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RESEARCH ARTICLE

Resolving complexity

Material flow analysis of a national wood flow system integrating the versatility of wood

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Abstract

A systemic understanding of the use of wood resources is required to defossilize society and promote bio-based developments. This study provides a novel approach to represent a comprehensive material flow analysis (MFA) spanning the entire wood value chain; encompassing wood harvest to products, use in society, collection, reuse, recycle, energy generation, and trade. By recognizing wood as a complex material, with changing properties throughout its lifespan, we developed a method where we employed a color-coded system for processes (27 boxes) and 110 flows to symbolize distinct life stages and the dynamic characteristics, including 23 different trade flows. The wood processes and flows are categorized (11 categories) into different wood types (e.g., softwood and hardwood) and harmonized to include all available data on each single step of the wood life cycle, improving data traceability and visualization, and allowing for replicable analysis with respective data noted for each process and flow. Methodological obstacles due to different units, uncertainty of flows, and discrepancies in data are addressed and adjustments proposed. Switzerland was chosen as a case study as a large number of various types of data were available to perform the analysis. The categorized and harmonized flows of woody biomass mapped and analyzed in the MFA provide a comprehensive basis to identify and recommend avenues to increase cascading use of wood as a carbon sink, by considering relevant aspects like the network of flows and processes, the quality and availability of the woody biomass, and the organization of the industry.

KEYWORDS
wood, cascading use of wood, wood value chain, defossilization, industrial ecology, material flow analysis

1 INTRODUCTION

Our society is facing environmental challenges such as climate change, energy availability, and resource sustainability. To address these issues, net-zero greenhouse gas emissions targets have been set by nations globally that involve the transition to a defossilized society and the enhancement of bio-based development (IPCC, 2023). Forest and wood use thus play an important role in reaching net-zero targets as CO_2 is sequestered in the forest biomass, CO_2 is stored in wood products, and fossil-based materials and energy sources are substituted by wood or woody components (Cames et al., 2023; FOEN, 2021e; Waring et al., 2020).

Wood is a versatile material and has a wide functional diversity (Sathre & Gustavsson, 2006; Thees et al., 2020; Vis et al., 2016). Thus, wood is seen as one of the most important resources for bio-based developments (Kammerhofer, 2016; NRP 66, 2023; Verkerk et al., 2022) and relies on sustainable material use principles. One such principle is the cascading use of wood where keeping materials within economic value chains as long as possible (repurposed or reprocessed multiple times) is prioritized to maximize the storage of carbon and increase substitution effects before using the material for energy or other purposes (e.g., biochar) (Erni et al., 2020; Höglmeier et al., 2013; Hurmekoski et al., 2021; Kammerhofer, 2014; Sirkin & Houten, 1994; Vis et al., 2016).

To better understand the wood value chain system and wood flows from the forest to industry and society, these flows must be quantified and characterized. The standard method to assess the flow of materials through a system is material flow analysis (MFA) (Brunner & Rechberger, 2016). Several MFA studies have examined wood flows in different countries, focusing on cascading wood utilization and optimizing its environmental impact (Höglmeier et al., 2015; Husgafvel et al., 2018; Szichta et al., 2022). Bais et al. (2015) quantified global wood flows while Mantau (2012) focused at the European level, suggesting that there are still considerable uncertainties due to variations in the patterns of wood and more specific flows, for example, of wood fuels. Numerous studies have been performed for specific countries or regions, mainly in Europe but also in Asia (Anspach et al., 2024; Cheng et al., 2010; Gonçalves et al., 2021; IRENA, 2019; Kayo et al., 2019; Knaggs & O'Driscoll, 2015; Parobek et al., 2014; Piškur & Krajnc, 2007; Vaahtera et al., 2023; Wang & Haller, 2024; Weimar, 2011), as well as on a regional level (Layton et al., 2021; Mantau, 2015). However, most studies do not cover the entire wood value chain, often omitting energy generation or paper industries. Comparisons among studies are further challenging due to differing methodologies, terminologies, data sources, and units (Marques et al., 2020). Consequently, applied analysis methods focusing on different regions cannot be directly adopted due to differences in units and categories documented.

Switzerland is a country with a wealth of available data for specific parts of the wood utilization pathway that can be used to build an analysis of wood flows within the country. As Swiss forest areas and growing stocks are increasing, there is raising interest in valorizing and improving the usage of Swiss wood or wood-derived products in various sectors (FOEN, 2021b, 2021d; Thees et al., 2020).[1] At present, Swiss studies are focusing on quantifying the primary production of woody biomass in Switzerland from both inside and outside (e.g., urban areas) forests, based on different models (Abegg et al., 2023; FOEN, 2021c; FSO, 2022a; Walther et al., 2009). Others focus on the industrial wood processing (FSO, 2023a), trade (FOCBS, 2023), or waste wood amounts (FOEN, 2021a, 2022b). Many reports and studies address the optimal wood use for energy (Bergeron, 2016; Erni et al., 2017; Mehr et al., 2018; SFOE, 2021; Thees et al., 2020, 2023; Werner et al., 2010), or quantify wood flows for specific industries (Gautschi et al., 2017; Lehner et al., 2014; Ostermeyer et al., 2018; SPKF, 2020; Thees et al., 2017; Winterberg et al., 2021). In this context, various attempts to summarize and analyze the Swiss wood flow system used MFA and life cycle analysis (LCA) aiming to calculate its environmental impact (Bergeron, 2016; Mehr et al., 2018; Suter et al., 2017). However, the potential of new material cascades have been rarely explored (Mehr et al., 2018) and the perspective of a bioeconomy establishment was not integrated despite of targets by the Swiss government (Kammerhofer, 2016, 2019, 2022; Riediker, 2021), nor the aspects of cascading use of wood (e.g., wood use in chemical products and wood-based industries) (NRP 66, 2023).

