^3, with 80% used for materials as the primary purpose and 20% for energy. The increasing trends in cutting and harvesting volume are linked to climate, forest management practices, and market demand.

The cumulative apparent consumption of industrial roundwood, primary wood products, secondary wood products, primary paper products, and secondary paper products reached 1386, 1036, 1026, 839, and 781 Mm^3, respectively. Production, import, export and consumption data of key wood and paper products are provided in Appendix B (Figs. B1, B2 and B3). Sawnwood and veneer in Germany have higher production outputs than wood-based panels. While only a fraction of the initial industrial roundwood (11.4% or 158 Mm^3) and slightly over 100 Mm^3 of sawmill by-products flowed to pulp mills, Germany’s domestic consumption of virgin wood pulp reached 414 Mm^3 from 1991 to 2020, supplemented by a significant quantity of imported wood pulp. Consequently, 508 Mm^3 of recovered wood pulp (about 95% sourced domestically) became the major component of paper and paper products. Regarding wood energy, there are abundant raw materials available, with consumers primarily concentrated in private households and industries. The total primary energy derived from wood reached 2964 terawatt-hours (TWh) or 10670 petajoules (PJ), with over half of it being utilized by households (Eurostat, 2020a).

3.2. Wood Consumption Trends in Germany: Volatile Patterns & Renewable Surge

As shown in Fig. 3, the apparent consumption of wood in Germany has grown volatilely over the past 30 years. Both primary wood and paper products peaked in 2007, followed by a sharp decline. This key change precisely reflects the decisive impact of forest disturbances on the wood supply chain. As discussed in Section 4.2, in 2007, the storm "Kyrill" swept through Germany on a massive scale, leading to salvage logging that not only increased domestic roundwood supply but also boosted wood product output throughout the wood supply chain. Restrictive harvests for post-disaster forest recovery and reduced demand from the construction industry for building materials may have been the primary reasons for the substantial decline in primary wood product production in 2008. Looking at the entire period, coniferous sawnwood and particleboard, the main components of primary wood products, demonstrated an alternating pattern of growth and decline. The main consumers for wood are construction, furniture, and packaging. Wood consumption in the packaging sector saw significant growth, especially in flat pallets, which increased from under 60 million pieces in 1997 to 132 million in 2020. Construction-related wood consumption showed a declining trend initially but rebounded, as observed through completed work in new construction and existing buildings. The furniture consumption closely correlates with annual new construction and construction stock, showing slow growth.

In the consumption of paper and paper products, graphic paper and packaging paper also show the opposite pattern, which aligns with the consensus. The demand for paper has increased due to population growth and social progress. However, the emergence of the electronic market has altered the traditional paper consumption pattern. Electronic media and data have reduced the need for physical newspapers and

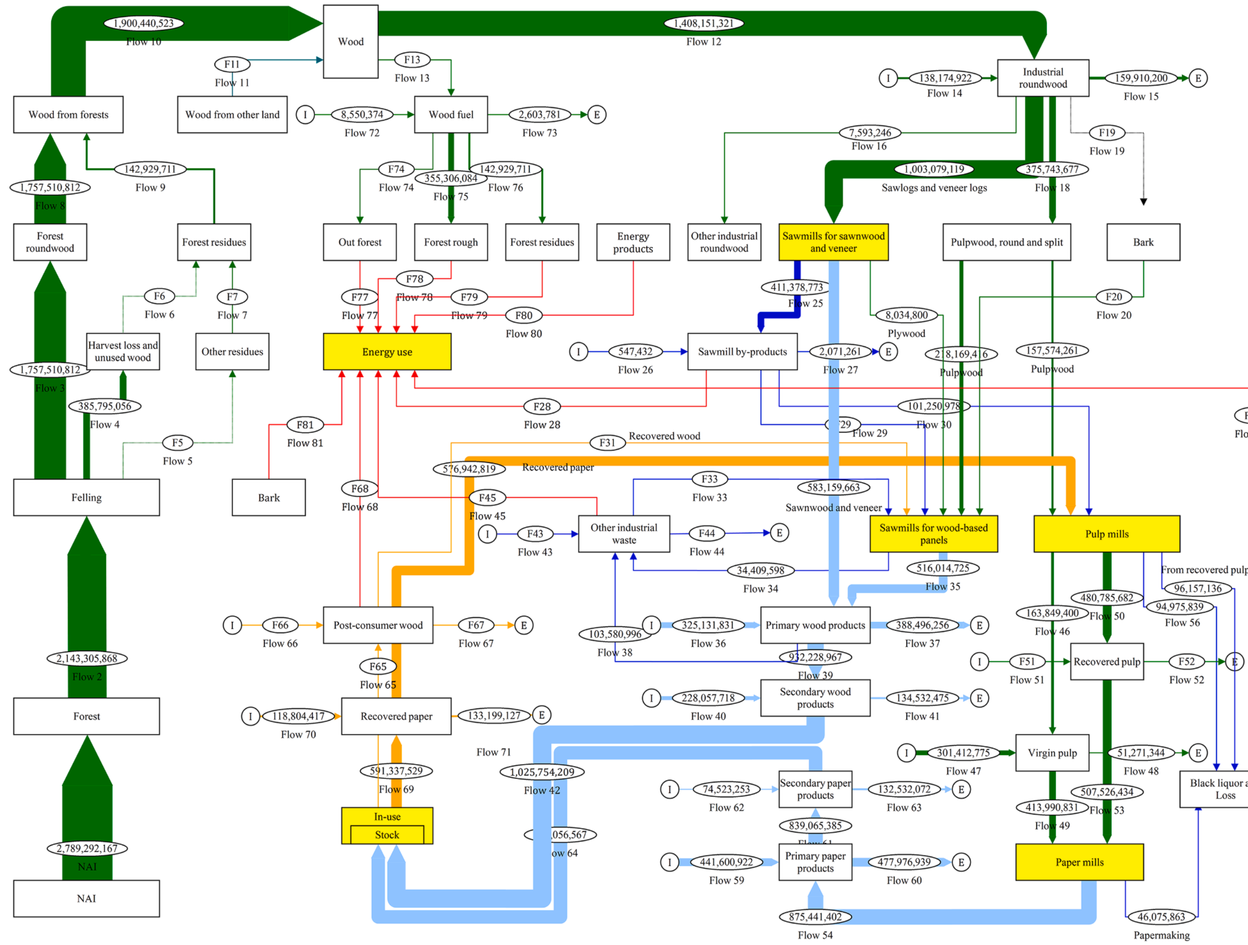

Fig. 2. Sankey diagram of the cumulative wood flows in Germany from 1991 to 2020. All values are measured in SWE.

printing, while the surge in fast food, express delivery services, and online shopping has become the main driver for paper packaging consumption.

Amidst climate action and energy transition efforts, the consuming non-combustible renewables and biofuels, primarily wood, was surging. Especially between 2002 and 2012, Germany's wood energy supply tripled to 165.9 TWh. Households have consistently been the largest consumers of wood energy, although their share decreased from 74.1% to 47.4%. The Renewable Energy Sources Act (EEG), which came into effect on April 1, 2000, is dedicated to regulating Germany's energy transition and the expansion of renewable energy, making the electricity supply greener yearly. Biomass plants, primarily based on combined heat and power (CHP), can increase total electricity and heat production with no significant change in primary energy consumption, thus enhancing overall energy utilization efficiency. In the industrial sector, wood energy mainly focuses on wood products, paper, pulp, and printing factories. An increasing amount of processing residues and recycled wood serve not only as intrinsic energy sources for factories but also as surplus output sold to the grid and used for district heating. The Figure of partial energy consumption indicates that forest logs, recovered wood, and forest residues are the main contributors, showing a growing trend.

3.3. Production of industrial roundwood and various products over time

Production levels are influenced not only by trade and consumption sectors but also constrained by the availability of raw materials. Overproduction may lead to the regression of forestry resources. Industrial roundwood experienced a growth of over 50% in the past 30 years, reaching a peak of around 65.6 Mm^3 in 2007 (Fig. 4). From 1991 to 2008, industrial roundwood maintained a net export surplus, but shifted to a net import scenario in the ten years to 2018. On average, 72.4% of apparent consumption was used for sawnwood, veneer, and plywood production, while 27.1% was used for wood-based panels and pulps. On the other hand, the import and export of wood fuel have remained relatively small, nearly keeping pace with consumption growth.

Sawnwood production doubled from 13.3 Mm^3 in 1991 to 26.2 Mm^3 in 2020, with the proportion of sawn softwood increasing from 87.1% to 96.2%. Veneer and plywood, although not showing the same downward trend, both shrunk to less than a quarter of the original output, about 0.1 Mm^3. Veneer fell precipitously in 2009 to one-third of the previous year. Wood-based panels also showed a similar trend, with continuous growth before 2007, followed by a rapid decline and stabilization.

Paper and paperboard production increased by 65%, and stabilized at 22 to 23 million tonnes (Mt) in recent years. The growth and decline trends of graphic paper around 2007 were quite similar, indicating the "2007 peak" reoccurrence. In contrast, household sanitary and packaging paper showed significant growth in the past 30 years, especially packaging paper, which increased by about 160%. Concerning pulp production, virgin wood pulp output fluctuated between 1.8-3.0 Mt, averaging about 2.4 Mt, and also reached its peak of 3.0 Mt in 2007. The production of mechanical and chemical pulp showed a significant tradeoff, of which the growth of kraft pulp is the internal driving force. Recovered fiber pulp, benefiting from increased consumption and recycling rates, could maintain a rapid growth trend, with production surpassing 14 Mt by 2020.

