

## MODELLING OF ENERGY WOOD FLOWS IN COUNTRIES WITH ABUNDANT FOREST RESOURCES AND EXPORT-ORIENTED FOREST INDUSTRIES

Igors Krasavcevs<sup>1</sup>, Astra Auzina-Emsina<sup>2</sup>

<sup>1</sup>Latvian State Forest Research Institute “Silava”, Latvia; <sup>2</sup>Riga Technical University, Latvia  
igors.krasavcevs@silava.lv, astra.auzina-emsina@rtu.lv

**Abstract.** EU initiatives to mitigate climate change and protect biodiversity, combined with ongoing changes in tree species composition and major shifts in wood-product trade patterns are reshaping forest resources supply and demand. The aim is to model the wood flows affecting production and export of firewood and wood chips to evaluate and optimize resource allocation, targeting the redirection of supply toward emerging and higher added-value sectors. The study applies national wood flow analysis to quantify wood biomass flow in Latvia for reference year 2023. The methodological approach follows the mass-balance principle, whereby all material inputs to the system are equal to outputs within a defined system boundary. The model integrates data from national forest inventory, industry production data, foreign trade statistics and national energy balance information, resulting in a comprehensive static material flow analysis (MFA) model of wood flow in the country. The model includes both tree species and assortment levels, conversion ratios across major forest-industry sub-sectors and production process interlinkages. Modelling results for year 2023 indicate an intensive level of wood-biomass mobilisation (21.4 million m<sup>3</sup>) while domestic processing capacity remains insufficient. Consequently, 30.5% of the available virgin fibre was exported as unprocessed raw material, supplying forest industries and consumers across the Baltic Sea region. The findings of MFA model can be applied to other forest resources abundant countries, to support development of forest industries by enabling evidence-based forest management decisions, and also contribute to a long-term forest-resource policy planning and implementation control at national and EU levels.

**Keywords:** wood flow, modelling, forest industry, energy wood biomass, material flow analysis.

### Introduction

In the context of sustainable development and the circular economy, forestry and wood-processing industries contribute to resource efficiency. Their strategic importance is reflected in EU frameworks such as the EU Bioeconomy Strategy and the European Green Deal, which promote wood as a low-emission substitute for fossil-intensive materials and set ambitious greenhouse gas reduction targets for 2030. For forest resources abundant countries, Material Flow Analysis (MFA) modelling is an important measure to evaluate forest resource use efficiency in natural and economic aspects [1]. Various studies specific to wood resources already have been conducted to gather data on regional [2; 3] and national (e.g., Germany [4], Austria [5], Portugal [6], Finland [7]) levels. MFA is widely used to quantify material flows and stocks in EU, yet for Latvia a harmonized and MFA is still not available. For countries with a high export ratio of wood products, it is important to identify supply changing major factors and give a quantitative evaluation of possible risks due to changes in wood availability. In volume terms, the energy wood resources flow, consisting of both primary wood biomass resources (firewood, wood chips, bark) and secondary wood biomass resources (industry by-products and waste), represents one of the most significant components of Latvia's national wood-resource supply and therefore requires more detailed research, particularly regarding upcoming potential changes during the next forestry planning period (2026–2030).

The aim is to model wood flows for Latvia, with a possibility for targeting on selected wood assortments - like firewood and wood (energy) chips - to evaluate and optimize resource allocation to supply toward emerging or high-added value sectors. Data from wood flow models is a reliable source for wood availability scenarios for certain types of wood assortments, including firewood and wood chips.

Research questions (RQ).

- RQ1: to what extent does a reduction in primary timber harvesting volumes constrain firewood export availability over a five-year forecast period?
- RQ2: to what extent does a reduction in primary timber harvesting volumes constrain the export availability of wood chips over a five-year forecast period?

