Bioenergy expansion amidst uncertain data – lessons of imbalance from the V4 countries

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This study explores the uncertainty in the production and consumption data of solid biomass for energy by comparing sources from the Joint Research Centre wood resource balances and uses from the Eurostat energy balances. It uses the Visegrad Four (V4) countries for illustration as their energy and climate policies promise ambitious further deployment of this energy source. This study's key concern is whether the revealed level of data uncertainty can compromise the sustainability of biomass energy and its integrity with climate objectives. Indeed, this study finds worrying evidence for the V4 countries. Specifically, the gap between the data on sources and uses of solid biomass energy was between 33% to 56% for the reported years. The unsustainability margin may be an alarming 52% for the V4 countries combined. The CO_2 balance of negative emissions from the wood-based removals and positive emissions from biomass combustion shifted from negative to positive in 2010, and has increased thereafter to as much as 54–56 million metric tonnes of net emissions in the V4 countries combined by the early 20s. CO_2 emissions from biomass energy increased from 1.8% to 14.2% of the total greenhouse gas emissions of the V4 group. The reviewed policy plans of the V4 forecast a further loss of up to 40% of carbon sequestration by wood resources and a continued increase in biomass energy production by 2030. To reduce data uncertainty, the designated authorities should rethink the monitoring, reporting, and verification rules for solid biomass sources and uses. The sustainability and climate neutrality of biomass energy should be reassessed, and government policies should be reconsidered to protect the sustainable use capacity of forests.

Keywords:
wood resource balances,
energy balances,
forest statistics,
climate policy,
sustainability,
carbon

Introduction

Biomass energy production has increased both in absolute and relative terms in the European Union (EU) in the past two decades. Solid biofuels based on woody forest biomass have remained the largest category of renewable energy sources in the EU despite the rapid growth of new renewable energy technologies such as photovoltaics and wind. However, forest biomass is not an unlimited natural resource. As climate policy is making biomass energy ever more attractive, ensuring its sustainability and compatibility with climate objectives is even more crucial. The only way to judge this is through data. This article explores the level of data uncertainty about the production and consumption of solid biomass for energy. We use the example of the V4 countries (the Czech Republic, Hungary, Poland, and Slovakia) to analyse official data and highlight policy consequences as their national energy and climate plans reveal very ambitious policies for further deployment of this energy source.

Literature review

Academic discussions about the sustainability of biomass energy have continued since a while. Since most solid biomass energy is produced from forest biomass[1], the sustainability debate focuses on the management of forest biomass resources. The narrow concept of sustainability of forest biomass production suggests that harvesting should not deplete forests' regenerative capacity (Tietenberg–Lewis 2018). The broader concept of sustainable forest management includes the ecological requirement that harvesting should not compromise ecosystem health or deplete biodiversity (Amacher et al. 2009).

However, profit-maximising forest management tends to induce harvest rates that result in a net loss of standing timber (Tietenberg–Lewis 2018). As demonstrated by the Faustmann optimisation model of forest economics, the harvesting decision requires a comparison of the increase in the net present benefit of the additional timber volume obtained by delaying harvesting with the net present benefit of harvesting the timber and investing the proceeds at market interest rates (Amacher et al. 2009). Therefore, sufficiently high interest rates may induce unsustainable harvesting. The risk is particularly high in the case of slow-growing natural forests as opposed to fast-growing tree plantations, as the latter's ecological value is negligible compared to the former.

Several authors discuss the significant uncertainties found in the statistics on the sources and uses of woody biomass. Cazzaniga et al. (2021) explored a growing gap between the sources and uses of woody biomass in the EU27. Some of this gap can be explained by the woody biomass produced and harvested outside forest land, as suggested by Liu et al. (2023) and Schnell et al. (2015). Kallio–Solberg (2018) find

[1] In the EU, woody biomass accounted for 66% of total solid biomass used for energy in (EC 2021).

significant inconsistencies between wood supply data and forest industry production in self-reported national statistics collected and published by the Food and Agriculture Organization (FAO) Ceccherini et al. (2020) used fine-scale satellite data to obtain independent information on harvested forest area and found an abrupt increase in harvested forest area after 2015 that is not reflected in harvest volumes statistics, further highlighting the uncertainty of official forest statistics. Their results were later challenged by others (Palahí et al. 2021).

One study (Nguyen et al. 2024) developed a complex sustainability assessment tool for biomass-based energy supply chains based on five sets of indicators (environmental quality, resource depletion, social, economic, and circularity). Forest biomass harvesting for energy is critical for some of the environmental quality indicators (global warming potential of forest floor soil disturbance during harvesting, and biomass carbon release and particulate matter formation during combustion) and in some resource depletion categories (primary energy consumption of the forest biomass value chain and the land use of even-aged forestry).

Some authors (Gregor et al. 2024) argue that the conflicting combination of policy objectives for forestry, biodiversity, and climate change mitigation act as effective constraints to improving forest ecosystem services. A study (Korosuo et al. 2023) assessed forest carbon sinks in the EU and found that they are rapidly declining due to several factors, such as decreasing wood increment, increasing harvesting and mortality, and forest management practices.