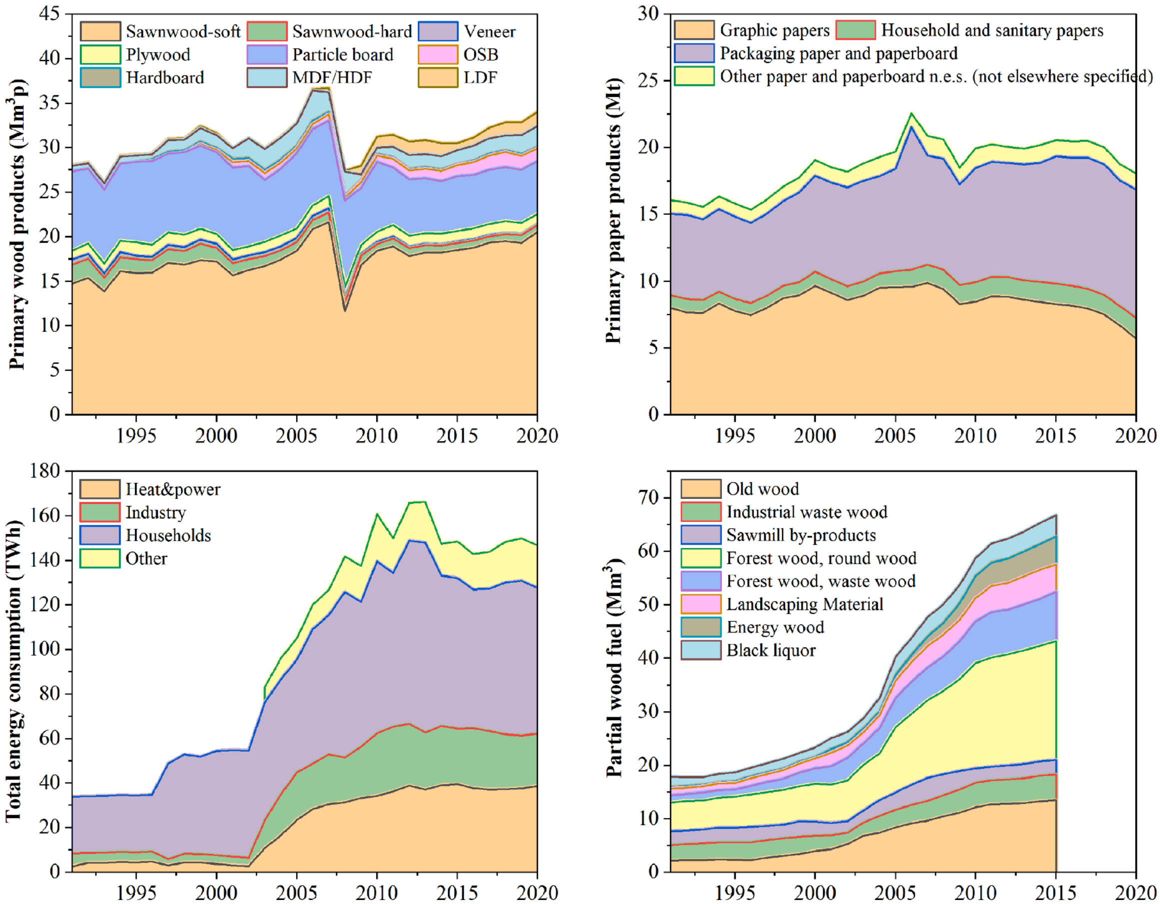

Fig. 3. Historical consumption trend of wood and wood products in Germany. Source:Eurostat (2020a), Eurostat (2020b), and Mantau (2012)

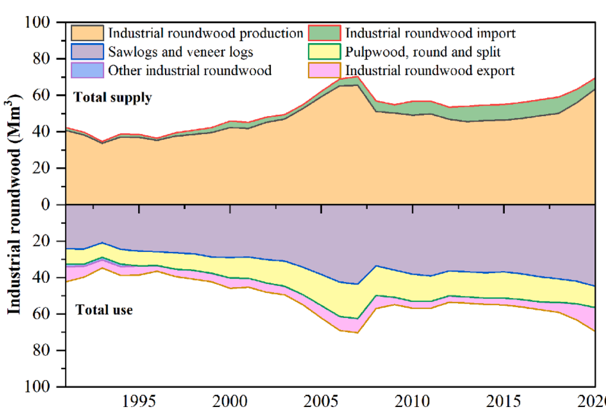

Fig. 4. The total supply and use of industrial roundwood in Germany from 1991 to 2020.

3.4. Germany's Wood Trade: Imports, Exports, and Shifts

Germany is a significant player in the global wood trade market, both as an importer and exporter (Fig. 5). The import volume of secondary wood products increased from 1.9 Mt in 1991 to 4.8 Mt in 2020, while the export volume increased from 1.0 Mt to 2.9 Mt. Overall, Germany's imports exceeded its exports, primarily driven by wooden furniture and packaging. Secondary paper products' import and export values increased by 57.7% and 132.8%, respectively. Except for a few years, most categories showed net exports, especially packaging paper, which experienced significant trade growth and a fivefold increase in net exports.

Both primary wood products and paper products were in a net export state. Especially sawn softwood's export volume increased yearly, without a substantial increase in imported primary wood products. It can be attributed to stable domestic demand, necessitating the export of excess production to countries, such as China, with high wood demand. Germany, however, heavily relied on imported wood pulp as a raw material supply. Imported kraft pulp provided the vast majority of virgin fiber supply, while dissolving pulp was 100% imported, as Germany had recently ceased production.

Although FAO/Eurostat statistics no longer disclosed trade values for roundwood sub-item since 1990, Germany has been mostly a net exporter of roundwood, except for the decade from 2009 to 2018. Of course, industrial roundwood mostly affects this, as wood fuel has a small trade value, which correlates to its value. As for other wood energy products, based on limited data from the past decade, Germany has been an exporter of pellets while importing briquettes and charcoal. In any case, It is worth noting that around 2007, something significant occurred that profoundly affected the subsequent timber supply chain, warranting further consideration.

3.5. Rising waste generation and cascading use driven by consumption

Wood waste has notably increased in Germany recently due to rising wood product consumption. However, the generation of construction and demolition waste wood has remained relatively stable, accounting for 1.2% to 1.5% of construction and demolition waste, hovering at 3 Mt over the past decade. The notable surge in wood waste comes from Section E (NACE Rev. 2 classification), which includes water supply, sewage, waste, and pollution control activities. The consumption of

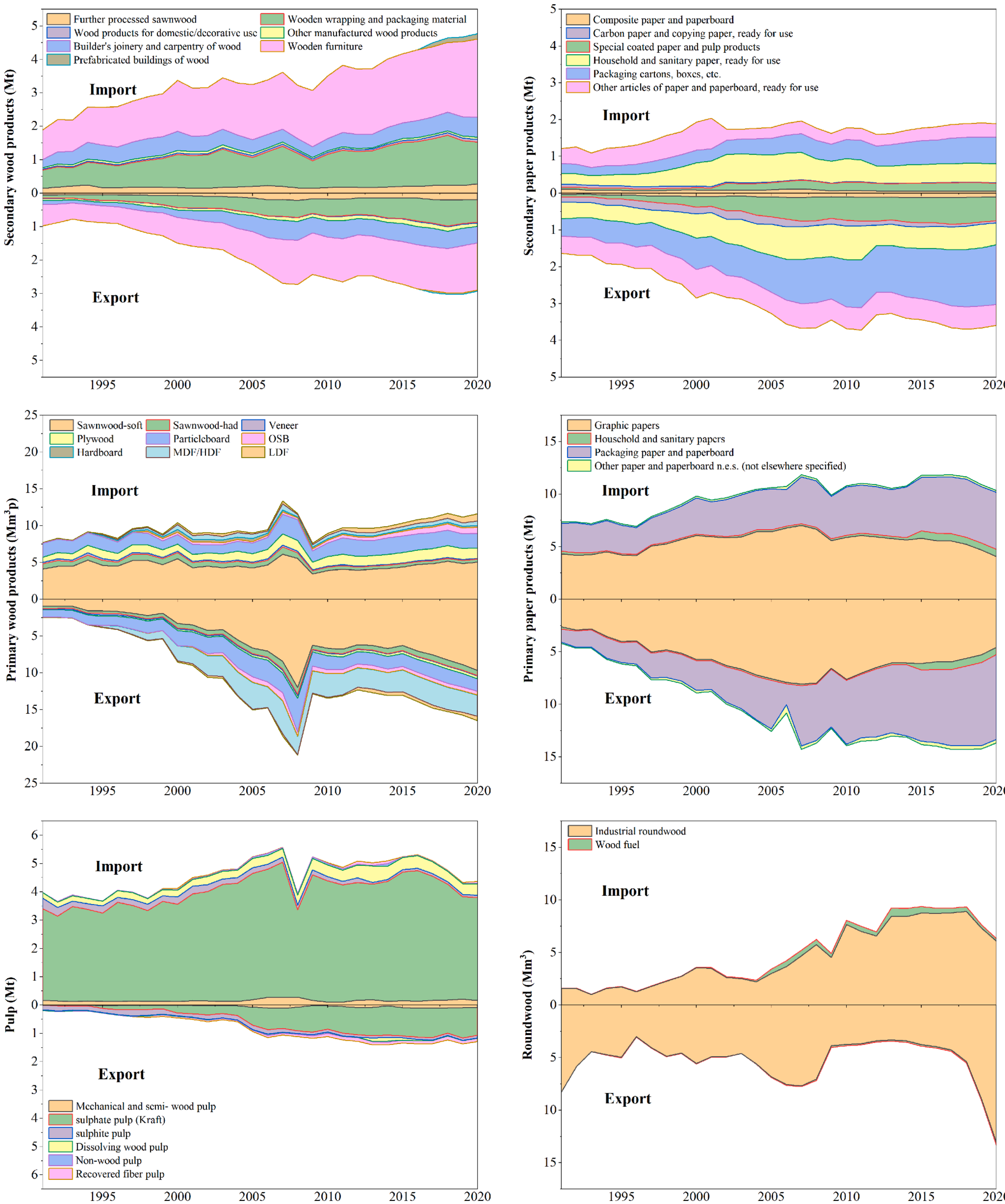

Fig. 5. Trade of wood and wood products in Germany from 1991 to 2020. Imports and exports are presented visually on both sides of the x-axis.

wooden packaging has particularly driven this rapid increase.