While sophisticated data and models are available in Switzerland, comprehensive MFA or data models for the entire wood value chain and material cascading use of wood are lacking. Therefore, comprehensive insights into the wood flows are required to provide a basis to establish a national strategy to cascade the use of wood. This study thus presents an MFA of an entire wood flow system, accounting for variable wood properties, enabling categorization and harmonization of wood flows, and including all available information to give a basis to identify avenues to increase cascading use of wood. Using a systemic approach, the study reveals inconsistencies and synergies within the wood value chain, filling a literature gap. It offers a comprehensive view of the Swiss wood flow system, addressing methodological obstacles in representing flows from forest to energy use.

2 MATERIAL AND METHOD

2.1 Categorization of processes and flows

To create a simplified overview of wood flows, this study categorized wood processes into boxes and wood flows into arrows within the MFA system. This systemic organization enhances understanding of the wood value chain, as wood is a complex material and, depending on the process, can undergo, for example, form, size, and compositional changes.

Category	Type of process	Processes	Definition	Data source
Initial production	Raw wood emergence	Biological service capacity	Biomass potential in Swiss forests	(Abegg et al., 2023)
		Raw wood (forest)	Woody biomass from Swiss forests	(FSO, 2022b)
		Raw wood (outside)	Woody biomass from outside Swiss forests	(Walther et al., 2009)
		Sawlogs with bark	Logs with bark used for sawmills	(FSO, 2023a)
	Raw wood utilization	Sawlogs	Wood fraction from trees used in sawmills	(FOEN, 2021c)
		Pulpwood	Wood fraction from trees for chemical and mechanical separation	
		Wood fuel	Wood fraction from trees for energy production	
Wood industry	Wood processing: First production stage	Production: Veneer, plywood, sawnwood	Sawmills produce semifinished products from logs	(FOEN, 2021c)
		Production: Particleboard, fibreboard	Board production produces semifinished products from pulpwood	
		Production: Groundwood, pulp	Pulp mills produce semifinished products from pulpwood	
	Wood processing: Second production stage	Production: Paper, cardboard	Paper mills produce finished products	
		Production: Finished products	Semifinished products processed into various finished products	
Material end use	Consumption of finished products	Wooden products end use	Various finished products consumed by society	(Winterberg et al., 2021)
		Paper, cardboard, printproducts end use	Finished products consumed by society	(SPKF, 2020)
Waste collection	Recycling of waste wood, waste paper	Waste wood collection	Waste wood collected from society	(FOEN, 2021c; SFOE, 2021)
		Waste wood collection unknown	Waste wood collected from society, balancing flow	
		Waste paper collection	Waste paper collected from society	(FOEN, 2021c; SPKF, 2020)
Energetic end use	Consumed wood used for energy generation	Wood for energy generation	All wood fractions for energy generation	(FOEN, 2021c; SFOE, 2021)
		Waste wood for energy generation	Waste wood collected for energy generation	
		Single room heating	Combustion types of category 1-6**	(SFOE, 2021)
		Building heating	Combustion types of category 7-11**	
		Automatic combustion	Combustion types of category 12-18**	
		Special combustion (RWIP)*	Combustion types of category 19**	
		Special combustion (WIP)*	Combustion types of category 20**	
Trade	Trade of woody bio-mass	Import	All fractions of woody biomass imported along the wood value chain	(FOEN, 2021c)
		Export	All fractions of woody biomass exported along the wood value chain	
Losses	Losses of woody bio-mass	Wood losses	All fractions of woody biomass lost along the wood value chain	(FOEN, 2021c)
Unknown	Unknown flows of woody biomass	Unknown	All fractions of woody biomass, along the wood chain, balancing flows	

* WIP= Waste incineration plant; RWIP= Renewable waste incineration plant
Combustion types and categories can be looked up in **SI D

FIGURE 1 Description of all processes (boxes) representing distinct stages and activities in the wood value chain in the material flow analysis.

The MFA processes (boxes) symbolize distinct stages and activities in the wood value chain and are not shown in relative sizes in the figures. The boxes represent raw wood emergence, utilization from the forest, first and second wood processing stages in the industry, material use of wood products, and finally waste collection and recycling and energetic end use. Moreover, the MFA incorporates import and export in all the processes, losses, and unknown flows (flows needed to balance other flows). Figure 1 shows a categorized list of processes based on the cited database.

Wood flows (arrows) symbolize measurable movement between processes and are shown in relative sizes in figures. There are 11 flow types that specify wood varieties: raw material, semifinished/finished products, export and import, collection, energetic end use, reuse, residues, losses, and unknown flows (see Figure 2 and SI A for detailed list of flows). Within flow types, there are different flows of goods; adding details to material flows like raw materials, semifinished/finished products, or residues contribute to a deeper understanding of the wood transformation and tracking over the whole wood chain.

2.2 | Material flow analysis

The MFA quantified wood flows in Switzerland from the forest, through different sectors to the end of life options for wood. Data for 2020 was used to create a static MFA, as it is the most complete year, compared to later years. If 2020 data were unavailable, data from previous years were used and documented transparently. The geographical system boundaries of the MFA were drawn at the national level of Switzerland and include the import and export of wood/wood products/woody components. The approach chosen for data reconciliation was both top-down and bottom-up to

Type of flow	Flows	Reference
Raw material	Bark, flurholz, harvest, other wood assortments, pulpwood, sawlogs, bark, wood chip, wood pieces	(Abegg et al., 2023; FOEN, 2021c; FSO, 2022a; Walther et al., 2009)
Semifinished products	Plywood, sawnwood, veneer, fibreboard, particleboard, groundwood, pulp	(FOEN, 2021c)
Import / Export	Import and export of various raw materials, semifinished products, finished products, and waste	(FOCBS, 2023; FOEN, 2021c)
Finished products	Construction, furniture, indoor/outdoor material, packaging, goods, paper, cardboard, printproducts	(FOCBS, 2023; FOEN, 2021c; SPKF, 2020; Winterberg et al., 2021)
Collecting	Collected waste wood and paper	(FOEN, 2022b; SPKF, 2020)
Energetic end use	Wood used for energy: residual wood, waste paper, waste wood, wood fuel	(SFOE, 2021; SPKF, 2020)
Reusing	Reuse of waste wood and paper	(FOEN, 2021c; SPKF, 2020)
Residues	Residual wood from industry used as material or energy	(FOEN, 2021c)
Losses	Losses from various processes	(FOEN, 2021c; SPKF, 2020)
Unknown	Flows needed to balance other flows	

FIGURE 2 Summarized description of flows (arrows) in the material flow analysis categorized by types.

harmonize different parts of the wood flow system. This study used the subSTance flow ANalysis (STAN) 2.7.101 software to construct the MFA system (TU Wien, 2012). See Table A.1 in SI A for a data overview and SI D for data sources description and their calculation methods.