Meanwhile, a study (Camia et al. 2021) developed six sets of indicators to quantify narrow and broad aspects of sustainability: status of forest resources, ecosystem health and vitality, production of timber, non-timber products and marketed services, biodiversity, protective function, as well as other socio-economic functions. An increase in the use of wood fuel has been observed in the reporting EU countries over the last two decades. The study finds that growth in fuelwood extraction has been well above gross domestic product growth since 2007. These results are based on the EU wood resource balances (WRB) developed by the Joint Research Centre of the European Commission (JRC).

EU wood resource balances versus EU energy balances

The JRC started a major statistical project to compile the WRB in 2005. The European WRB combines data from the joint forest sector questionnaire (JFSQ) of the FAO, Eurostat, and the results of the Joint Wood Energy Enquiry (JWEE), the biennial survey of the United Nations Economic Commission for Europe (UNECE). Since its first publication, the WRB 'demonstrated the lack of reliable data and the need for further research' (Mantau 2010).

The concept of the WRB and methodology behind it have been published in some studies (Jonsson et al. 2021), among others. In the WRB, the primary and secondary wood resources are combined to reflect the circularity of the forest product sectors.

For example, industrial roundwood (primary) is processed into sawn-wood, while the by-products (secondary) are inputs for the panel and pulp industry, and wood pellet producers. Together with fuelwood (primary), which is directly used for energy, these secondary sources of biomass provide wood resources to energy uses in the form of products or post-consumer wood. Therefore, in the WRB, the primary and secondary sources of wood material are plotted against the various uses of wood for material or energy (heat and/or power, [H&P]). In Appendix Figure A1 shows the conceptual framework developed by the JRC based on a prior study (Mantau 2010).

The WRB accounts for the different forms of wood resources of biomass energy on the source side of the balance. Fuelwood and some industrial wood, as primary sources, are channelled into energy production as 'direct wood'. Meanwhile, secondary sources such as wood pellets, by-products, and post-consumer wood are channelled into biomass energy production as 'indirect wood'. In addition, the net imports are mostly reported. Importantly, the reported consumption of wood fuel for energy is greater than the reported sources in each of the EU member states in each year, with significant differences between them. The JRC (Avitabile et al. 2023) finds that the EU27 average of the gap in WRB is 104 million cubic metres (Mm^3) of solid wood equivalent (SWE) compared to 875 Mm^3 SWE of total uses (a gap of about 12%); of this, 424 Mm^3 SWE was energy use in 2017. As reported by the JRC in a previous study (Jonsson et al. 2021), the gap between reported uses and sources increased from 87 to 118 Mm^3 SWE in the EU from 2009 to 2015, exhibiting a trend of increasing data uncertainty.

JRC (Avitabile et al. 2023) provides a summary of the 2017 WRB for all EU member states based on the annual releases of the WRB, which is reported in Table 1. Below, we quote the latest 2017 WRB balance for the V4 group. Countries with significantly negative (e.g. the Czech Republic) or positive (e.g. Poland) overall balances can be considered as countries with significant unreported sources or uses, respectively.

Table 1

Summary of wood resource balances for the V4 countries, 2017

(thousand m^3 SWE)

Country	Sources				Uses			Balance	Gap compared to	
	primary	second-dary	post-consu-mer wood	total	material	energy	total	sources – uses	total sources	total uses
									%	
Czech Republic	16,509	5,935	296	22,740	14,024	13,544	27,568	–4,828	–21	–18
Hungary	6,014	972	0	6,986	2,917	3,465	6,382	604	9	9
Poland	50,136	11,247	1,272	62,655	35,895	22,888	58,783	3,872	6	7
Slovakia	9,404	3,084	130	12,618	8,368	4,478	12,846	–228	–2	–2

Source: sources and uses data from JRC (2021) and Avitabile et al. (2023).

In the WRB system, it is not possible to derive a partial balance for energy sources and uses when data on energy use are missing, as it is the case for two (Hungary and Poland) of the four V4 countries for 2009–2016. Hence, and to compare the well-established wood resources data of JRC WRB to equally sophisticated data on energy uses, we include the energy balances (EB) published by Eurostat in our analysis.

The EB are compiled according to a common methodology for each EU member state for each energy carrier ('energy product') as defined by the Standard International Energy Product Classification (SIEC). Each energy product is balanced, considering its primary production, imports, exports, and stock changes on the source side, and the total energy supplied for energy transformation and final consumption for energy use on the use side.

The sources and uses of most energy products in the EB are monitored by the national energy authorities based on legal obligations. These are electricity, coal, crude oil refinery products, and natural gas. Although some details of these energy product balances are estimated using statistical methods, a comprehensive balance of sources and uses is ensured by direct data reporting from operators at bottlenecks in the system.

Conversely, certain energy products have a diverse technical and market structure such as the solid biofuels. Therefore, the EB of the primary solid biofuels (PSB) is compiled by the energy authorities through a complex procedure. Plant operators in the transformation sector (heat and power plants) self-report their use of PSB, subject to audits and consistency checks. The use of PSB in the industrial and residential sectors is calculated by the energy authorities based on statistical surveys and, for households, based on representative computable building energy models.

The definition of PSB used by Eurostat and the EU Commission is based on the EU Commission Decision (EC 2009). The nomenclature of the solid biofuels is broken down to the following categories: direct wood supply, indirect wood supply, agricultural crops, and by-products used for energy[2]. According to this EC Decision, the biodegradable fraction of municipal and industrial waste should also be included in the PSB category. However, the Eurostat EBs report renewable municipal waste as a separate, independent category. Table 2 shows the EBs of PSBs in the V4 countries.