Waste paper recycling had a higher growth rate than paper product consumption, and the collection in 2009 was twice as high as that in 1991 (as shown in Fig. 6). Although various definitions of recycling and utilization rates exist, both have undeniably improved. Particularly in Germany, despite consistently exporting secondary paper products, the export value of paper products surpassed the import value for the first time in 2002, with the gap continuously widening. To adapt to the decrease in total waste paper, the German market changed in 2010, significantly increasing the import of waste paper and completely reversing its previous net export status.

Eurostat statistics show that in the past ten years, the utilization rate of waste wood has reached 89% of the production volume, of which 65% was used for energy generation while 24% was utilized as secondary

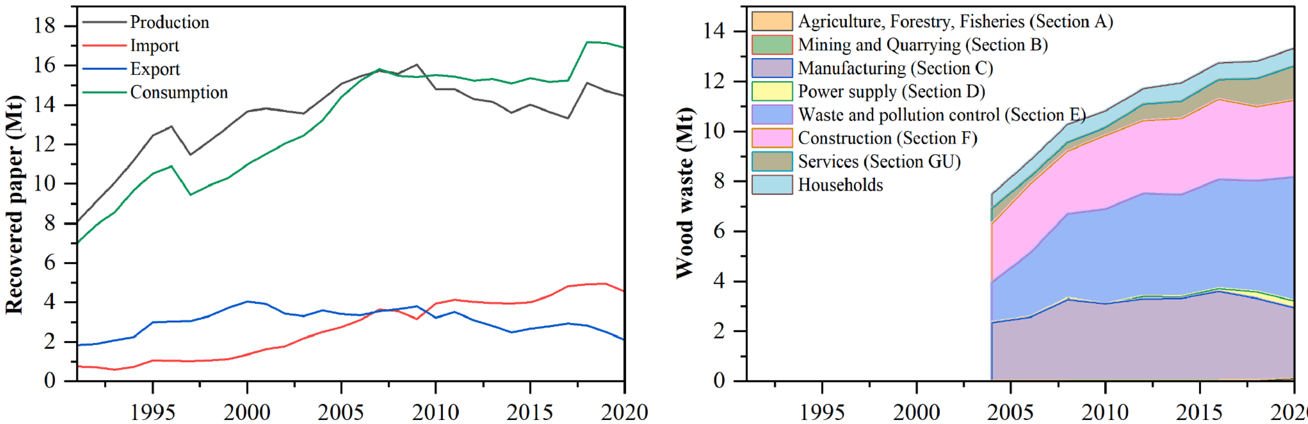

Fig. 6. Generation of waste paper and waste wood in Germany.
Source: Eurostat (2020b) and Eurostat (2020c)

materials. The majority of energy waste wood was consumed by large and small biomass plants, as well as households, of which large biomass plants used more than 80%. Less than half of the material waste wood was used for particleboard production, while the remainder may be used for other purposes or as internal fuel by wood-based panel manufacturers. Encouragingly, the proportion of material recycling is steadily increasing each year.

3.6. *Gradually slowing growth of forest reserves and wood fiber stocks*

German forests account for about one-third of the country's land area, and the standing timber in forests has increased by about 21.9% in the past three decades, reaching 3800 Mm^3 (Eurostat, 2020b). The net increment of forest reserve remained positive until 2007 when it encountered negative forest growth. Subsequent adjustments led to a recovery in forest increment, but it has declined recently. As of 2020, the annual forest increment has dropped to 2.5 Mm^3, though this estimation may still be underestimated due to wood fuel calculations by FAO/Eurostat. Another analysis of circular wood flows in Germany in 2020 revealed that the volume of wood felling had exceeded the NAI, and the reverse growth of forest volume has reappeared.

Despite importing a substantial amount of secondary wood products, Germany's overall trade balance turned positive after 2000 as the export of primary wood products in solid wood equivalent surpassed imports. Accounting for losses from woodworking and construction installation, the actual conversion of wood fibers into storage increased from 10.8 Mt to 14.0 Mt in 2020, with a peak in 2007 (14.8 Mt) and a sharp decline in 2008 (9.8 Mt). The collection of waste wood has been consistently increasing from 2014 to 2020, leading to a continuous reduction in the net increase of wood in society, stabilizing at 5.5 Mt/yr.

The fiber of paper products consumed in Germany increased from 9.4 Mt in 1991 to 12.5 Mt in 2006, then fell back to 9.8 Mt in 2020. However, overall, the consumption of paper products remains stable, averaging about 10.5 Mt per year. The quantity of recovered paper experienced significant growth before 2010 but fluctuated in the past decade. The annual fiber increment of paper products shows an absolute downward trend from the initial year, but no clear rule can be generalized. Furthermore, much non-recyclable waste paper has not been counted, suggesting that the paper stock would theoretically be smaller.

3.7. *Decline in forest carbon sinks and unaddressed substitution effects*

Under the current statistical rules, once trees are cut down, they are considered carbon emissions, while carbon storage only includes forest carbon sinks and wood products stock (Schulze et al., 2021). The potential substitution effects of materials and energy have not been accounted for. The carbon in waste wood and paper is counted again when used as secondary materials, while using them as secondary fuels produces carbon emissions. Therefore, whole waste is excluded from society's carbon sink. The ongoing wood demand growth in Germany, coupled with the approaching NAI, has led to a decline in the growth rate of forest carbon sinks.

Over 30 years, the forest carbon sink has only increased by about 160 million tons of carbon (MtC), reaching a total carbon sink of 868 MtC in standing timber by the end of 2020. The full carbon stored in consumed wood and paper products has reached 332 MtC, with an average annual increase of 11 MtC. However, as waste wood and paper production increased, carbon storage in these products declined significantly. Over the past 15 years, the net carbon increment of wood and paper products decreased from 6.4 MtC in 2006 to 3.4 MtC in 2020. In contrast, the forest carbon sink increment was less than 0.6 MtC in 2020.

Wood, as the main component of biofuels, represents a stable, clean, and renewable energy source. When wood comes from sustainable forest, meaning a net growth in carbon sinks, its combustion emissions are considered zero. Without considering the combustion efficiency, the primary energy consumption from wood has increased from 34 TWh in 1990 to 159 TWh in 2020. Compared to lignite, wood fuels have the potential to reduce carbon emissions by 343 MtC over 30 years, and even when compared to cleaner natural gas, they can still lower emissions by 173 MtC. The substitution effects of wood, especially energy use, should not be overlooked.

4. Discussion

4.1. *Uncertainty: comparison to other wood flow analysis*

Our comprehensive assessment of wood flows in Germany from 1991 to 2020 employs a bottom-up approach, focusing on roundwood and wood product consumption, trade, and production. However, due to limited data on the energy sector, we could not conduct an in-depth analysis in that area. Various statistical data are limited in capturing the full extent of wood usage, as they are subject to statistical thresholds, do not account for timber from small private forests, and fail to address illegal logging (Jochem et al., 2015).

So far, we only have access to partial official statistics, which we can compare with our evaluation results. FAO and Eurostat share the same roundwood and forest products dataset, while the Federal Ministry of Food and Agriculture (BMEL), Germany's forest monitoring agency, publishes the timber market report annually. However, discrepancies exist between BMEL and FAO/Eurostat regarding forest product production, leading to significant differences in the reported logging volume. Furthermore, these discrepancies primarily stem from variations in survey methodologies and data sources. BMEL, for instance, relies on data compiled by the Federal Statistical Office from state-level data, while FAO/Eurostat gather and consolidate statistics through Joint Forest Sector Questionnaire (UNECE/FAO, 2021). The Thünen Institute plays a crucial role in wood monitoring and evaluation and possesses the most detailed surveys on the consumption of various raw materials.

Our evaluation of forest harvesting generally follows a similar trend to these official statistics but differs in specific values (Fig. 7). According to a study by the Thünen Institute (Jochem, 2022), BMEL's official statistics significantly underestimated the harvesting volume, covering only about 79% of the total, with an average annual unrecorded logging volume of approximately 140,000 m^3. Such a substantial discrepancy could h have significant implications for the calculation of forest reserves and carbon sinks. Persistently incorrect data, where wood harvesting remains far below NAI, can lead to erroneous decision-making by governments, the wood industry, and consumers. While our simulation results are not real wood flow data, more accurate figures can reduce the occurrence of such misjudgments. On the other hand, the data from FAO and the Thünen Institute align closely, with only minor discrepancies in the early figures. As our assessment relies on data from FAO/Eurostat for wood fuel and estimates industrial roundwood production based on their forest product data, the gap between the two data sets is relatively small. Compared to the three official statistics, our assessment data show more moderate fluctuations around 2000, 2007, 2009, and 2017.