2.3 | Unit and conversion factors

Ensuring consistency within the MFA required adopting a homogeneous unit for the entire wood chain, due to the diverse units in which wood product data are reported. This study expresses flows and processes in cubic meter (m^3) solid wood equivalents (SWE),[2] the unit for the m^3 of solid wood substance (FOEN, 2021c). This unit corresponds to the unit used in the FOEN report and other literature for mass flows (FOEN, 2021c; Lenglet et al., 2017; Suter et al., 2017).

For cases where data sources provided volume-, mass-, or energy-based values other than m^3 of SWE, specific goods-oriented conversion factors were used based on reports (see SI D). These factors enabled the transformation of values with different units into m^3 of SWE and ensured consistency in measurements across diverse data sources, although the harmonization (conversion of different units in the same unit, i.e., SWE) might increase the inaccuracy.

2.4 | Calculations

Some calculations were needed to align and harmonize the different reports, databases, and statistics. The total wood use in society cited by FOEN (2021b) (2.59 mio.m^3) is lower compared to Winterberg et al. (2021) (3.18 mio.m^3) reporting wood end use in Switzerland and corresponds to about 81.5% of the extrapolated volume. To align the numbers, the total wood use from FOEN (2021b) and the share of the five "finished products" flows (see Figure 2) from Winterberg et al. (2021) were used. Consequently, individual flows were multiplied by a factor of 0.815.

The waste wood burned reported in FOEN (2021b) and SFOE (2021) is almost the same (1.05; 1.07 mio.m^3), but higher than the cited waste wood collected in the waste wood statistics (0.73 mio.m^3) (FOEN, 2022b). To align all statistics, we added a "wastewood_collected_unknown" flow (see Figure 2), which includes the missing amount (0.34 mio.m^3), which, along with the "wastewood_collected" flow feeds into the "waste wood energy generation" process and then to special combustions.[3]

"Wood fuels" is a sum process of all the wood streams for energetic end use. This box is divided into five incineration types and five fuel types according to SFOE (2021). This statistic reports weather-adjusted amounts of wood burned in various incineration types. Different fuel types were allocated to incineration types, based on regulations and reasonable assumptions (see Table 1). Waste wood and old paper flows were allocated to special combustion (waste incineration plant [WIP] and renewable waste incineration plant [RWIP]) based on the Ordinance on Air Pollution Control (OAPC) (Der Bundesrat, 1986; SFOE, 2021). The "residualwood_industry" flow was diverted to automatic combustion according to SFOE (2021). In SI D, all subcategories of incineration types were listed and allocated based on their names, for example, pellets to "pellet stove wood." As no further details were available, amounts were distributed according to these assumptions.

The amounts and definitions of produced and used "paper_cardboard" and "print products" flows highly differ (FOCBS, 2023; FOEN, 2021c; SPKF, 2020). The used print products amount is calculated by the subtracting exports from imports (tariff number[4] 49) reported in FOCBS (2023), considering no production in Switzerland (FOEN, 2021b). The imported and exported paper and cardboard amounts are calculated based on the FOCBS (2023) including the entire tariff number 48. With no specific production data, the quantity produced is inferred from various input and output flows. Collection and recycling of waste paper amounts are taken from the SPKF (2020) and FOEN (2021b).

TABLE 1 Allocation of wood fuel types to incineration types. Old paper is not considered in the energy wood statistics but is burned in special combustion renewable waste incineration plant according to the Ordinance on Air Pollution Control (Der Bundesrat, 1986; SFOE, 2021).

Wood fuel type/incineration type	Wood pellets	Untreated wood pieces*	Untreated wood non-pieces**	Residual wood: wood processing industry	Waste wood	Old paper
Single room heating	X	X				
Building heating	X	X	X			
Automatic combustion	X		X	X		
Special combustion (RWIP)			X		X	X
Special combustion (WIP)					X	

*Pieces: pieces of wood with bark, for example, logs, wood briquettes, brushwood, and cones as well as cuttings of solid wood.
**Non-pieces: non-particulate wood, for example, wood chips, shavings, sawdust, sanding dust, or bark.

The unknown flows are any amounts that are not collected, reused, or recycled. The flows are defined as balancing flows for differences between used and collected paper (FOEN, 2021c; SPKF, 2020) or wooden products used and collected as waste wood (FOEN, 2021c).

2.5 | Uncertainty analysis

The uncertainty analysis of input data followed the approach of Laner et al. (2016). This method includes five indicators for data quality, scored from 1 (good) to 4 (poor): (1) reliability, assessing data documentation and availability; (2) completeness, evaluating how complete the information is; (3) temporal and (4) geographical correlation, relating to the mismatch between the year and location of the data and the assessment; (5) other correlations, assessing uncertainties not covered by the other indicators. For all indicators, their sensitivity level is assessed, from high to low, based on the influence of the indicator (see SI C for sensitivity analysis of indicators). The input data is considered to be normally distributed and the final uncertainty value corresponds to the sum of coefficients of variation (CV, standard deviation divided by mean) for each indicator, represented in Equation (1).

$$CV_{total} = \sqrt{CV^2_{reliab} + CV^2_{compl} + CV^2_{geogr.corr} + CV^2_{temp.corr} + CV^2_{other.corr}} \quad (1)$$

CV_{total}, total coefficient of variation (uncertainty); CV_{reliab}, coefficient of variation of reliability; CV_{compl}, coefficient of variation of completeness; $CV_{geogr.corr}$, coefficient of variation of geographical correlation; $CV_{temp.corr}$, coefficient of variation of temporal correlation; $CV_{other.corr}$, coefficient of variation of other correlations.