National-level wood flow accounting has gained importance in forest-based bioeconomy planning, as it provides a transparent link between forest harvest potential, industrial processing structure, energy use and international trade [8]. Increasing policy attention to renewable energy targets, circular bioeconomy strategies and climate mitigation measures has strengthened the demand for reproducible wood flow balance systems that can be used for monitoring and scenario assessment. MFA is commonly applied to assess transparent data about material utilization and support decision-making regarding resource management. MFA analysis results are widely used for enhancing wood efficiency [1], trade flow modelling [9], monitoring sustainability effects of bioeconomy [4] and also tracking progress toward various targets such as the Green Deal's 55% emission reduction goal. Most existing studies contain methodological limitations that affect wood material flow analysis (MFA). A common limitation is the assumption of fixed values for incoming wood-biomass flows. However, wood supply is becoming increasingly dynamic due to several factors, including climate-related disturbances such as bark beetle outbreaks, evolving the EU climate and forestry regulations (e.g., deforestation policies and biodiversity protection measures) and turbulences in the international trade. Consequently, the application of scenario-based MFA approaches is becoming increasingly important for producing reliable estimates of future wood-product supply, supporting both policy development and macroeconomic forecasting.

### Materials and methods

Material Flow Analysis (MFA) of wood products enables a comprehensive evaluation of national wood-resource utilisation, capturing virgin fibre and secondary wood products flows [10]. It eases to identify wood consumption and assess export potential, if certain wood-resource categories are not fully utilised by domestic markets. The framework of MFA modelling comprises the following components: raw material supply, wood and paper production, energy use, consumer usage and recycling [11]. Transportation and international trade of raw materials and products occur at nearly every stage of the wood flow. The MFA of wood resources for Latvia is based on 2023 data, serving as the baseline of this study on energy wood – firewood (industrial 3.0 m, chopped firewood), wood chips, industrial by-products, bark – availability scenario modelling.

In the study, energy wood availability 2026-2030 scenarios were calculated. Three scenarios are elaborated for supply and consumption modelling. Data from MFA gives volume of virgin fiber wood biomass consumption in wood product industry as raw material for production (wood based panels, wood pellets, densified wood products) and secondary wood biomass available for energy wood product industry (pellets, briquettes). Also, energy wood consumption with energy wood consumption in energy production, combining consumption volumes from district heating plants and cogeneration plants (DH/CHP), industries and households is used to calculate consumption. General information about wood biomass supply data is based on harvested volumes (National Forest Inventory (NFI) data), but detailed split by wood assortments and species is based on MFA calculations for the corresponding year.

Indicator *Energy wood availability for export* is used as an indicator of supply sufficiency. Positive values indicate adequate levels of resource supply, while negative values show a signal for deficit that must be covered by alternative energy wood assortments. Energy wood availability calculations are based on following formula:

$$Q_{exp(i)} = S_{dom(i)} + S_{imp(i)} - \sum C_{dom(y,i)}, \quad (1)$$

where  $Q_{exp(i)}$  – quantity of energy wood, available for export, m<sup>3</sup>;  
 $i$  – type of energy wood, m<sup>3</sup>;  
 $S_{dom(i)}$  – domestic energy wood supply, m<sup>3</sup>;  
 $S_{imp(i)}$  – imported energy wood supply, m<sup>3</sup>;  
 $C_{dom(y,i)}$  – energy wood consumption (i) from segment (y), m<sup>3</sup>.

Domestic energy wood supply is as sum of consumption by main domestic segments:

$$C_{dom(i)} = C_{dh(i)} + C_{ib(i)} + C_{ip(i)} + C_{hh(i)}, \quad (2)$$

where  $C_{dom(i)}$  – consumption of energy wood type.  
 $i$  – type of energy wood, m<sup>3</sup>;  
 $C_{dh(i)}$  – consumption in district heating, m<sup>3</sup>;

- $C_{ib(i)}$  – consumption in industry heating boilers, m<sup>3</sup>;  
 $C_{ip(i)}$  – consumption in industry production as raw material, m<sup>3</sup>;  
 $C_{hh(i)}$  – consumption in households, m<sup>3</sup>.