The most reasonable explanation for these differences lies in the data collection methodologies. All three official statistics rely on questionnaire surveys to gather wood data throughout Germany. In contrast, our assessment is based on production data and fixed conversion factors unaffected by specific circumstances. For instance, the yield of sawnwood frequently fluctuates (Eurostat, 2020b; Mantau et al., 2010), unlike our assumption of 59% for softwood and 60% for hardwood. Additionally, unrecorded roundwood still enter the consumer market and are processed into different products, even though no official records exist.

4.2. Retrospective wood flows, trends and divers from 1991 to 2020

Due to increased forest harvesting maturity, natural disturbances, salvage logging, and the expansion of the wooden and energy markets, Europe's total harvested forest area increased by 49% for 2016-2018 compared to 2011-2015. (Ceccherini et al., 2020). The construction and furniture sectors are major consumers of wood in Germany. Fluctuations in construction trends, economic conditions, and consumer preferences can impact wood consumption patterns. Wood fuel constitutes a minor portion of the roundwood supply, having little impact on trade exchange. Instead, industrial roundwood and wood products remain the primary drivers regulating the wood supply chain. Germany faced a shortage of sawnwood for domestic consumption before 2003, necessitating net imports of up to 4.0 Mm^3, covering 22% of the demand.

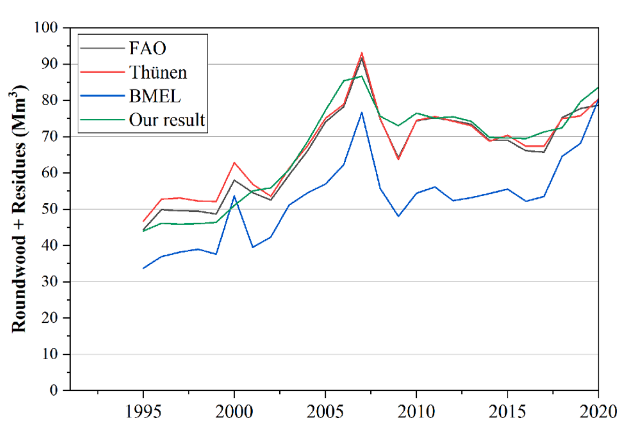

Fig. 7. Comparison of forest wood removal from different sources.

However, since 2003, the gap between production and consumption has been widening, leading to two export peaks in 2008 and 2020, with net export volumes reaching 6.6 and 4.9 Mm^3, respectively.

Salvage logging plays a significant role in altering the import and export trade situation in response to forest disturbances caused by climate change-triggered extreme weather events like wildfires, storms, snowstorms, insect outbreaks, droughts, and heat waves (Ceccherini et al., 2020). One notable example in Germany was the storm "Kyrill" in 2007, as shown in Fig. 8, which resulted in substantial forest damage amounting to 31.3 Mm^3 of dead wood, with 95% of the damaged timber being Norway spruce, profoundly affecting the wood supply chain (Holzwarth et al., 2020). This incident led to a peak in annual felling volume in 2007, reaching about 109 Mm^3. Surprisingly, there was also a slight increase in the import and export of industrial roundwood, sawnwood, and wood-based panels, marking an unprecedented peak in domestic consumption. The same year also witnessed record production and consumption values for virgin wood pulp, paper, and paperboard.

Additionally, the increasing damage caused by the bark beetle and droughts has become a concern in recent years. Bark beetle outbreaks often follow storms, and their infestation occurs when the temperature is above 16°C, leading to an increase in damage due to climate change-induced early arrival of summers in Germany. Severe droughts in 2003, 2018, and 2019 have also contributed to forest disturbances. Salvage logging is the most common practice for restoring economic and ecological value. Restorative afforestation prefers coniferous trees over deciduous trees, as they offer faster financial returns, resulting in about twice the plantation of coniferous trees (Kamp et al., 2020). Fortunately, Georgiev et al. (2021) found that these disturbances and salvage logging do not affect the quality of streamwater and drinking water.

4.3. Qualitative future trend for wood demand in Germany

Estimating future development trends by scenario analysis is a common practice. However, quantitatively analyzing the entire wood flow in Germany proves challenging due to the complexities of import and export trade and fluctuations in product demand. Numerous development plans in Germany are expected to change wood demand over the next 30 years. For example, Germany's Climate Protection Plan 2050 (BMUB, 2016), passed in November 2016, focuses on protecting and enhancing the carbon sink of forests. The Forest Strategy 2050 (BMEL, 2021b) also emphasizes sustainable forest management, such as selective logging, reforestation, and biodiversity conservation, to ensure a continuous wood supply while minimizing negative environmental impacts. The "Charter for Wood 2.0" (BMEL, 2018) covers core action areas, including using wood in urban and rural construction, exploring the new potential in the bioeconomy, material and energy efficiency,

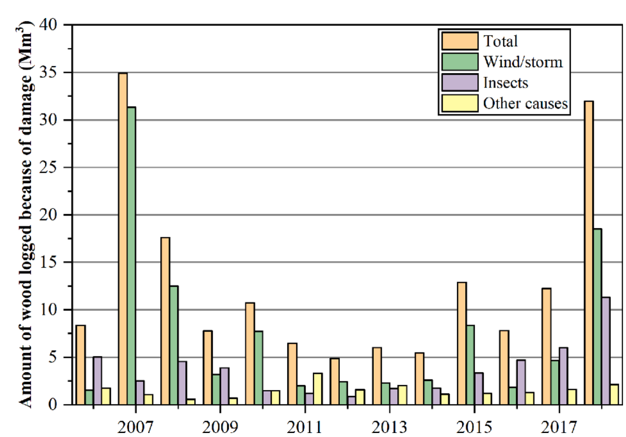

Fig. 8. Amount of wood logged because of damage in Germany from 2006 to 2008.
Source: Statistisches Bundesamt (Destatis), 2023

and the responsible utilization of forests and wood as resources.

In the context of renewable energy transformation, biofuels have played a significant role in Germany's primary energy supply (Fig. 9), with wood contributing about 142.4 TWh, growing from 0.8% in the 90s to 4.4% in 2020. Apart from energy conversion, the final energy consumption of wood also increased from 1.2% to 4.8%, with households accounting for about 68.4%, totaling 1621 TWh. Wood has provided more than 10% of household energy, mainly heating and hot water. However, given Germany's ambitious plan to achieve 80% of electricity from renewable sources by 2050, the absolute value of wood energy is bound to grow (Klaus et al., 2010).

The construction industry, as a major contributor to GHG emissions, faces a pressing need to respond to climate policies. Current efforts focus mainly on reducing the non-renewable primary energy consumption during the operational phase, particularly through existing building retrofits. To achieve the building sector's climate protection targets outlined in the Federal Climate Protection Act, the federal government plans to promote further energy-efficient building renovations, including increasing the renovation rate and transitioning to decarbonized heating. That may increase demand for low-density insulation panels and other wood products.

As energy efficiency improves, attention will be given to the non-renewable primary energy and materials required for building construction, as well as the efficient use of raw materials and carbon emissions. Resource-efficient and climate-friendly constructions, such as wooden structures and lightweight buildings, have been gaining popularity and have seen a rise in their proportion in new constructions in recent years, as shown in Fig. 10. However, the overall demand for wood and wood products in new buildings might not increase significantly due to falling building permits caused by a sharp increase in existing building areas (Destatis, 2020, 2022).

Wooden furniture generally has a stable service life, and the demand for furniture matching new buildings and regular updates in stock buildings is expected to continue growing. Recent trends indicate an increasing annual consumption of wood and paper packaging products, benefiting from the prosperity of the consumer market.

4.4. *Future strategies for sustainable wood flow*

With the net annual growth of forests remaining unchanged, the increasing demand for roundwood consumption and exports has approached the available potential of sustainable forest management. The loss of German forests is no longer a mere warning. Past production and consumption gaps show that although exporting wood and wood products brought substantial economic benefits, it also resulted in missed opportunities for domestic use and carbon storage of roundwood. Especially in qualitative analysis, domestic wood consumption in Germany is expected to continue rising over the next 30 years. Therefore, it is suggested to adjust the forestry logging plan and reduce exports of wood and wood products, such as industrial roundwood and sawnwood, combined with domestic demand. Although this might sacrifice some economic benefits for ecological significance, it is the simplest strategy to address the imbalance between wood supply and demand.