[2] EU Commission Decision (EC 2009).

– Direct supply of woody biomass from forests and other wooded land for energy generation includes: fellings, residues from fellings (tops, branches, bark, and stumps), or landscape management residues (woody biomass from parks, gardens, tree rows, and bushes).

– Indirect supply of woody biomass includes: residues from sawmilling, woodworking, furniture industry (bark and sawdust), by-products of the pulp and paper industry (black liquor and tall oil), or processed fuelwood, post-consumer recycled wood (recycled wood for energy generation and household waste wood).

– Agricultural crops and fishery products directly provided for energy generation: arable crops (cereals, oilseeds, sugar beet, and silage maize), plantations, short rotation trees, other energy crops (grasses), and algae.

– Agricultural by-products/processed residues and fishery by-products for energy generation: straw, manure, animal fat, meat and bone meal, cake by-products (including oil seed and olive oil cake for energy), fruit biomass (including shell and kernel), fishery by product, clippings form vines, olives, and fruit trees.

Table 2

PSB EBs of the V4 countries, 2023

(TJ)

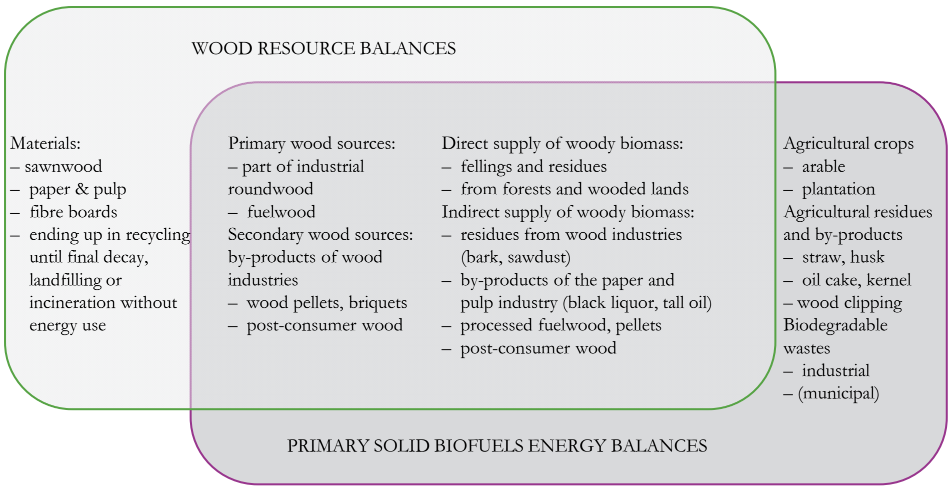
		Czech Republic	Hungary	Poland	Slovakia
Sources	Primary production	141,116	78,631	348,902	48,857
	Imports	4,861	3,181	12,126	233
	Exports	–11,269	–2,221	–12,805	–373
Total energy supply		134,708	79,591	348,223	48,717
Uses	Transformation input – energy use	34,131	16,438	74,204	16,627
	Final consumption – industry sector – energy use	19,229	10,665	66,310	12,812
	Final consumption – households – energy use	80,497	50,974	183,250	18,640
	Transformation losses, energy sector use, other final consumption	852	1,514	24,459	638

Source: Eurostat (2025).

As shown, PSB EBs are always equalised by a 'primary production' data entry, which is made up to balance total consumption without further source data verification or breakdown to subcategories of PSB sources.

Figure 1

Compatibility map of the WRB* and the PSB EB**



* of Joint Research Centre. ** of Eurostat.
Source: author's compilation based on JRC (2021) and Eurostat (2025).

PSB EBs and WRBs are only partially compatible. WRB categories are broader because they include wood that ends up in materials that do not necessarily enter the energy sources as post-consumer wood at the end of their life cycle (decayed, landfilled, reused, etc.). Meanwhile, the PSB definition of the EBs is broader to include solid biomass sources such as agricultural crops, by-products and residues, and biodegradable wastes. Figure 1 provides a summary of the compatibility between the two concepts.

Next, we construct a joint WRB–EB balance using the V4 countries as an example, with solid biofuel energy sources as published in the WRB and solid biofuel energy uses as published in the EB.