3 | RESULTS

3.1 | Material flow analysis of wood use in Switzerland

The MFA of wood use in Switzerland for the year 2020 is represented and described in SI B and summarized in Figure 4. In the following chapter, the various flows and processes of the MFA are explained.

3.1.1 | Wood from inside and outside Swiss forests

The average annual wood growth in the Swiss forest area is 10.01 mio.m^3. In 2020, 5.73 mio.m^3 of raw wood (roundwood) was used from Swiss forests (FOEN, 2021c). The amount of utilized raw wood from outside the forest (flurholz) is 0.31 mio.m^3 (Walther et al., 2009). Wood flows from raw wood include sawlogs (2.55 mio.m^3), pulpwood (0.57 mio.m^3), and wood fuel (2.92 mio.m^3). The 2.23 mio.m^3 sawlogs and 0.97 mio.m^3 pulpwood are the output for the wood industry and different residual wood from other production processes (sum of 0.9 and 0.68 mio.m^3) reenter the raw material processes. The total input and output of flows for all the raw materials processes sum up to 8.26 mio.m^3.

The flows of raw wood material can be divided into hardwood and softwood (see Figure 3). This categorization is only possible until the first processing step; afterward it cannot be differentiated based on the available data. Notably, most hardwood is used for energy generation (1.29 out of 1.71 mio.m^3), while most softwood is used as material (2.7 out of 4.02 mio.m^3).

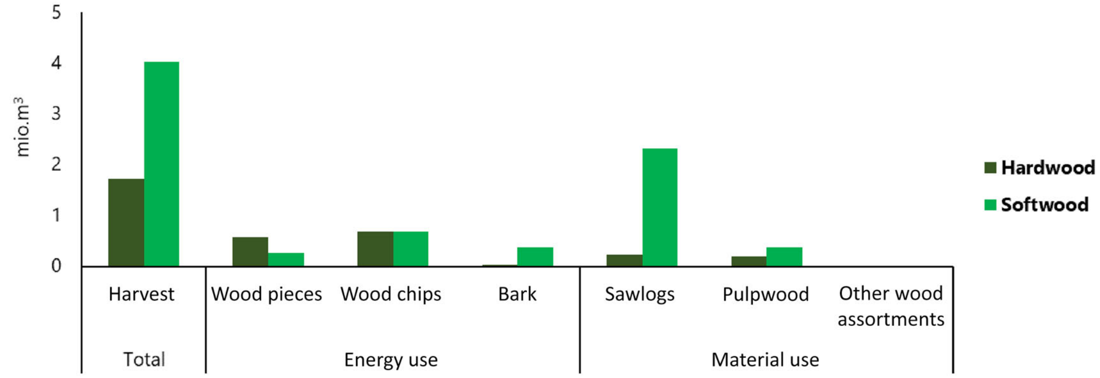

FIGURE 3 Overview of all flows that can be divided into hard and softwood (see SI B for a more detailed Table B.1).

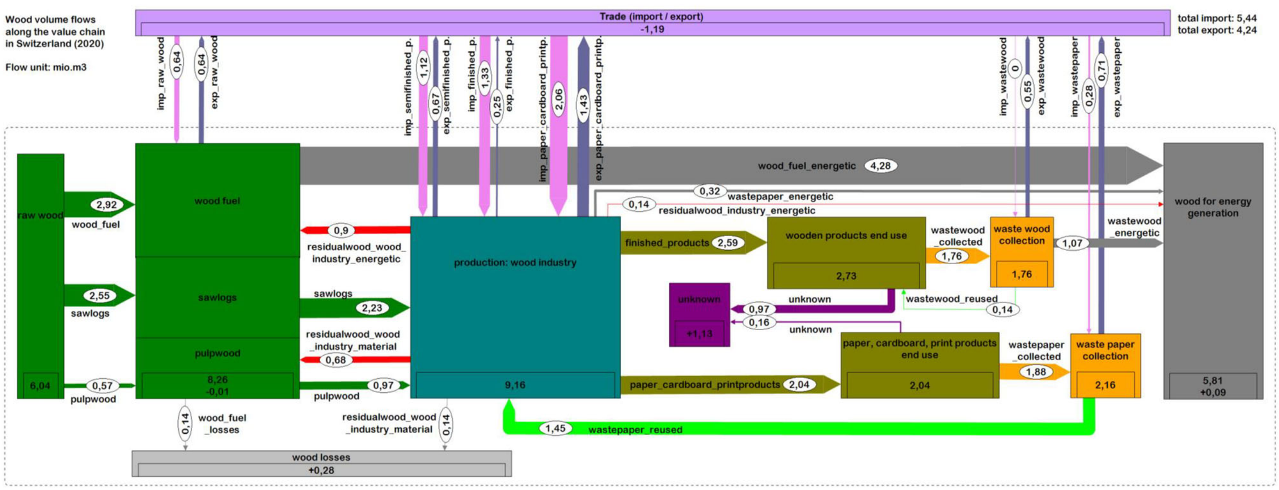

FIGURE 4 Summarized overview of the material flow analysis of wood use along the value chain in Switzerland for the year 2020 in mio.m^3. The colors represent raw material (green), semifinished products (teal), finished products (olive green), waste wood (orange), wood for energy (dark gray), wood losses (light gray), waste reused (bright green), residual wood (red); unknown (dark violet), import (pink), and export (lavender) (see SI A). The "unknown" flow can be interpreted as a stock increase in society.

3.1.2 | Wood processing industry

The Swiss wood processing industry (9.16 mio.m^3) includes the first stage (production of veneer, plywood, and sawnwood (2.77 mio.m^3); production of particleboard and fiberboard (1.21 mio.m^3); groundwood and pulp production (0.35 mio.m^3) and second-stage production (2.12 mio.m^3)[5] of semifinished products (including sawlogs) used for finished product production (3.45 mio.m^3), and 0.15 mio.m^3 of groundwood, and 0.17 mio.m^3 of pulp used for paper and cardboard production (3.83 mio.m^3).