For energy wood availability scenarios the following major factors were taken into account: changes in the forest land area, available for wood supply (FAS); forecasts for consumption in energy production both in district heating and industrial use, and households, including new capacities in DH/CHP; changes in virgin fiber and secondary wood availability as raw material in industries for energy wood product manufacturing. According to national statistics, in 2024 total forest land area was 1.39 mil ha, of which 0.23 mil ha (17%) were under management restrictions – leaving 1.16 mil ha available as FAS in Latvia. Changes in FAS will determine the volumes of wood for harvesting and supply in the following scenarios:

- Scenario A (Baseline scenario for domestic forestry policy) - FAS land area (in 2024) in state forests is reduced by 63 000 ha – according to the “Cabinet of Ministers Regulations on the Maximum Permissible Volume of Tree Harvesting for 2026-2030” [12] (2025/01/23) and requirements for the protection of the most valuable habitats of EU importance (EU Habitats Directive, EU Birds Directive). For scenario A, FAS is estimated on a level of 1.09 mil ha.
- Scenario B (Moderate scenario with additional EU restrictions for biodiversity protection). For scenario B, comparing with scenario A, FAS land area is additionally reduced by 49 000 ha – fulfilling requirements for the protection of all habitats of EU importance in state forests. In scenario B, FAS land is estimated on a level of 1.04 mil ha.
- Scenario C (Maximum biodiversity protection restrictions) - For scenario C, comparing with scenario B, FAS land is additionally reduced by 118 000 ha – fulfilling requirements for the protection of all habitats of EU importance in private forests (and replacing with FAS in state forests by compensation law). For scenario C, FAS land is estimated on a level of 0.97 mil ha.

Energy wood availability for export ( $Q_{exp}$ ), as well as domestic energy wood supply ( $S_{dom}$ ), are primarily determined by harvesting potential, but also reflect competition among end-users of low-grade wood assortments, including the energy sector, wood-based panel industry, and densified wood product producers (aggregated consumption represented in Formula (2) by  $C_{ib}$  and  $C_{ip}$ ).

MFA was constructed using wood-resource input data, using the National Forest Inventory (NFI) statistics, national PRODCOM data for wood-industry production, national energy-balance statistics for domestic energy-wood consumption, wood resources foreign trade flow data (in natural quantities) were derived from national statistics on wood and wood products (CN 44), EUROSTAT data were used for wood product foreign trade balance calculations (CN 44, CN47 and CN 3803-3807).

On the EU level wood product trade balance actual data are available for wide range of countries, starting from wood product import dependant countries (Denmark [13]) and export oriented countries (Poland [14], Finland [7]). Table 1 presents the trade balance of wood products in selected EU countries in 2025. The results indicate substantial heterogeneity in external trade performance across the countries, reflecting differences in forest resource endowment, industrial structure, and the degree of export orientation.

Table 1

#### Wood product trade balance in the selected EU countries in 2025

Country	Export, mil euro	Import, mil euro	Foreign trade balance computed, mil euro	Ratio of foreign trade balance/Export, ratio
Latvia	3022.4	609.3	2413.1	0.798
Estonia	2126.3	781.6	1344.7	0.632
Czechia	2826.2	1569.2	1257.1	0.445
Lithuania	1475.8	929.3	546.4	0.370
Portugal	1822.4	1345.1	477.3	0.262
Hungary	969.6	920.1	49.5	0.051
Ireland	760.2	870.5	-110.3	-0.145
Spain	2906.5	3342.1	-435.6	-0.150
Greece	232.4	741.9	-509.6	-2.193

Cross-country intra EU comparison reveals that countries can be divided into three major groups: with high foreign trade balance (absolutely and relatively on exports value), as Latvia, Estonia, Czechia, Lithuania; countries with moderate positive trade balance (as Portugal and Hungary), and the countries with negative trade balance (as Ireland, Spain, Greece) (see Table 1). Overall, the ratio of foreign trade balance to exports serves as a valuable indicator of export intensity and net resource outflow, highlighting the role of forest-based industries as key contributors to national trade performance.