The gap between wood resource and energy balances

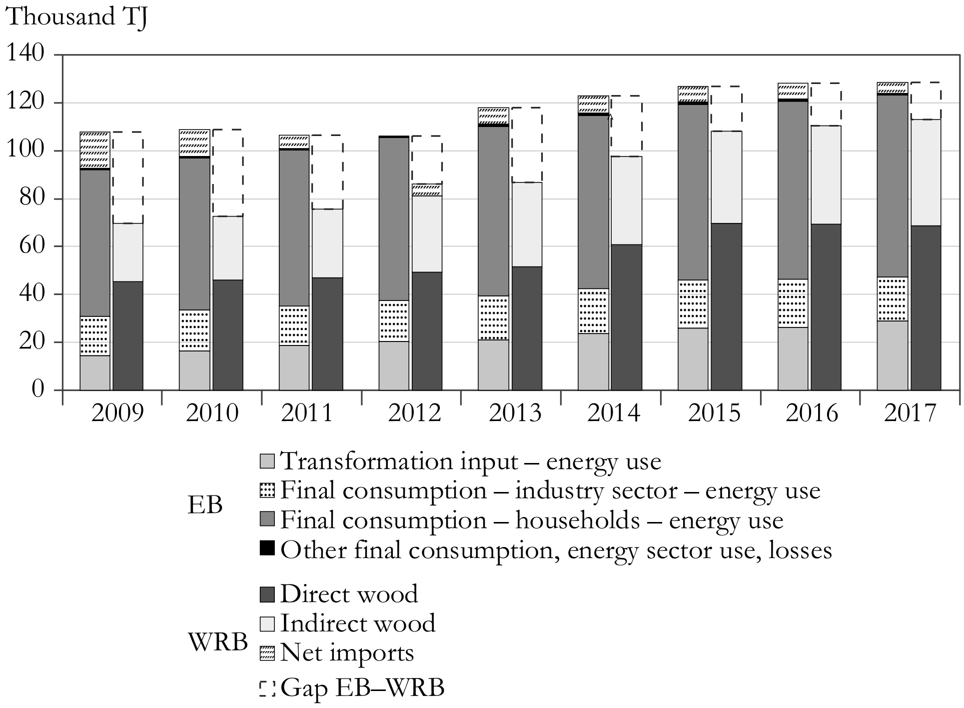
As explained above, EBs are effective in collecting energy *use* data disaggregated by energy product based on legal data reporting obligations to authorities. The WRB is the most reliable for the data on woody biomass *sources*. This is because it is based on questionnaires that are part of the data reporting routines of FAO/UNECE, the official data hub for governments to report their biomass sources to. Therefore, to combine the advantages of the two methodologies, we construct the hybrid WRB–EB balances, demonstrated for the V4 countries, with sources from WRB and uses from EB. Unfortunately, the WRBs are only published from 2009 to 2017. Hence, this exercise can only be done for this limited time frame. However, the results may have wider implications.

In Figures 2 to 5, the stacked columns in shades of brown represent the main energy use categories for PSB by the transformation and final consumption sectors. The stacked columns in shades of green represent the sources of PSB types broken down into the WRB categories of direct, indirect, and unknown wood. The blue column is the balance of exports and imports as reported by the WRB, presented as net imports and added to the stacked column of sources when the net imports are positive, it is added to the stacked column of uses when the net imports are negative. The vertical axis represents the same amount of biomass in energy terms (TJ) for the source and use categories. Since the source data are reported in SWE by the WRB, those are converted to Joule using fuelwood parameters according to the FAO methodology.[3]

[3] Fuelwood SWE: m^3 roundwood/oven-dry metric tonne (EU avg.): 2.1, product basic density (solid volume, oven-dry): 521 kg/m^3, higher heating value: m^3 roundwood/GJ: 0.12 (equal to 8.33 GJ/m^3). Source: FAO (2009).

Figure 2

WRB sources and EB uses of PSB for energy in the Czech Republic



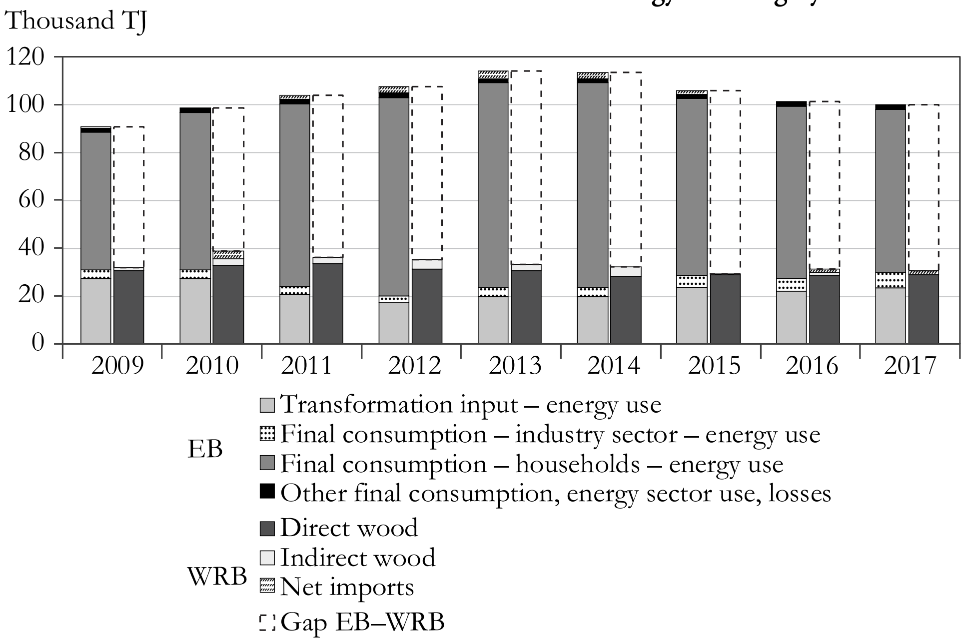
Source: own chart based on JRC (2021), Cazzaniga et al. (2021) and Eurostat (2025).