3.1.3 | Wood end use in society

The paper and cardboard use process (2.04 mio.m^3) relies heavily on imports (2.06 mio.m^3) and exports (1.43 mio.m^3). The 1.88 mio.m^3 of waste paper is collected, of which 0.28 mio.m^3 is imported, 0.71 mio.m^3 is exported, 0.32 mio.m^3 is used for energetic end use, and the remaining 1.45 mio.m^3 is recycled in paper and cardboard production.

Five different finished products flows enter the wooden product end use (2.59 mio.m^3) and 2.73 mio.m^3 of finished wood products are used in the society. The amount of collected waste wood is 1.42 mio.m^3, and 0.14 mio.m^3 of it is reused and 0.55 mio.m^3 is exported. Moreover, 0.34 mio.m^3 enters the unknown amount of collected waste wood. All the collected waste wood flows are burned for energy generation (1.07 mio.m^3).

The combined wood flow losses over the different processes sum up to 0.28 mio.m^3. Half of these losses (0.14 mio.m^3) come from the wood fuel process, which can be attributed to, for example, losses in forest or transport. The unknown process is composed of 0.16 mio.m^3 from paper, cardboard, and, print products end use, and 0.97 mio.m^3 from wood products end use; amounting to 1.13 mio.m^3.

TABLE 2 Overview of the composition of the total amount of wood used for energy generation.

	Flow names		Flows (mio.m^3)	Sum of flows (mio.m^3)	Total (mio.m^3)
Total amount of wood used for energy generation	Wood fuel	Sum of raw materials	2.78	5.81	**5.90**
		Trade of wood fuel	–0.02	4.28	
		Sum of residual wood material	1.52		
	Residual wood from industry		0.14		
	Waste paper		0.32		
	Waste wood for energy generation		1.07		
	Difference: wood fuel and burning in incinerations		0.09		

3.1.4 | Wood trade

In the year 2020, Switzerland recorded a total import volume of 5.44 mio.m^3 and a total export volume of 4.24 mio.m^3, consequently, there was a net import of around 1.2 mio.m^3. As there are 23 different goods imported/exported, the amounts are not discussed in detail (see SI B for specific numbers). It should be emphasized here that a considerable share of waste paper (0.71 mio.m^3) and waste wood (0.55 mio.m^3) is exported and is not used for energy recovery in Switzerland.

3.1.5 | Energetic use of wood

Different processes feed into the wood energy generation in Switzerland (see Table 2). The biggest flow is wood fuel, this process is fed with raw wood materials (2.78 mio.m^3) and various residual wood flows (summed up to 1.52 mio.m^3). The wood for the energy generation process sums up to 4.28 mio.m^3. The residual wood from industry (0.14 mio.m^3) is directly diverted to automatic incineration. Waste wood for energy generation (1.07 mio.m^3) is fed into the two special incineration options (0.63 mio.m^3 to RWIP; 0.44 mio.m^3 to WIP). Moreover, waste paper (0.32 mio.m^3) is also diverted to the special incineration RWIP.

The total amount of wood being used for energy generation is 5.81 mio.m^3, however, an additional 0.09 mio.m^3 was burned in the various incineration types coming from the flow of wood for energy generation. Consequently, in the year 2020, 5.9 mio.m^3 of wood was used for energy in Switzerland

3.2 | Uncertainty analysis of data harmonization

The various flows in the MFA had to be harmonized based on data from the different reports, necessitating the use of some assumptions or calculations. The following list explains the uncertainties of the various adjustments of the flows and summarizes them in Figure 5 (see SI C for a detailed calculations and indicators):

One aspect that causes uncertainty is the usage of the unit “m^3 SWE” in this study, as it is limited by the conversion factors. The factors rely on average values, which may not fully capture total accuracy. Conversion factors defined by the (FOEN, 2021c) (see SI E) were used for the flows **(2)**, **(4)**, **(5)**, **(6)**, **(9)**, **(10)**, and **(11)**. The conversion factors were either used by the FOEN (2021e) in its reports for certain flows and we adopted the calculated data, or we used the factors for our calculations.

In flow **(1)**, the comparison of timber harvest data from the Forest Statistics (FSO, 2022b) and utilization/growth data from the National Forest Inventory (NFI) (Abegg et al., 2023) needed adjustment factors (Altwegg et al., 2010), as demonstrated by FOEN (2021e). The NFI model offers insights into timber stock and increment, resulting in 5.7 mio.m^3 as effectively used wood. In contrast, the FSO records 4.8 mio.m^3 timber harvest. Recognizing the underestimation of harvested wood, because of, for example, private use of wood and use of different units, in the FSO, adjustments were applied to align the data with NFI figures. In flow **(2)** of wood, trade amounts hinges on the accuracy of customs tariff numbers assigned to products; for example, there is currently no specific code for glulam and plywood (to be incorporated by 2024). Unquantified elements, like minor wood fractions in products and various packaging, limit the current system, highlighting the need for a more comprehensive approach for accurate trade data representation.

	Flow type	Flows	Type of uncertainty	Quantification
(1)	Raw material	Harvest	NFI and Forest Statistics: Adjustment factors	± 3%
(2)	Import/export	All import and export flows in the system	Accuracy of customs tariff numbers, conversion factor (flows calculated by the FOEN (2021e))	± 5.5%
(3)	Finished products	Outside, wooden_goods, packaging, construction, furniture_interior_work	Differences in statistics and models; adjusted with factor 0.815	± 7%
(4)		Paper_cardboard, printproducts	Own calculations because of differences in reports/statistics; conversion factor	± 7%
(5)	Collecting	Wastewood_collected, wastewood_collected_unknown	Addition of flow to align/balance statistics; conversion factor	± 6%
(6)		Wastepaper_collected	Conversion factor	± 3.5 %
(7)	Energetic end use	Wood fuel	Sum of flow	± 5%
(8)		Wood_non-piece_1-3, wood_pellets_1-3, wood_piece_1-2	See **Table 1** for assumptions on the distribution of wood types to incinerations; conversion factors	± 7%
(9)		Wastewood_energetic_1, wastewood_energetic_unknown	Conversion factor; addition of flow to align statistics (see (5))	± 3.5-6%
(10)	Reusing	Wastepaper_reused	Conversion factor	± 3.5%
(11)		Wastewood_reused	Conversion factor	± 3.5%
(12)	Unknown	Unknown_1-2	Own calculation for explanations balancing of gaps in statistics and reports	± 44%

FIGURE 5 Overview of uncertainties in flows in the material flow analysis. The quantification of the uncertainty was done according to the methodology of Laner et al. (2016).