The second approach is to adapt the raw material input of wood products to expand the cascade potential of post-consumer wood and processing residues. According to the research report by Döring et al. (2021), there have been significant changes in the raw materials used for wood-based panels in recent years. The share of industrial roundwood has decreased, and the cascade factor for wood products has increased. For example, in MDF/HDF, the proportion of industrial roundwood declined from 67% in 2010 to 36% in 2020, with sawmill by-products (62%) becoming the main component. While particle board, the most important cascade product, the share of post-consumer wood and other industrial waste wood increased from 24% to 42%, reducing the demand

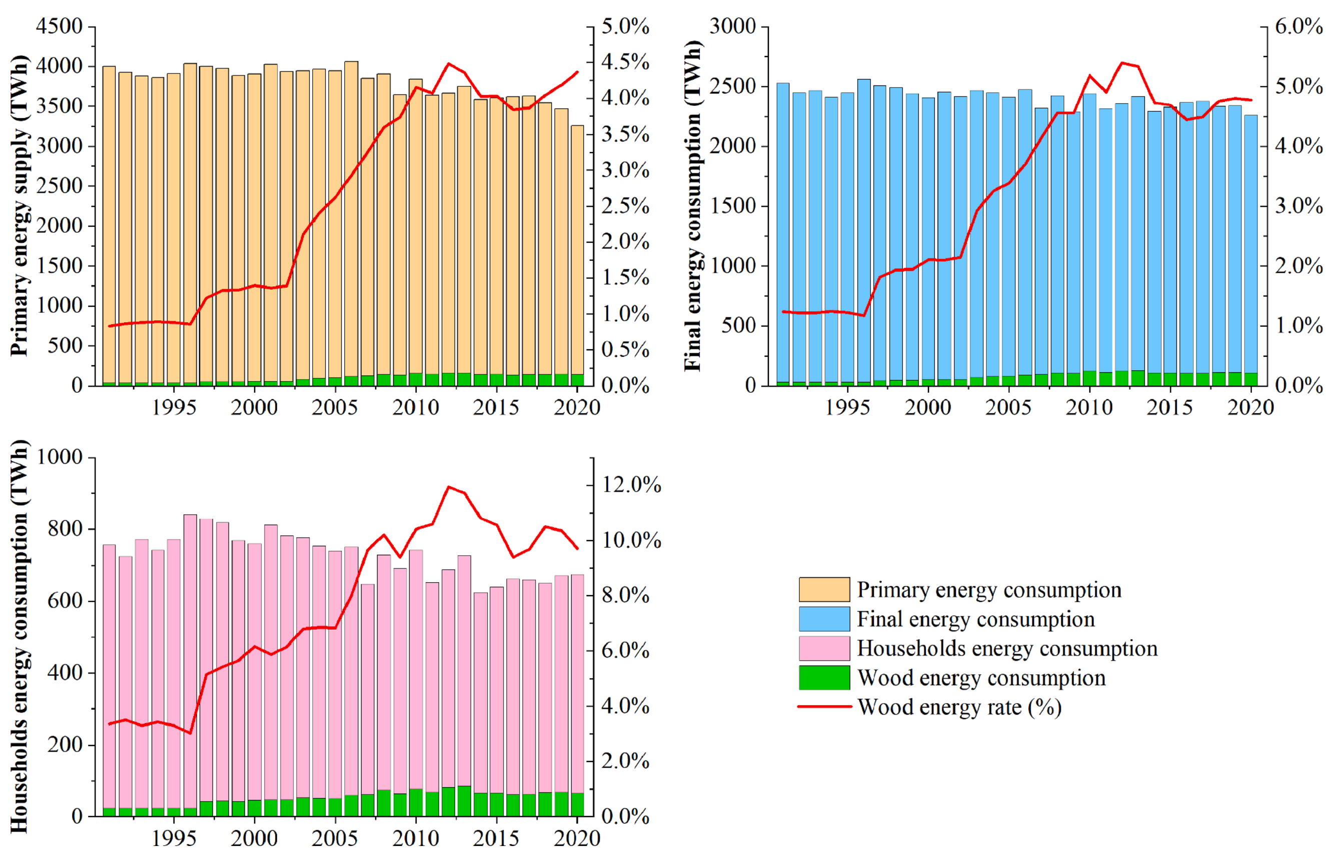

Fig. 9. Changes in the utilization of wood energy in primary energy supply, final energy consumption and household energy consumption in Germany from 1991 to 2020.

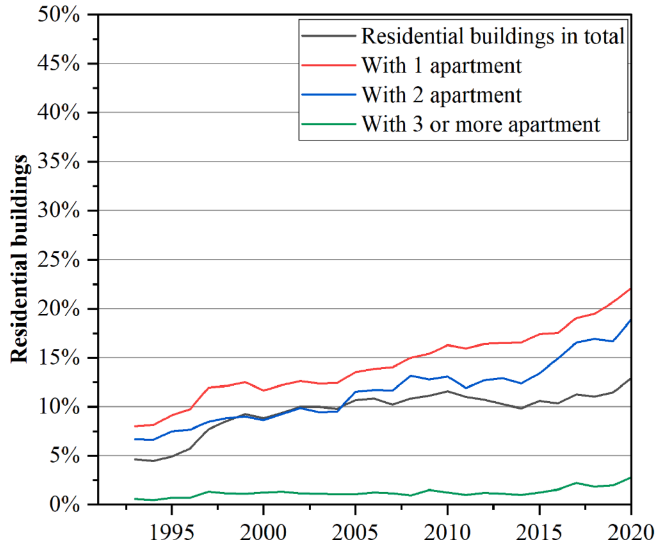

Fig. 10. Volumetric share of wooden buildings in new buildings in Germany.

for sawmill by-products and industrial roundwood. Italy has even produced particleboard without using roundwood, relying on 95% recovered wood and 5% industrial waste wood (Meinlschmidt et al., 2016), which indicates significant potential for Germany to adjust its raw material supply for wood-based panels.

Furthermore, using sawmill by-products to produce virgin wood pulp and energy products, especially pellets, consumes significant raw materials (DEPI, 2023). The shortage of sawmill by-products in secondary materials can be alleviated by utilizing low-pollution waste wood and forest residues for pellet manufacturing.

Increasing wood cascades will reduce the amount of direct waste wood fuel, necessitating the exploration of additional wood sources. Forest residues, including harvest losses, unused stemwood, bark, branches, tree tops, leaves, roots and stumps, offer considerable potential as harvesting by-products. The amount of forest residues produced almost equal to the quantity of harvested roundwood. However, currently, only around 30% of these residues can be utilized due to their diverse types and removal difficulty, resulting in the utilization of 7.4 Mm^3 of forest residues in 2020, which accounted for 9.5% of the theoretical production and only 30.6% of the exploitable amount. If all available forest residues can be cost-effectively removed, Germany's annual wood supply could increase by at least 10 Mm^3, providing robust support for renewable energy supply.

Additionally, wood is commonly used as an energy source for private households, sawmills and pulp mills. The conversion types of wood into electricity and heat can be categorized into cogeneration (CHP), pure heat, and pure power (Eurostat, 2020a). Technological progress has improved energy efficiency, with pure power generation having the lowest efficiency at around 30%, while heat production can reach 80%. The combined heat and power plant (CHP) boasts a conversion efficiency ranging from 50% to 70%, especially for active producers, where the heat-power output ratio has increased from 0.31 to 1.94, significantly improving the overall conversion efficiency from 42.8% to 68.3%. Currently, wood accounts for 4% of the heating type in new buildings, but by 2020, over 5.5 million apartments were still using wood (Dominik Jochem, 2023). Implementing heating system renovations, such as CHP and district heating, can effectively reduce wood losses in energy conversion and achieve wood savings.

Engineered wood and composite wood offer superior strength and stability to traditional solid wood and can be designed with special functionalities. For instance, compressed wood is extensively used in furniture, construction, packaging, and even musical instruments. In the wood tubes study conducted by Haller, compressed wood with a tubular structure demonstrated high mechanical properties while using minimal material (Sandberg et al., 2013). Furthermore, the absence of adhesives ensures that it will not be treated as hazardous waste after disposal (Kutnar et al., 2015; Namari et al., 2021), increasing the possibilities for cascading and demonstrating environmental friendliness.

5. Conclusions

Based on a bottom-up approach, the wood flow analysis in Germany from 1991 to 2020 reveals critical findings. German forests have been the primary source of wood consumption, with 76.8% of the net annual increment felled in the last three decades. Germany's prominence as a global wood trade player is evident, demonstrated by significant import and export volumes. Wood consumption showed substantial growth and volatility, primarily driven by clean energy and packaging demands. Besides market demand, wood flow patterns were also influenced by climate change and forest management. Notably, wood played a crucial role in carbon sequestration and energy substitution, resulting in 160 MtC in the forest carbon sink, 332 MtC in carbon storage from wood products, and 343 MtC in emissions reduction compared to lignite. The improvement in recycling rates for wood waste and paper contributes to sustainability efforts.

However, the study acknowledges certain limitations, including the absence of comprehensive data on the energy sector, with a primary focus on industrial roundwood. This led to shortcomings in depicting specific usage and trends of all wood fuels and energy products represented as primary energy content. Additionally, official data for wood waste only covers the years 2014 to 2016, while specific usage quantities for secondary wood products in construction, furniture, packaging, and other sectors are also lacking. Furthermore, due to the design objectives of the current flow model and the limitations of existing historical data, this study cannot measure the effectiveness of policies and actions in German wood flows by material flow indicators, as has been demonstrated by studies such as Hashimoto and Moriguchi (2004) and Hashimoto et al. (2004). Looking ahead to Germany's future wood development demands over the next thirty years, the study utilized qualitative rather than quantitative research, providing macro trends without detailed values. Future research should prioritize quantitative data gathering through scenario analysis to overcome these limitations. This approach will enable the evaluation of different strategies' potential and prioritize actions that maximize carbon storage and support sustainable development.

CRediT authorship contribution statement

Ruisheng Wang: Writing – review & editing, Writing – original draft, Conceptualization. **Peer Haller:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Conversion Factors

Tab. A.1
Conversion factors of sawnwood, wood-based panels, pulp and paper.