The Czech forest sector suffered from a severe bark beetle outbreak during the observed period, resulting in extensive salvage harvesting and the dumping of much of this timber on export markets. The salvage harvest boosted most product categories. Thus, the unexplained gap of 35% between WRB sources and EB uses in 2009 narrowed to 12% in 2017.

Hungary is one of the countries where significant amounts of non-wood PSB have been identified and could be added to the WRB sources (see Figure 1 for the WRB and EB compatibility mapping). The data were collected by interviewing the national energy authority responsible for energy statistics. However, the figures are relatively low, fluctuating between 6,000 and 9,000 TJ. Thus, even after considering this non-wood PSB production in addition to WRB sources, a significant gap remains between the source and use data for PSBs in Hungary. It ranges from 53% to 66% of the PSB consumption data reported in the official energy balance, representing an alarming level of data uncertainty.

Figure 3

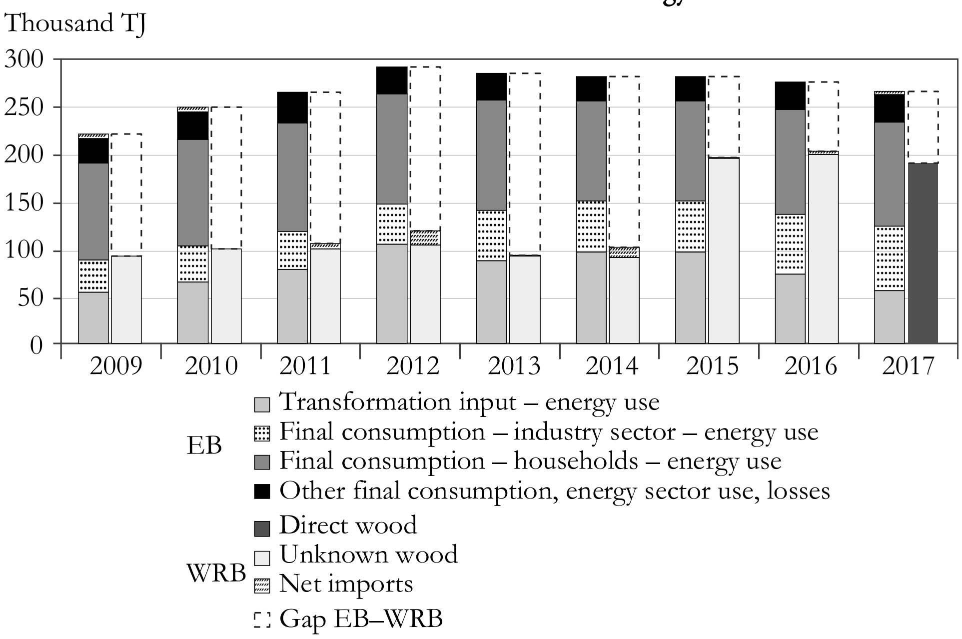
WRB sources and EB uses of PSB for energy in Hungary



Source: own chart based on JRC (2021), Cazzaniga et al. (2021) and Eurostat (2025).

Figure 4

WRB sources and EB uses of PSB for energy in Poland

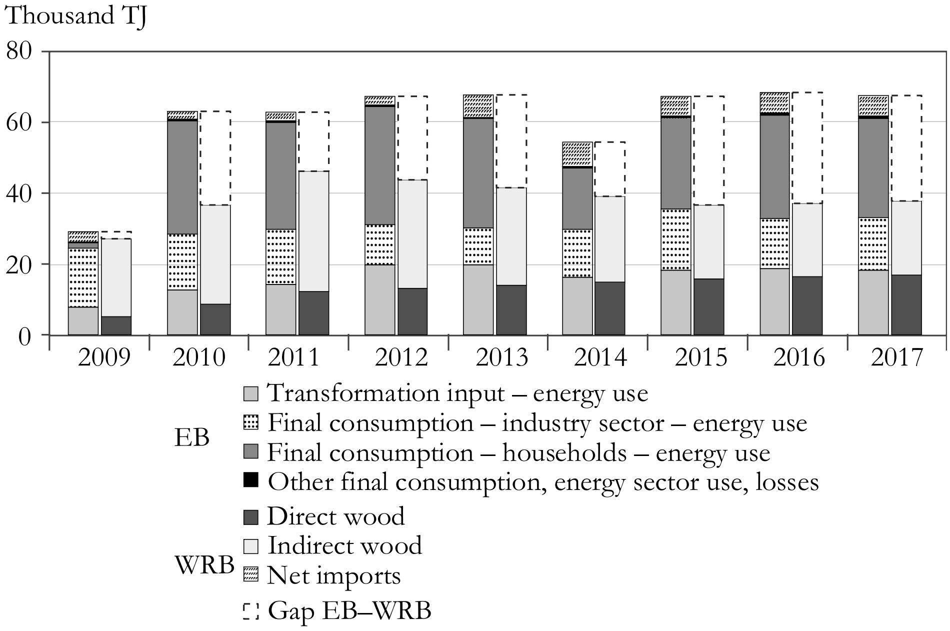


Source: own chart based on JRC (2021), Cazzaniga et al. (2021) and Eurostat (2025).