In the material end use of wood **(3)**, the FOEN (2021c) reported 2.6 mio.m^3 and Winterberg et al. (2021) 3.2 mio.m^3 as final wood consumption, hence the flows are adjusted with a factor 0.815. The discrepancy arises because FOEN (2021) quantifies final wood consumption with the cutting in sawmills, while Winterberg et al. (2021) model wood use in building parks based on their calculations on building permits, assuming each permitted building is constructed that year. In flow **(4)**, the amounts of traded print products are the same in the SPKF (2020) and FOCBS (2023) (import: 0.26 mio.m^3, export: 0.02 mio.m^3), but different in FOEN (2021) (import: 1 mio.m^3, export: 0.2 mio.m^3), although they used FOCBS (2023) as database. This difference may be tracked back to a different definition or inclusion of products defined in tariff number 49. For "paper_cardboard" trade, sources (FOEN, 2021c; SPKF, 2020) reported different amounts. To remain consistent, we included the entire tariff number 48 from FOCBS (2023) (import: 1.8 mio.m^3, export: 1.41 mio.m^3), leading to higher amounts than in SPKF (2020) and FOEN (2021). This discrepancy could be avoided with a more specific definition of the tariff numbers in the reports. Consequently, this study relies on assumptions for the "print products" and "paper_cardboard" flows, leading to variations from reported amounts (FOCBS, 2023; FOEN, 2021c; SPKF, 2020). Moreover, the produced amount of paper, cardboard, and print products could not be tracked back from the SPKF (2020), due to a lack of differentiation between consumed and produced amounts and old paper collection.

To align all waste wood statistics (FOEN, 2022b, 2021c; SFOE, 2021) (**(5)** and **(9)**), we added a "wastewood_unknown" flow (0.34 mio.m^3) to account for "missing" waste wood that was not collected but used for energy generation (balancing flow). The waste wood statistic reports domestically received, forwarded, imported, and exported waste by disposal companies (FOEN, 2022b), while the energy wood statistics reports the energy produced and allocates this to the wood fuel assortments (SFOE, 2021). The difference also arises if the wood is burned through the operating waste and is therefore not declared as waste wood. For this reason, the declared amount of waste wood is smaller than the amount of reported burned waste wood.

The flow "wood_fuel" **(7)** in this study is a sum of all flows that can be assigned to energy generation but not to a specific incineration type. Such a summation can lead to higher uncertainty as no precise allocation leads to intransparency. In flow **(8)**, the allocation of wood categories to combustion plants is based on our assumptions (see Table 1) due to the lack of information in the statistics (SFOE, 2021). However, including the distribution of wood types in our analysis was important, as it improves decisions on which wood types or categories should be better used for a material cascade or another end-of-life use, for example, biochar. For special incineration (RWIP), our analysis shows 1.09 mio.m^3 of burned wood, 0.32 mio.m^3 higher than reported by SFOE (2021) and Vock (2021), because old paper (0.32 mio.m^3) diverted to this incineration type (OAPC) (Der

Bundesrat, 1986; SFOE, 2021). The total wood burned for energy according to FOEN (2021) is 5.79 mio.m^3 and the amount in our findings of 5.90 mio.m^3 is comparably similar.

To provide explanations and balance for gaps in statistics and reports we introduced a category that specifically accounted for unknown processes and flows (see **(12)**). Notably, these unknown flows are coming from used wood (0.97 mio.m^3) and used paper (0.16 mio.m^3), which is why they might be considered as stock (increase) in society, as they might not been collected within the same year. This approach enhances our understanding of material dynamics and contributes to an increased comprehension of societal stock.

4 | DISCUSSION

4.1 | Data harmonization

Successful data harmonization was conducted without a predefined goal of wood being used for a certain purpose, provided a comprehensive national material flow overview, enhancing the understanding of wood material versatility and potential material cascade development. The harmonization was elaborated by considering the accessibility of data integrating assumptions and looking for explanations at intersections where statistics or reports did not align, allowing for an analysis of data gaps and discrepancies, which were mostly based on reporting schemes and specific focus in the according reports and statistics (see SI A and SI C). This data harmonization enabled us to elaborate on various uncertainties of wood flows and to calculate them according to the method of Laner et al. (2016), as it has been done in the study of Gonçalves et al. (2021). Recently, Anspach et al. (2024) presented a new model as an implementation of MFA data reconciliation, targeted where data are relatively scarce. Other studies did not conduct an uncertainty analysis; Wang and Haller (2024) mentioned the underestimation of the actual consumption and Mehr et al. (2018) did account for taken assumptions, but the sensitivity analysis was done for environmental impacts and not for single flows. The uncertainty analysis enhanced the transparency of our combined top-down and bottom-up data reconciliation process, by integrating sub-systems from different perspectives to create a logical and coherent system view, thereby enabling a better understanding of the entire wood flow system.

The uncertainties range from ±3.5% to ±7% for the various flows based on the identified uncertainty type (see Figure 5). However, the highest uncertainty (±44%) is seen in the unknown flows introduced in this study to balance flows and to explain the data gaps. These adjusted flows for consistency across the whole system and the analysis of whether and how these flows exist should still be done. Compared to Gonçalves et al. (2021) we found lower uncertainties, due to the availability of detailed data and numbers for all individual flows, ensuring high-quality, precise figures with minimal uncertainty. The numbers only needed to be compared and harmonized rather than calculated. The uncertainties for the individual flows could be determined, but without considering the connections or interactions of the uncertainties with other flows. The main conclusions of the results have not changed through the integration of the uncertainties; the majority of the harvested and untreated wood is directly burned, wood recycling is not yet established, and there is a high export of waste (see chapter 4.3 for a discussion of these flows).