	Original unit	Yield	RWE	SWE	ODMT
Sawnwood/soft	m^3p	0.59	1.69	1.00	0.389
Sawnwood/hard	m^3p	0.60	1.67	1.00	0.563
Veneer sheets	m^3p	0.55	1.82	1.00	0.561
Plywood	m^3p	0.55	1.82	1.00	0.467
Particle board	m^3p	0.96	1.35	1.30	0.556
OSB	m^3p	0.90	1.44	1.30	0.516
Hardboard	m^3p	0.88	2.72	2.40	0.968
MDF/HDF	m^3p	0.90	1.88	1.70	0.685
Other fiberboards	m^3p	0.95	0.63	0.60	0.238
	Original unit	Yield	RWE	SWE	ODMT
Mechanical pulp	t (10% MC_w)	0.93	2.48	2.31	0.900
Kraft pulp	t (10% MC_w)	0.48	4.82	2.31	0.900
Sulfite pulp	t (10% MC_w)	0.48	4.11	1.98	0.900
Dissolving pulp	t (10% MC_w)	0.35	6.33	2.21	0.900
Non-wood pulp	t (10% MC_w)	0.40	5.54	2.21	0.900
Recovered pulp	t (10% MC_w)	0.83	3.03	1.52	0.600
Papermaking	t (7.9% MC_w)	0.95	2.99	1.50	0.592
Recovered paper	t (10% MC_w)	-	2.92	1.46	0.578

Appendix B. Production, import, export and consumption data of key wood and paper products

Data source: Eurostat (2020b)

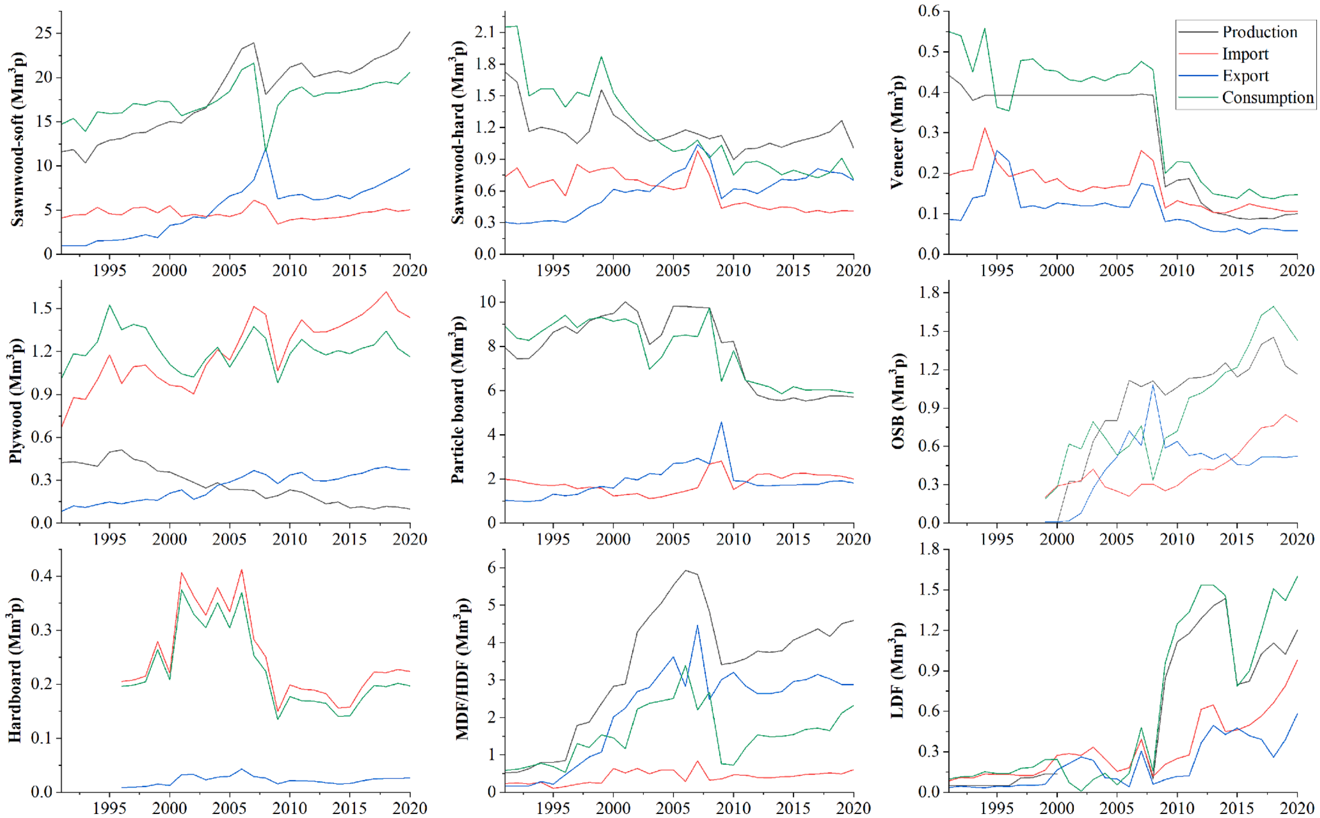

Fig. B1. Production, import, export and consumption data of primary wood products.

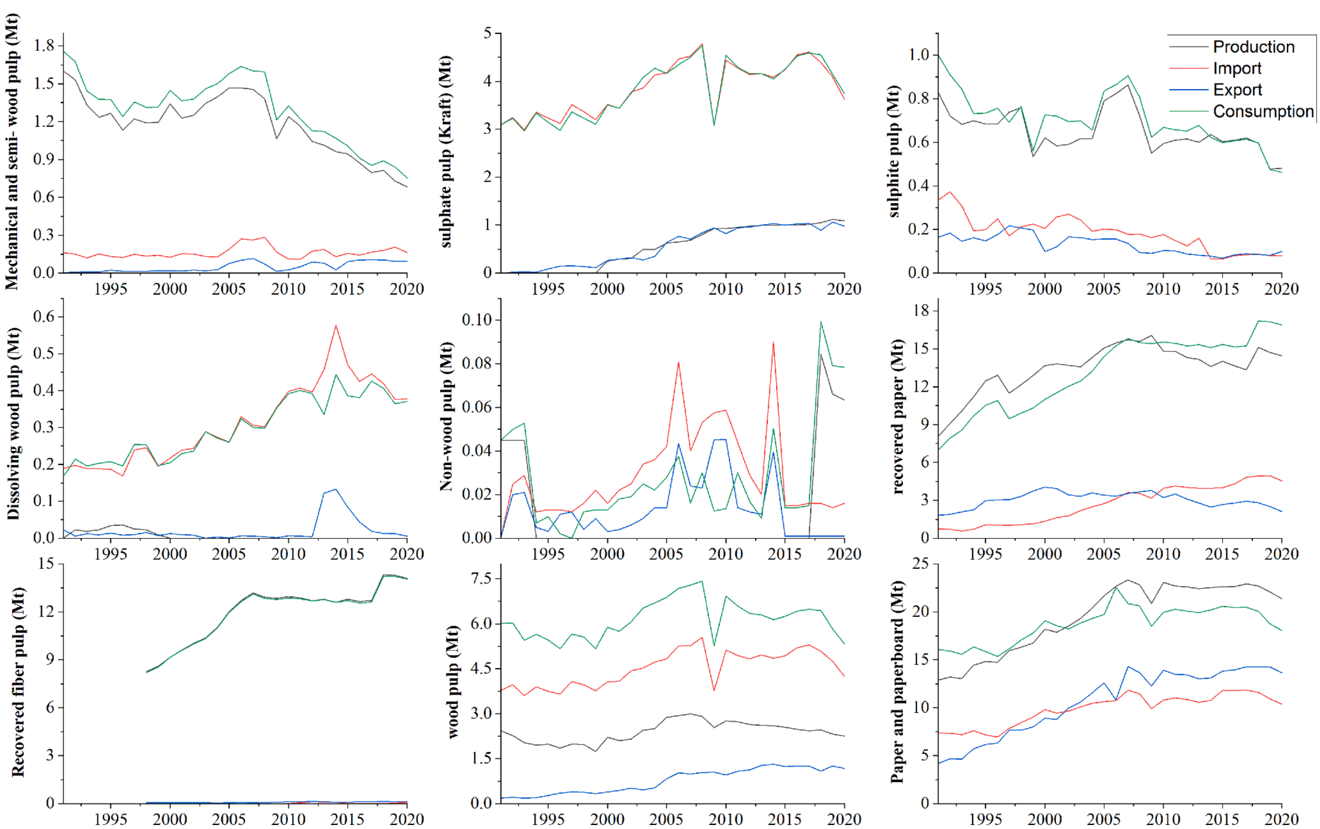

Fig. B2. Production, import, export and consumption data of pulps.