In the energy wood segment, the ratio of foreign trade balance to exports is even higher than for total wood products (see Table 2), indicating an exceptionally strong net export position in this sub-sector. In Latvia, this ratio exceeded 0.95 in 2024 and has remained consistently high over the past three years. This trend reflects a structurally significant surplus in energy wood trade, driven by both increased export volumes and limited import dependency. The observed upward trajectory since 2020 can be linked to broader geopolitical and regulatory developments, particularly the European Union's restrictions on imports of wood products and energy wood from Belarus and the Russian Federation [15]. These measures have restructured regional trade flows, increasing demand for biomass from EU-based suppliers and strengthening the export position of countries such as Latvia.

Table 2

**Trade balance of firewood and wood chips in Latvia in 2019-2025**

Year	Firewood, 1000 m <sup>3</sup>				Wood chips, 1000 m <sup>3</sup>			
	Export volume	Import volume	Foreign trade balance (+/-)	Ratio foreign trade balance/export	Export volume	Import volume	Foreign trade balance (+/-)	Ratio foreign trade balance/export
2019	484	84	400	0.826	918	398	521	0.568
2020	354	87	267	0.754	922	698	224	0.243
2021	474	57	417	0.880	929	377	552	0.594
2022	637	52	585	0.918	1198	170	1028	0.858
2023	782	49	733	0.937	1 393	92	1 301	0.934
2024	736	37	699	0.950	1 709	70	1 639	0.959
2025E	478	35	443	0.927	1 470	110	1 360	0.918

In 2025, Latvia maintained a strong position in wood chip exports and recorded notable firewood export volumes, primarily supplying Scandinavian countries.

## Results and discussion

In Scenarios A, B, and C, inventoried forest felling areas and standing stock volumes were adjusted according to scenario-specific reduction factors. These adjustments are implemented with a temporal lag. For the period 2025-2026, only minor reductions are applied (1-6%), primarily reflecting weak market conditions in wood-product sectors. In contrast, more pronounced adjustments are projected for 2027-2030, ranging from 13% to 21%, depending on the scenario assumptions. Imported energy wood volumes according to model results will remain on insignificant levels below 0.10 mil, m<sup>3</sup> annually.

The results of consumption modelling, based on formulas (1), (2) reveal mixed trends. Wood chips and residues are forecasted to remain as the dominant type of energy wood, consumed in Latvia with stable levels and annual volume 4.86-5.02 mil m<sup>3</sup> (see Table 3). In this segment heating segment (DH) remains a key consumer with forecasted consumption of 3.06 mil m<sup>3</sup> in 2030. Over the period 2026-2030, the consumption is projected to increase by 16%, driven mainly by higher utilisation rates of DH capacities commissioned during 2021-2024 (approximately + 0.3 million m<sup>3</sup>), as well as additional DH/CHP capacities currently under development for 2026-2030 (approximately 0.1 million m<sup>3</sup>). In contrast, wood chip and residue consumption in industrial boilers is projected to decline in line with reductions in harvesting volumes. As a result of cuts in domestic wood-resource supply, lower production output in certain wood-processing industries is forecasted, correspondingly reducing the demand for industrial energy (heat) sources. However, the rate of decline is not expected to be uniform across all wood-product segments. Sawnwood production is more constrained by raw-material availability.

Consumption of firewood, mostly utilised in private households (heat production) and industry (as raw material), is forecasted with a minor decline due (3.80 mil m<sup>3</sup>) to lower consumption in the private household sector. Consumption in the wood-based panel and pellet production industry is projected to remain stable, demonstrating relatively high sourcing flexibility, supported by substantial export volumes of pulpwood logs that can be redirected to domestic processing if required. As a result, production volumes in these segments are expected to remain relatively stable, with corresponding stability in energy-wood consumption both as fuel and as a raw material.