This study adopts "m^3 SWE" as a reference unit, aligning with practices in comparable studies (Bais et al., 2015; Gonçalves et al., 2021; Knaggs & O'Driscoll, 2008; Layton et al., 2021; Mantau, 2012, 2015; Suter et al., 2017; Szichta et al., 2022; Wang & Haller, 2024; Weimar, 2011) and various Swiss statistics and reports (FOEN, 2021c; FSO, 2022b; SFOE, 2021; Winterberg et al., 2021). Specific conversion factors are determined for each country and wood-based product. However, uniform factors are used across product categories due to data limitations, particularly moisture rates (FAO, 2020; UNECE & FAO, 2010). Calculating moisture rates is challenging since the moisture content of wood and bark varies by species and seasonal variation (Thivolle-Cazat, 2008). Other studies like Bösch et al. (2015) underscore the use of "m^3 of roundwood equivalent" to compare wooden product quantities, but this leads to double-counting by-products like sawmill residues, rendering it unsuitable for MFA studies. Similar issues arise when using m^3 or tons, as they treat additives and components as wood while ignoring drying-induced volume changes (Lenglet et al., 2017). Conversely, "m^3 SWE"[6] of a semifinished product only represents the volume of solid biomass before shrinkage, excluding by-products like sawmill residues (Szichta et al., 2022). Nevertheless, these are the only conversion factors allowing for converting different volume- or mass-based values and harmonizing numerous reports and statistics.

4.2 | Material flow analysis

This study integrated and harmonized all the available data from 21 different sources (see SI A) on the Swiss national wood value chain for 2020. We were able to show and analyze the entire wood value chain, from wood extraction from forests to energetic end use, and to categorize all the different flows and processes. Unlike other international studies, which did not analyze the entire value chain—Bergeron (2014) and Mehr et al. (2018) excluded the paper industry, Parobek et al. (2014) and Piškur and Krajnc (2007) focused only on raw wood flows, Cheng et al. (2010), Weimar (2011), Szichta et al. (2022), Anspach et al. (2024), Knaggs and O'Driscoll (2008), and Layton et al. (2021) examined industrial use of wood without considering energy generation—we provided a method for a comprehensive analysis.

By recognizing wood as a complex material, with changing properties throughout its lifespan, we developed a method where we employed a color-coded system for processes (27 boxes) and flows (110 arrows) to symbolize distinct life stages and dynamics of characteristics of wood. This categorization (11 categories) improves data traceability and visualization of data, allowing the analysis to be replicated with respective data noted for each process and flow. Further details could be elaborated for the trade of 23 wood flows according to their tariff number. In international comparison, the studies trade flows in a more summarized way (e.g., total amount per process step) (Gonçalves et al., 2021; Mantau, 2015; Suter et al., 2017; Wang & Haller, 2024). Additionally, more information on flows can be analyzed, for example, by assigning criteria or functionality. Other studies did not consider such a categorization of processes and flows as done in this study.

The allocation of wood types to incineration types according to the assumptions in Table 1 has created added value by completing the end of the wood value chain, by providing insights into the structure and size of the wood being burnt and thus into which flows could be used for material cascades. In comparison to other studies, some did differentiate between incineration types (Bergeron, 2014; IRENA, 2019; Mantau, 2012) and others did not (Gonçalves et al., 2021). None of them allocated a certain wood type to a specific incineration type like this study, this could be due to the lack of data availability.

This paper does not consider temporal aspects, as it looks at the Swiss wood flow system for 1 year in a static way. The product lifespan and stock lifetime were not quantified due to a lack of data. However, for the integration of the cascading use of wood, obtaining dynamic data on wood stocks within society is essential to understand the resource's life cycle (Bais et al., 2015; Wang & Haller, 2024).

This study was able to differentiate between softwood and hardwood, and identified wood species, showing differences in energetic and material use of these wood types. However, this analysis was only possible up to the first processing step, due to a lack of traceability throughout the entire value chain. Thus other MFA studies were not able to elaborate on such details in the visualizations or allocate wood types to energy or material purpose, except for Weimar (2011) who mentioned assumptions and differentiation difficulties. All these findings provide valuable insights to better our understanding of current wood usage and facilitate the development of material cascade uses of wood in Switzerland.

4.3 | Insights into cascading use of wood

Analyzing the categories within flows, processes, and data accessibility allows us to provide comprehensive insights to identify wood material cascade flows and compare them with other studies. We highlight flows expected to change in the future, where specific material cascades are undefined, suggesting potential for future scenario development.

There is an interest in increasing the wood utilization and harvest (Kammerhofer, 2016; Thees et al., 2023). The sustainable additional amount of wood that can be extracted from Swiss forest while maintaining a constant growing stock sums up to around an additional ~4%[7] (Abegg et al., 2023). This would increase volumes for cascading wood uses in the future (FOEN, 2021c; FSO, 2023b). Moreover, the share of hardwood in forests will increase because of climate-induced stress like heat and dryness (Flury et al., 2024; Hanewinkel et al., 2013). At the moment hardwood is often directly used for energy (75%) and softwood for material use (67%). Changes in the wood processing industry are needed to establish a hardwood value chain in the future and to enable material utilization (FOEN, 2021e; Kammerhofer, 2016).

Residual wood is, by definition, untreated and results from various processing steps in the wood value chain. Some of the residual wood is reused as material in the wood processing industry (0.68 mio.m^3), but most is used for energy generation (1.66 mio.m^3). This untreated wood could instead be valorized in a material cascade before being used for energy, as seen in other studies like Mantau (2015) or Gonçalves et al. (2021).