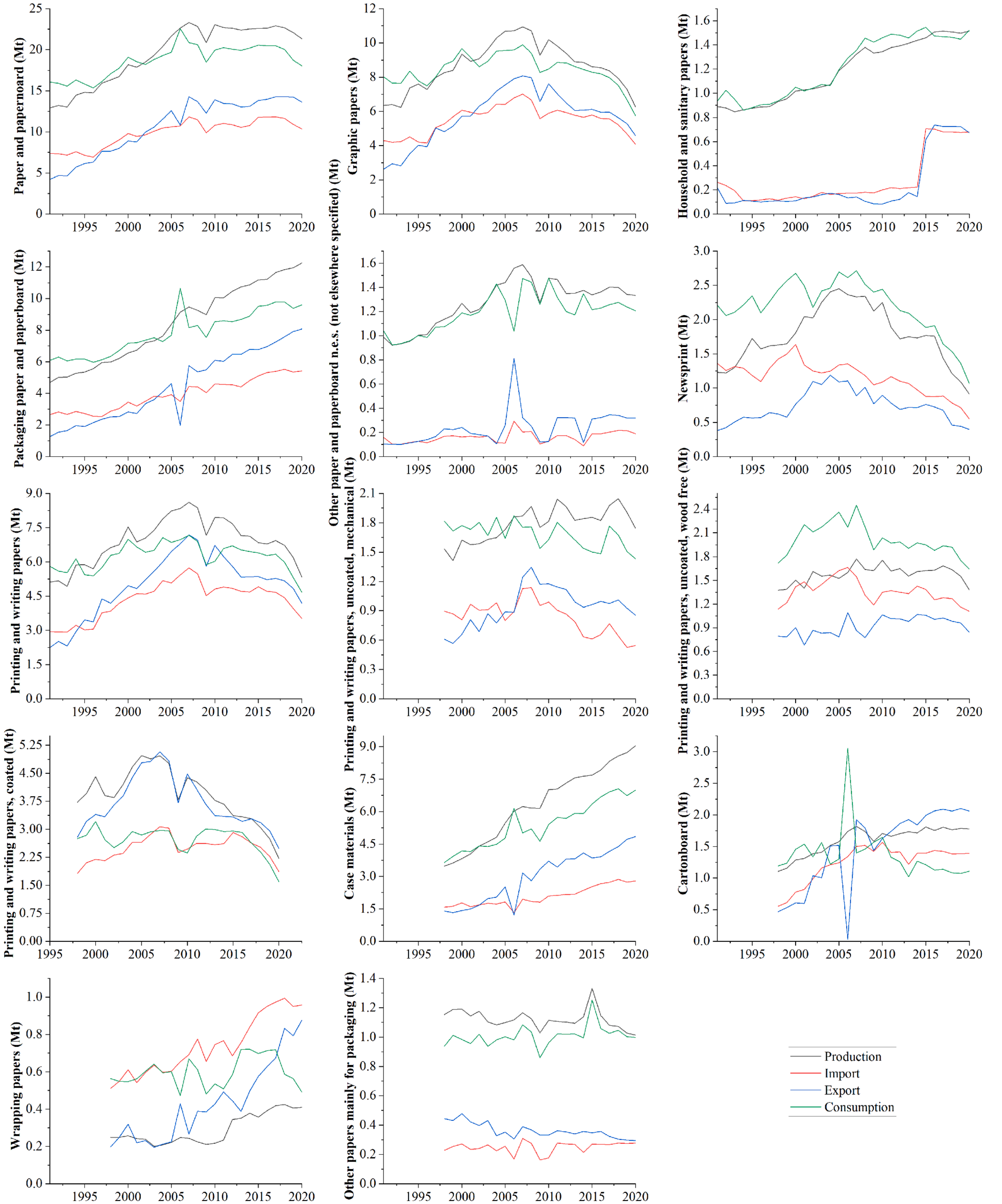

Fig. B3. Production, import, export and consumption data of primary paper products.

References

Abbass, K., Qasim, M.Z., Song, H., Murshed, M., Mahmood, H., Younis, I., 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ. Sci. Pollut. Res. Int. 29 (28), 42539–42559. https://doi.org/10.1007/s11356-022-19718-6.

Augiseau, V., Barles, S., 2017. Studying construction materials flows and stock: A review. Resour. Conserv. Recycl. 123, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002.

Augustsson, A., Sorme, L., Karlsson, A., Amneklev, J., 2017. Persistent Hazardous Waste and the Quest Toward a Circular Economy The Example of Arsenic in Chromated Copper Arsenate-Treated Wood. J. Ind. Ecol. 21 (3), 689–699. https://doi.org/10.1111/jiec.12516.

Bais, A.L.S., Lauk, C., Kastner, T., Erb, K., 2015. Global patterns and trends of wood harvest and use between 1990 and 2010. Ecol. Econ. 119, 326–337. https://doi.org/10.1016/j.ecolecon.2015.09.011.

Bergeron, F.C., 2014. Assessment of the coherence of the Swiss waste wood management. Resour. Conserv. Recycl. 91, 62–70. https://doi.org/10.1016/j.resconrec.2014.07.011.

Bergeron, F.C., 2016. Energy and climate impact assessment of waste wood recovery in Switzerland. Biomass & Bioenergy 94, 245–257. https://doi.org/10.1016/j.biombioe.2016.09.009.

BMEL, 2018. Mitigating climate change. Creating value. Utilising resources efficiently. https://www.bmel.de/SharedDocs/Downloads/EN/_Forests/charter-for-wood-2.pdf?__blob=publicationFile&v=5. Accessed 01.08.2023.

BMEL, 2021a. Holzmarktbericht 2020: Abschlussergebnisse für die Forst- und Holzwirtschaft des Wirtschaftsjahres 2020. https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/holzmarktbericht_2020.html. (Accessed 01.06.2023).

BMEL, 2021b. Waldstrategie 2050. https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/Waldstrategie2050.html. (Accessed 01.08.2023).

BMUB, 2016. Climate Action Plan 2050 - Principles and goals of the German government's climate policy. https://www.bmuv.de/en/publication/climate-action-plan-2050-en. (Accessed 01.08.2023).

Brunet-Navarro, P., Jochheim, H., Kroiher, F., Muys, B., 2018. Effect of cascade use on the carbon balance of the German and European wood sectors. J. Cleaner Prod. 170, 137–146. https://doi.org/10.1016/j.jclepro.2017.09.135.

Brunner, P.H., Rechberger, H., 2016. Handbook of material flow analysis: For environmental, resource, and waste engineers. CRC press.

Ceccherini, G., Duveiller, G., Grassi, G., Lemoine, G., Avitabile, V., Pilli, R., Cescatti, A., 2020. Abrupt increase in harvested forest area over Europe after 2015. Nature 583 (7814), 72–77. https://doi.org/10.1038/s41586-020-2438-y.

Cote, M., Poganietz, W.R., Schebek, L., 2015. Anthropogenic Carbon Stock Dynamics of Pulp and Paper Products in Germany. J. Ind. Ecol. 19 (3), 366–379. https://doi.org/10.1111/jiec.12210.

DEPI, Pellet production. https://www.depi.de/pelletproduktion. (Accessed 01.06.2023).

Destatis, 2020. Buildings and housing statistical Database. https://www-genesis.destatis.de/genesis/online?operation=themes&levelindex=0&levelid=1685630672308&code=31#abreadcrumb. (Accessed 01.06.2023).

Destatis, 2022. Baugenehmigungen von Wohn- und Nichtwohngebäuden nach überwiegend verwendetem Baustoff - Lange Reihen von 1980 bis 2021. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Publikationen/Downloads-Bautaetigkeit/baugenehmigungen-baustoff-pdf-5311107.html. (Accessed 01.06.2023).

Dominik Jochem, C.M., Sebastian Glasenapp, Holger Weimar, 2023. Energetischer Holzverbrauch der privaten Haushalte. https://www.umweltbundesamt.de/publikationen/energetischer-holzverbrauch-der-privaten-haushalte. (Accessed 01.06.2023).

Döring, P., Gieseking, L., Mantau, U., 2020. Sägeindustrie 2018 - Einschnitt- und Produktionsvolumen. http://www.infro.eu/downloads/studien/SGW_2018_Teilbericht.pdf. (Accessed 01.06.2023).

Döring, P., Gieseking, L., Mantau, U., 2021. Holzwerkstoffindustrie 2020 - Entwicklung der Produktionskapazität und Holzrohstoffnutzung. http://www.infro.eu/downloads/studien_neu_2022/S02%20Holzwerkstoffindustrie%202020.pdf. (Accessed 01.06.2023).

Džubur, N., Laner, D., 2018. Evaluation of Modeling Approaches to Determine End-of-Life Flows Associated with Buildings: A Viennese Case Study on Wood and Contaminants. J. Ind. Ecol. 22 (5), 1156–1169. https://doi.org/10.1111/jiec.12654.

Egenolf, V., Vita, G., Distelkamp, M., Schier, F., Hüfner, R., Bringezu, S., 2021. The Timber Footprint of the German Bioeconomy—State of the Art and Past Development. Sustainability 13 (7). https://doi.org/10.3390/su13073878.

Eurostat, 2020a. Energy balances statistical Database. https://ec.europa.eu/eurostat/cache/infographs/energy_portal/enviz.html?language=EN. (Accessed 01.06.2023).

Eurostat, 2020b. Eurostat Forestry statistical Database. https://ec.europa.eu/eurostat/web/forestry/data/database. (Accessed 01.06.2023).

Eurostat, 2020c. Waste generation and treatment. https://ec.europa.eu/eurostat/databrowser/explore/all/envir?lang=en&subtheme=env.env_was.env_wasgt&display=list&sort=category&extractionId=ENV_WASGEN. (Accessed 01.06.2023).

FAO/ITTO/UN, 2020. Forest product conversion factors. 10.4060/ca7952en. (Accessed 01.06.2023).

Furubayashi, T., Sumitomo, Y., Nakata, T., 2017. Wood Flow Chart for Japan: Material and Energy Utilization. Journal of the Japan Institute of Energy 96 (7), 206–216. https://doi.org/10.3775/jie.96.206.

Georgiev, K.B., Beudert, B., Bässler, C., Feldhaar, H., Heibl, C., Karasch, P., Müller, J., Perlík, M., Weiss, I., Thorn, S., 2021. Forest disturbance and salvage logging have neutral long-term effects on drinking water quality but alter biodiversity. For. Ecol. Manage. 495 https://doi.org/10.1016/j.foreco.2021.119354.

Gieseking, L., Döring, P., Mantau, U., 2021. Holz- und Zellstoffindustrie 2019 - Entwicklung der Produktionskapazität und Faserrohstoffnutzung. http://www.infro.eu/downloads/studien_neu_2022/S03%20Holz-%20und%20Zellstoffindustrie%202019.pdf. (Accessed 01.06.2023).

Gieseking, L., Karstedt, M., Mantau, U., 2020. Sperrholzindustrie 2019 - Industriestruktur- und Produktionsvolumen. http://www.infro.eu/downloads/studien_neu_2022/S05%20Sperrholzindustrie%202019.pdf. (Accessed 01.06.2023).