Table 3

### Results of energy wood assortment availability ( $Q_{exp(i)}$ ) modelling in Latvia in 2026-2030, mil m<sup>3</sup>

		2025	2026	2027	2028	2029	2030
Scenario A	Inventoried stock logging volumes	14.90	14.10	13.10	13.10	13.10	13.10
	Supply of firewood	4.35	4.12	3.83	3.83	3.83	3.83
	Consumption of firewood	3.89	3.89	3.80	3.80	3.80	3.80
	Firewood, available for export	0.49	0.23	0.03	0.03	0.03	0.03
	Supply of wood chips and residues (incl.bark)	6.48	5.94	5.34	5.34	5.34	5.34
	Consumption of wood chips and residues	5.01	5.07	4.97	5.02	5.02	5.02
	Wood chips, available for export	1.47	1.07	0.36	0.31	0.31	0.31
Scenario B	Inventoried stock logging volumes	14.90	14.10	12.90	12.90	12.90	12.90
	Supply of firewood	4.35	4.12	3.77	3.77	3.77	3.77
	Consumption of firewood	3.89	3.89	3.80	3.80	3.80	3.80
	Firewood, available for export	0.49	0.23	-0.03	-0.03	-0.03	-0.03
	Supply of wood chips and residues (incl.bark)	6.48	5.94	5.25	5.25	5.25	5.25
	Consumption of wood chips and residues	5.01	5.07	4.94	5.00	5.00	5.00
	Wood chips, available for export	1.47	0.87	0.31	0.26	0.26	0.26
Scenario C	Inventoried stock logging volumes	14.90	14.10	12.90	11.90	11.90	11.90
	Supply of firewood	4.35	4.12	3.77	3.48	3.48	3.48
	Consumption of firewood	3.89	3.89	3.80	3.80	3.80	3.80
	Firewood, available for export	0.49	0.23	-0.03	-0.32	-0.32	-0.32
	Supply of wood chips and residues (incl.bark)	6.48	5.94	5.25	4.85	4.85	4.85
	Consumption of wood chips and residues	5.01	5.07	4.94	4.86	4.86	4.86
	Wood chips, available for export	1.47	0.87	0.31	-0.01	-0.01	-0.01

Predicted constraints on wood biomass supply at both national and EU levels, combined with strong domestic demand, are expected to significantly reduce Latvia's export potential for energy raw wood materials. At the same time, available wood resources are projected to remain sufficient to sustain high export volumes of processed energy products (wood pellets).

### Conclusions

1. European Union policy initiatives aimed at climate-change mitigation and biodiversity protection are expected to significantly constrain the availability of energy-wood resources for export. Under the baseline scenario (A), domestic forestry policy conditions in 2030 will result in positive export of energy wood chips; however, export volumes are projected to decline by 79% of the 2025 level. Firewood exports are expected to remain limited, largely confined to niche market segments such as split hardwood firewood for residential heating.
2. Under the moderate scenario (B), export volumes of energy wood chips are projected to decline further, reaching only 17% of their 2025 level by 2030. At the same time, export of industrial quality firewood is expected to be largely eliminated, while domestic firewood prices are likely to increase due to tightening supply conditions.
3. In the most stringent biodiversity-protection scenario (C), structural adjustments within the wood-processing sector are anticipated. In particular, industries are expected to substitute part of their raw-material base with higher-grade roundwood, thereby reducing the availability of pulpwood for export by at least 0.3 mil m<sup>3</sup>. This shift reflects increasing competition for limited wood resources and a reallocation of assortments towards higher value-added domestic processing.
4. Policy initiatives in forestry are recommended to balance forestry, industry, and biodiversity dimensions, keeping wood supply on sufficient levels for renewable energy domestic production and export of processed energy wood products.

### Author contributions

Conceptualization, I.K.; methodology, I.K.; software, I.K.; validation, I.K.; formal analysis, I.K. and A.A.-E; investigation, I.K. and A.A.-E; writing – original draft preparation, I.K. and A.A.-E; writing – review and editing, I.K. and A.A.-E.; visualization, I.K. All authors have read and agreed to the published version of the manuscript.

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