For paper, cardboard, and print products the recycling rate is 67%.[8] Here we have an established cascade, which explains the high production volume of paper and cardboard in Switzerland. In contrast, the wood recycling rate is low at 7.9%.[9] Comparing with Gauch et al. (2017) or Gonçalves et al. (2021), which cite a ~5% recycling rate for wood and ~81% for paper in Switzerland and Portugal, show similar wood recycling rates but much higher for paper. This difference can be explained as follows: FOEN (2021c), used as reference for Swiss studies, states that the collection rate equals the recycling rate (82%), although Haupt et al. (2017) emphasizes that the recycling rate is lower than the collection rate in Switzerland. Thus, the recycling rate in this study might be a good approximation, but is limited by our calculations, as it is unclear whether waste wood is reused within society or recycled in production. However, the potential to reuse and recycle wood and use it in material cascades has not been exploited yet. Studies like Höglmeier et al. (2013), Szichta et al. (2022), and Husgafvel et al. (2018) have also seen the potential for reuse and recycling of, for example, furniture or material from construction. To enhance wood-based industries, detailed exploration of industry-specific data on wood or woody biomass utilization, including recycling and reuse quantities in chemical products, is crucial (Höglmeier et al., 2013; Kammerhofer, 2016, 2019). This could be the basis for an advanced cascade analysis (Gonçalves et al., 2021; Mantau, 2015).

A relevant share of 31% of waste wood and 32% of waste paper is exported. By reducing the export of waste wood, this amount could be reused in the value chain or for energy generation (Bergeron, 2014; Besserer et al., 2021), as it is a highly needed resource for special incinerations (Quartier, 2018), replacing fossil sources. In many former Swiss political strategies, energy generation with wood as a renewable resource was prioritized. The 48%[10] of the harvested wood (inside and outside forests) is directly used for energy, comparable to 49% in Portugal (Gonçalves et al., 2021) and 56% globally (Bais et al., 2015). However, this prioritization of energy over material use is changing as the material cascading use of wood is now increasingly discussed and elaborated (FOEN, 2021e; Vis et al., 2016). This can lead to a conflict of interest between the role of wood as a material and energy source, which may be reinforced by demand for upcoming applications such as, for example, biochar. Our study revealed that a significant quantity of untreated wood (wood fuel 4.28 mio.m^3) is still burned for energy supply, despite its potential suitability for material use compared to treated wood (e.g., waste wood) (Besserer et al., 2021; Höglmeier et al., 2013).

5 | CONCLUSIONS AND OUTLOOK

We were able to integrate wood flow data from diverse sources, each using different methods and units, to generate a comprehensive MFA spanning the entire life cycle of wood; including wood harvest, raw material to semifinished, finished products, wood use in society, collection, reuse, recycling, and energy generation, and finally encompassing import and export flows. Given the versatility of wood, we addressed methodological challenges like identifying relevant inconsistencies, selecting a harmonized unit (mio.m^3 SWE), using conversion factors, introducing uncertainty analysis, and categorizing processes and flows.

The results of this study can serve as a basis to enable and increase the cascading use of wood as a carbon sink, by considering the relevant aspects like the network of sub-systems, flows and processes, the organization of the industry, and the introduction of flows explaining uncertainty. This enables the elaboration of certain scenarios where wood flows are diverted to other processes or purposes. However, potential competition between the material and energy use of wood must be studied further. To elaborate on the establishment of material cascades based on this study, criteria should be developed so that the exact path of material use of wood can be determined and more sector-specific data is required on the reuse and recycling of wood.

Future wood MFAs will likely involve more processes like biorefineries and pyrolysis and consider the change of wood demand influenced by climate-induced changes and developments of the industry that will gain relevance in the future (e.g., use of wood components for small material cascades). Consequently, it is important to include aspects of bio-based development into these cascades to make the most sustainable decisions possible on where and how the wood should best be used.

AUTHOR CONTRIBUTIONS

Conceptualization: Nadia Malinverno, Simon Buschor, and Claudia Som. *Methodology*: Nadia Malinverno, Simon Buschor, and Claudia Som. *Formal analysis*: Nadia Malinverno and Simon Buschor. *Investigation*: Nadia Malinverno and Simon Buschor. *Data curation*: Nadia Malinverno. *Writing—original draft preparation*: Nadia Malinverno. *Writing—review and editing*: Nadia Malinverno, Kealie Vogel, Francis Schwarze, Golo Stadelmann, Esther Thürig, Gustav Nyström, Bernd Nowack, and Claudia Som. *Visualization*: Nadia Malinverno and Simon Buschor. *Supervision*: Bernd Nowack and Claudia Som. *Project administration*: Claudia Som. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available in article supporting information.

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ENDNOTES

[1] In the year 2021, 5–7 million cubic meters (mio.m^3) of wood was harvested (Abegg et al. [2023] cites ∼7 mio m^3 and FOEN [2022a] which is based on the FSO [2022b] ∼5 mio.m^3 [see SI C]) in Switzerland (4% more than in 2020) (Abegg et al., 2023; FOEN, 2022a), and around 40% of this harvested wood was directly used for energy purposes (FOEN, 2021e, 2021c; Thees et al., 2023).

[2] This unit is known in German as Festmeter.

[3] The burning of waste wood is only allowed in special combustion incineration type from category 19 (RWIP) and 20 (WIP).

[4] Each commodity is listed under a tariff number, determining the customs duty rate and aiding in the identification and coding of goods; this eight-digit code categorizes products, offering detailed information through its breakdown, with the first two digits indicating the main category (SME Portal, 2024).

[5] Sum of flows: sawnwood, veneer, plywood, sawlogs, particleboards, and fiberboards.

[6] The names "m^3 of fiber equivalent" (Bösch et al., 2015; Weimar, 2011) and "m^3 SWE" (Mantau et al., 2010; UNECE & FAO, 2010) refer to the same thing (Lenglet et al., 2017).

[7] Annual increment: ∼10 mio.m^3; losses: ∼2.6 mio.m^3; harvest: ∼7.1 mio.m^3.

[8] The 1.45 mio.m^3 out of 2.16 mio.m^3 collected paper.

[9] The 0.14 mio.m^3 out of 1.76 mio.m^3 collected wood, sum of 1.42 mio.m^3 collected waste wood, and 0.34 mio.m^3 unknown collected waste wood.

[10] The 2.92 mio.m^3 from 6.04 mio.m^3.

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