Gieseking, L., Mantau, U., 2020. Furnierindustrie 2019 - Industriestruktur und Produktionsvolumen. http://www.infro.eu/downloads/studien_neu_2022/S0420Furnierindustrie202019.pdf. (Accessed 01.06.2023).

Guo, D.M., Huang, L.Z., 2019. The State of the Art of Material Flow Analysis Research Based on Construction and Demolition Waste Recycling and Disposal. Buildings 9 (10). https://doi.org/10.3390/buildings9100207.

Hashimoto, S., Moriguchi, Y., 2004. Proposal of six indicators of material cycles for describing society's metabolism: from the viewpoint of material flow analysis. Resour. Conserv. Recycl. 40 (3), 185–200. https://doi.org/10.1016/s0921-3449(03)00070-3.

Hashimoto, S., Moriguchi, Y., Saito, A., Ono, T., 2004. Six indicators of material cycles for describing society's metabolism: application to wood resources in Japan. Resour. Conserv. Recycl. 40 (3), 201–223. https://doi.org/10.1016/S0921-3449(03)00101-0.

Holzwarth, S., Thonfeld, F., Abdullahi, S., Asam, S., Da Ponte Canova, E., Gessner, U., Huth, J., Kraus, T., Leutner, B., Kuenzer, C., 2020. Earth Observation Based Monitoring of Forests in Germany: A Review. Remote Sens 12 (21). https://doi.org/10.3390/rs12213570.

Islam, M.T., Huda, N., 2019. Material flow analysis (MFA) as a strategic tool in E-waste management: Applications, trends and future directions. J. Environ. Manage. 244, 344–361. https://doi.org/10.1016/j.jenvman.2019.05.062.

Jochem, D., 2022. Wood resource monitoring. https://www.thuenen.de/en/thuenen-topics/renewable-resources/bioeconomy/wood-resource-monitoring. (Accessed 01.08.2023).

Jochem, D., Weimar, H., Bosch, M., Mantau, U., Dieter, M., 2015. Estimation of wood removals and fellings in Germany: a calculation approach based on the amount of used roundwood. European Journal of Forest Research 134 (5), 869–888. https://doi.org/10.1007/s10342-015-0896-9.

Kalcher, J., Praxmarer, G., Teischinger, A., 2017. Quantification of future availabilities of recovered wood from Austrian residential buildings. Resour. Conserv. Recycl. 123, 143–152. https://doi.org/10.1016/j.resconrec.2016.09.001.

Kalt, G., 2015. Biomass streams in Austria: Drawing a complete picture of biogenic material flows within the national economy. Resour. Conserv. Recycl. 95, 100–111. https://doi.org/10.1016/j.resconrec.2014.12.006.

Kamp, J., Trappe, J., Dübbers, L., Funke, S., 2020. Impacts of windstorm-induced forest loss and variable reforestation on bird communities. For. Ecol. Manage. 478 https://doi.org/10.1016/j.foreco.2020.118504.

Kayo, C., Dente, S.M.R., Aoki-Suzuki, C., Tanaka, D., Murakami, S., Hashimoto, S., 2018. Environmental Impact Assessment of Wood Use in Japan through 2050 Using Material Flow Analysis and Life Cycle Assessment. J. Ind. Ecol. 23 (3), 635–648. https://doi.org/10.1111/jiec.12766.

Klaus, T., Vollmer, C., Lehmann, K.W.H., Müschen, K., Vollmer, C., Lehmann, K.W.H., Müschen, K., 2010. Energy target 2050: 100% renewable electricity supply. https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050_kurz.pdf.

Kutnar, A., Sandberg, D., Haller, P., 2015. Compressed and moulded wood from processing to products. Holzforschung 69 (7), 885–897. https://doi.org/10.1515/hf-2014-0187.

Mantau, U., 2012. Holzrohstoffbilanz Deutschland: Entwicklungen und Szenarien des Holzaufkommens und der Holzverwendung von 1987 bis 2015. https://franzjosefadrian.com/wp-content/uploads/2015/09/Mantau_Holzrohstoffbilanz-2012.pdf.

Mantau, U., 2015. Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. Biomass & Bioenergy 79, 28–38. https://doi.org/10.1016/j.biombioe.2014.08.013.

Mantau, U., Gschwantner, T., Paletto, A., Mayr, M.L., Blanke, C., Strukova, E., Avdagic, A., Camin, P., Thivolle-Cazat, A., Döring, P., Petrauskas, E., Englert, H., Schadauer, K., Barreiro, S., Lanz, A., Vidal, C., 2016. From inventory to consumer biomass availability—the ITOC model. Ann. For. Sci. 73 (4), 885–894. https://doi.org/10.1007/s13595-016-0582-1.

Mantau, U., Saal, U., Prins, K., Steierer, F., Lindner, M., Verkerk, H., Eggers, J., Leek, N., Oldenburger, J., Asikainen, A.J.H.E., Methodology report, 2010. EUwood - Real potential for changes in growth and use of EU forests. https://www.probos.nl/images/pdf/rapporten/Rap2010_Real_potential_for_changes_in_growth_and_use_of_EU_forests.pdf. (Accessed 01.06.2023).

Mehr, J., Vadenbo, C., Steubing, B., Hellweg, S., 2018. Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades. Resour. Conserv. Recycl. 131, 181–191. https://doi.org/10.1016/j.resconrec.2017.12.026.

Meinlschmidt, P., Mauruschat, D., Briesemeister, R., 2016. Altholzsituation in Europa und Deutschland. Chem. Ing. Tech. 88 (4), 475–482. https://doi.org/10.1002/cite.201500023.

Muller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. 48 (4), 2102–2113. https://doi.org/10.1021/es403506a.

Namari, S., Drosky, L., Pudlitz, B., Haller, P., Sotayo, A., Bradley, D., Mehra, S., O'Ceallaigh, C., Harte, A.M., El-Houjeyri, I., Oudjene, M., Guan, Z.W., 2021. Mechanical properties of compressed wood. Constr. Build. Mater. 301, 124269 https://doi.org/10.1016/j.conbuildmat.2021.124269.

Nissing, C., Blottnitz, H.V., 2007. A material flow analysis of wood and paper in Cape Town: is there potential to redirect flows in formal and informal sectors to foster use as a renewable resource? International Journal of Environment and Sustainable Development 6 (2), 147–156. https://doi.org/10.1504/ijesd.2007.014199.

Parobek, J., Palus, H., Kaputa, V., Supin, M., 2014. Analysis of Wood Flows in Slovakia. Bioresources 9 (4), 6453–6462. https://doi.org/10.15376/biores.9.4.6453-6462.

Rahmstorf, S., Markle, B.R., 2019. Abrupt Climate Change, Encyclopedia of Ocean Sciences 405–411.

Rüter, S., Matthews, R.W., Lundblad, M., Sato, A., Hassan, R.A., 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/. (Accessed 01.06.2023).

Saal, U., Iost, S., Weimar, H., 2022. Supply of wood processing residues – a basic calculation approach and its application on the example of wood packaging. Trees, Forests and People 7. https://doi.org/10.1016/j.tfp.2022.100199.

Sandberg, D., Haller, P., Navi, P., 2013. Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products. Wood Mater. Sci. Eng. 8 (1), 64–88. https://doi.org/10.1080/17480272.2012.751935.

Schulze, E.-D., Rock, J., Kroiher, F., Egenolf, V., Wellbrock, N., Irslinger, R., Bolte, A., Spellmann, H., 2021. Klimaschutz mit Wald: Speicherung von Kohlenstoff im Ökosystem und Substitution fossiler Brennstoffe. Biol. unserer Zeit 51 (1), 46–54. https://doi.org/10.11576/biuz-4103.

Schweinle, J., Geng, N., Iost, S., Weimar, H., Jochem, D., 2020. Monitoring Sustainability Effects of the Bioeconomy: A Material Flow Based Approach Using the Example of Softwood Lumber and Its Core Product Epal 1 Pallet. Sustainability 12 (6). https://doi.org/10.3390/su12062444.

Suter, F., Steubing, B., Hellweg, S., 2017. Life Cycle Impacts and Benefits of Wood along the Value Chain: The Case of Switzerland. J. Ind. Ecol. 21 (4), 874–886. https://doi.org/10.1111/jiec.12486.

Szarka, N., Haufe, H., Lange, N., Schier, F., Weimar, H., Banse, M., Sturm, V., Dammer, L., Piotrowski, S., Thrän, D., 2021. Biomass flow in bioeconomy: Overview for Germany. Renewable Sustainable Energy Rev 150. https://doi.org/10.1016/j.rser.2021.111449.

Szichta, P., Risse, M., Weber-Blaschke, G., Richter, K., 2022. Potentials for wood cascading: A model for the prediction of the recovery of timber in Germany. Resour. Conserv. Recycl. 178 https://doi.org/10.1016/j.resconrec.2021.106101.

Taskhiri, M.S., Garbs, M., Geldermann, J., 2016. Sustainable logistics network for wood flow considering cascade utilisation. J. Cleaner Prod. 110, 25–39. https://doi.org/10.1016/j.jclepro.2015.09.098.

UNECE/FAO, 2010. Forest product conversion factors for the UNECE Region. United Nations Economic Commission for Europe (UNECE) and Food and Agriculture Organization of the United Nations. FAO, Geneva.

UNECE/FAO, 2021. 2021 Joint Wood Energy Enquiry. https://unece.org/forests/joint-wood-energy-enquiry. (Accessed 01.06.2023).

Werner, F., Taverna, R., Hofer, P., Thurig, E., Kaufmann, E., 2010. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environ. Sci. Policy 13 (1), 72–85. https://doi.org/10.1016/j.envsci.2009.10.004.