In Poland, the WRB data looks equally uncertain: the only reported category is labelled as 'unknown wood' until 2017. Further, we observe an unexplained doubling of annual 'unknown wood' sources after 2015. However, the gap is reduced from 60% to 30%, which is still significant. Poland is the only V4 country to report significant amounts of consistently positive net imports in its official EBs. This is not reflected in its WRB net import figure, which alternates between small negative and positive amounts several times over the period.

Figure 5

WRB sources and EB uses of PSB for energy in Slovakia



Source: own chart based on JRC (2021), Cazzaniga et al. (2021) and Eurostat (2025).

The supply–demand gap is also very explicit in the case of the Slovak official data. The increase in exports is explained by a wave of salvage logging like in the Czech Republic. The significant increase in household PSB use in 2010 is explained by the retroactive change in the statistical practice of the Slovak energy authority, following EU regulations (EC 2013). Since 2010, the household PSB energy use is the result of a complex methodology that includes surveying and energy modelling of the household building sector, similar to most other member states. Consequently, a significant gap of 26% to 46% appears after 2010, offsetting the supply surge of salvage logging.

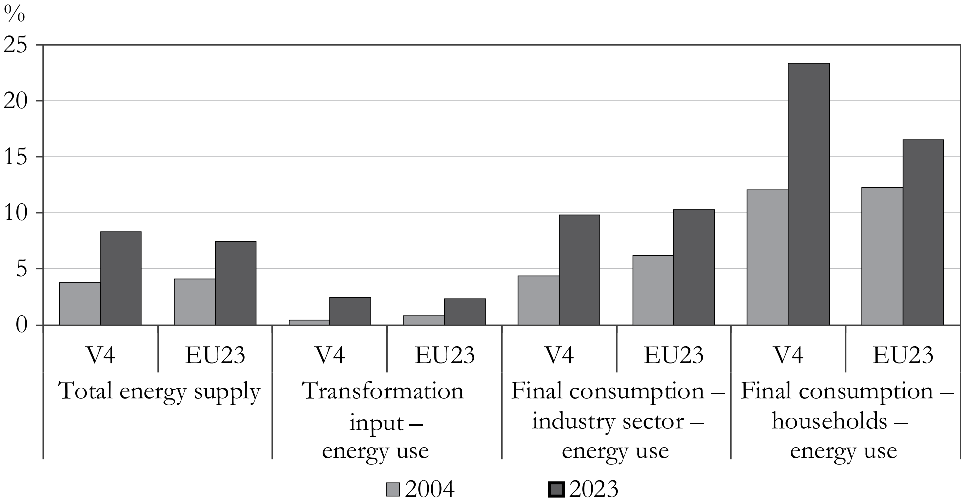
The gap observed in all V4 countries is likely to be explained by a combination of illegal logging, unregistered imports of wood fuels, use of roundwood product categories other than fuelwood, wood from non-forest land, agricultural biomass, burning of household waste, and possible statistical issues on both the energy and forestry side (surveying, sampling, methodology, modelling, etc.).

Dynamics of change within the energy balances

Having identified this significant uncertainty, we now assess the potential of policy instruments to make a difference by analysing how two decades of biomass energy policies have affected the use of PSB for energy transformation and final energy consumption. The share of PSB in the main EB categories is shown in Figure 6.

Figure 6

Share of PSB in total of energy products by major EB categories



Source: own chart based on Eurostat (2025).

The depicted growth in PSB shares shown over the last two decades is the product of a decreasing total energy supply and an increasing PSB use. While all but three EU member states decreased their total energy supply (including the Czech Republic, Hungary, and Slovakia but excluding Poland among the V4 group), all but two member states increased their total PSB supply over the same period (including all V4). The absolute change in total energy products and PSB use for energy in the V4 countries over the two decades is shown in the following graph by main EB categories.

A clear effect of biomass energy policies can be observed: while total energy consumption decreased in all V4 countries except for households in Poland and industry in Hungary, PSB use increased in all main EB categories. In Appendix Figure A3 illustrates the relative change of total and PSB energy use in the V4 and EU23 groups of countries from 2004 to 2023 by the main EB categories.

Although their total input for energy production has decreased, electricity and heat producers (i.e. the transformation sectors) have significantly increased their use of solid biofuels because of direct and indirect policy incentives in the EU: while the use of PSB for energy transformation more than doubled in the EU23, it more than quadrupled in the V4.

In the V4, PSB for final energy consumption in the industrial sectors has almost doubled over the last two decades. Meanwhile, in the rest of the EU, it has only increased by 27%. In 20 out of 27 member states, the industrial sectors increased their final energy consumption of PSB between 2004 and 2023. Meanwhile, in 22 member states, the total final energy consumption of the industrial sectors decreased over the same period, including in the Czech Republic, Poland, and Slovakia from the V4, with the EU average being 22%.

The household sector is the largest of the biomass-using sectors in the V4, which represents 14% of the EU population but consumes 21% of the total household PSB in the EU.

EU23 and V4 households also reduced their total final energy consumption between 2004 and 2023 by 15% and 1%, respectively. However, they increased their PSB final energy consumption by more than 90% in the V4 and 15% in the rest of the EU over the same period.[4]

In summary, the observed absolute changes in PSB use are not temperature-corrected. An even higher increase is recorded in 2021 in all energy segments discussed above. Hence, the observed growing trend is likely to be a policy-induced fundamental change and not just the effect of the energy crisis in 2022.

Potential impacts on the sustainability and climate benefits of biomass energy

Growing demand coupled with data uncertainty requires additional analysis of biomass-related issues. The sustainability of biomass energy is questionable if annual harvest exceeds net annual increment (NAI). In addition, the climate benefits of biomass energy may be compromised if annual CO_2 emissions from biomass energy exceed annual CO_2 sequestration by forests. Next, we explore the potential impacts of biomass data uncertainty on sustainability and climate mitigation using the V4 examples.

Sustainability

Regarding sustainability, a useful approach is making an assessment assuming the worst-case scenario wherein all missing wood needed to fill the gap between the data

[4] A part of the observed increase in household PSB can be explained by substantial changes in the statistical methodology behind the EB data (EC 2013).

on sources and uses is forest wood that is harvested and used without being accounted for. In this case, the use of wood biomass is sustainable if the total annual removal does not exceed the NAI. NAI is the figure that represents the natural annual growth of the forest minus the losses due to natural mortality. Harvest intensity (HI) is a measure of forest utilization rates that compares annual removals to NAI. Utilization rates where the HI exceeds 100% indicate unsustainable forest management.

To assess sustainability, we compare the NAI with the sum of the assumed non-energy and energy use from the PSB EBs, as reported in Table 3. The non-energy use of wood resources is calculated from the WRB: historically (2009–2017), the V4 countries used on average 46% of their total harvested wood sources for energy purposes, ranging from 20% in Slovakia in 2013 to 60% in Poland in 2017. Assuming a constant historical rate of energy use, we calculate the maximum sustainable amount of wood available for energy use for each V4 country based on their NAI data published by the Eurostat.

Table 3

Sustainability assessment of PSB use for energy in the V4 countries

Country	Net annual increment (NAI) in 2020, 1,000 m^3	Observed rate of energy use, 2009–2017 average, %	Estimate of the maximum sustainable energy source, 1,000 m^3	Total PSB use for energy in 2020, 1,000 m^3	Possible overuse rate, %
Czech Republic	36,301	52	18,749	16,916	90
Hungary	11,947	62	7,349	10,311	140
Poland	77,861	27	21,235	46,878	221
Slovakia	13,411	42	5,603	6,599	118
V4	139,521	46	52,936	80,703	152

Source: own calculations based on JRC (2021), Cazzaniga et al. (2021) and Eurostat (2025).

The italicized entries in Table 3 show that three of the V4 countries and the bloc together may be using unsustainable amounts of wood for energy. This assumes that the historical rate of energy use of harvested wood and total PSB energy use data are real and derived from forest harvesting. The unsustainability margin is an alarming 52% for the V4 countries combined.

Climate mitigation by biomass energy?

Before climate change policies began to influence the relative attractiveness of energy fuels and technologies, the use of wood fuels for energy was stable, and mostly dominated by household final consumption of fuelwood and harvest residues for space heating. Direct and indirect policy interventions began around 2005 through renewable energy targets with subsidies and the EU Emissions Trading Scheme (EU ETS 2003). The EU ETS effectively made woody biomass an attractive fuel choice with no carbon cost for entities under the policy, thanks to the carbon neutrality claim of biomass energy.

The climate neutrality of biomass energy is a concept that has been questioned by scientists and experts (EASAC 2018). Although the carbon stored in forest biomass comes from the atmosphere and not from fossil deposits, it is released back into the atmosphere when burned for energy. The specific carbon emission of fuelwood is the highest of all combustible fuels, and even higher than that of coal or lignite (IPCC 2006). However, according to the United Nations Framework Convention on Climate Change protocol (IPCC 2006), the release of carbon in the forest sector must be accounted for when the wood is harvested, with all uncertainties discussed above.

Many authors argue that significant additional carbon emissions are related to biomass energy production, such as soil disturbance (Achat et al. 2015) and further emissions along the biomass supply chain (Berndes et al. 2016, Favero et al. 2023). However, biomass combustion for energy is rewarded with a zero emission factor, giving it a false image of climate neutrality, when in fact biomass burning is severely depleting humanity's extremely constrained carbon budget as of the Paris Agreement.

A rapid decline in forest carbon sequestration is foreseen in strategic government documents (national energy and climate plans) in many EU member states and the V4 countries. This is due to several factors such as the ageing of the forest stock, increasing intensity of harvesting due to rising demand pressure, failure of afforestation plans, and onset of climate change.

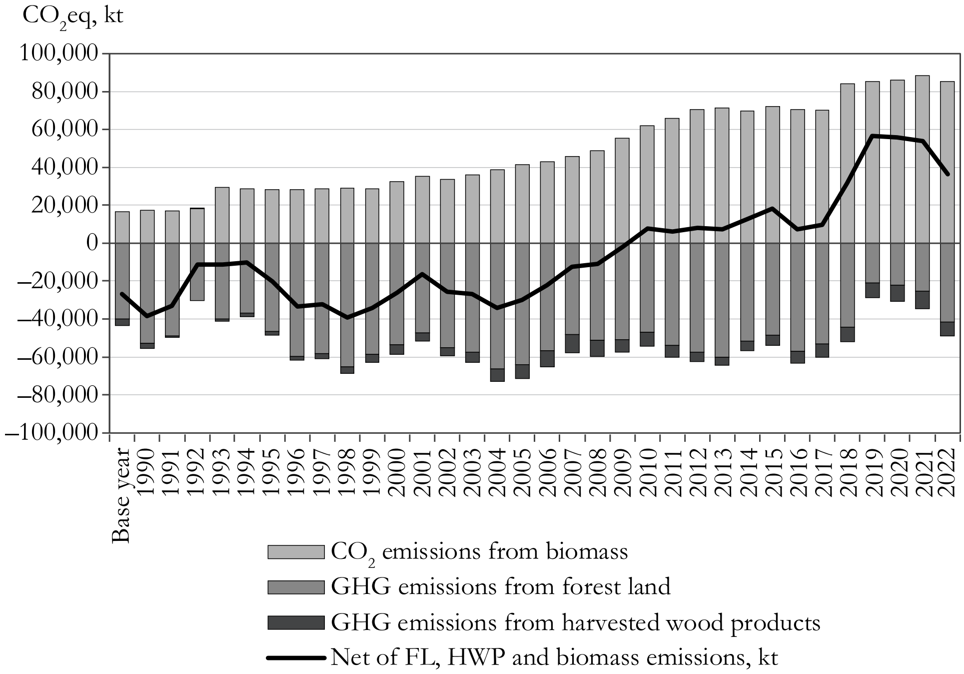
New EU regulations and policies aim to further increase the demand for biofuels. The EU ETS 2 (EU, 2003) aims to reduce carbon emissions in the transport and buildings sectors, potentially leading to a significant shift in space heating to biomass. The EU Carbon Removal Certification Framework Regulation (EC 2024a) and EU industrial carbon management strategy (EC 2024b) aim to facilitate and promote investment in bioenergy with carbon capture and storage (BECCS) and increased use of biomass, mainly forest wood, to replace carbon-intensive materials.

Trends in forest carbon sequestration and biomass energy

The quantitative result of the policy influences described above is summarised here. We use data on the negative emissions from forest land in the V4 achieved through net forest growth, which translates into net carbon sequestration. In Figure 7, the historical trends in net carbon sequestration are plotted and compared with carbon emissions from biofuels. Finally, future policy trends for forest carbon sequestration and biomass energy production are quantitatively illustrated from the national energy and climate plans of the V4 countries.

Figure 7

CO_2eq emissions from biomass, forest land, and harvested wood products in the V4 countries



Source: own chart based on National Inventory Reports of the V4 countries (IPCC 2023).

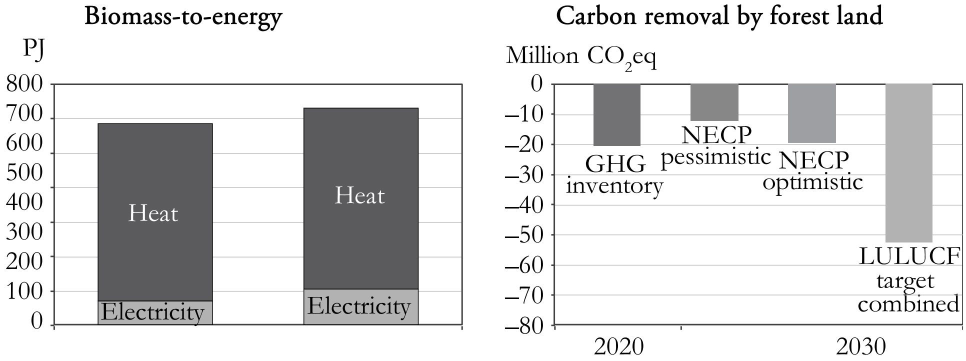
The trend is worrying: increasing CO_2 emissions from biomass combustion, decreasing carbon sequestration by forests, and very slowly increasing carbon sequestration by harvested wood products (HWP).[5] The balance of negative emissions from the forest land (FL) and harvested wood products (HWP) inventory categories, and positive emissions from biomass combustion turned from negative to positive in 2010. This has risen to as much as 54–56 million tonnes of net emissions in the V4 countries combined by the early 20s. CO_2 emissions from biomass increased from 1.8% to 14.2% of the total greenhouse gas (GHG) emissions of the V4 group.

Against this trend, assessing how government policies are addressing the issue is important. The national energy and climate plans of the V4 countries were reviewed to summarise the impact of policies and measures on biomass use for energy and carbon removal by forests (NECP-CZ 2024, NECP-HU 2024, NECP-PL 2024, NECP-SK 2024). These are summarised in Figure 8.

[5] If there is more mitigation potential in the HWP category for V4 countries or if HWP is close to saturation, more research is needed, as suggested by other authors (Pilli et al. 2015).

Figure 8

Policy plans for biomass-to-energy and carbon removal by forests in the V4 countries, 2030



Source: own chart based on NECP-CZ (2024), NECP-HU (2024), NECP-PL (2024), and NECP-SK (2024); land use, land use change, and forestry (LULUCF) targets for 2030, in ktCO_2eq: CZ: –1228; HU: –5724; PL: –38098; SK: –6821; V4 combined: –51871 (EC 2018).

According to the reviewed energy plans and policies of the V4, biomass electricity is expected to increase by 49% between 2020 and 2030. Biomass heat is planned to only grow moderately at 2%, still accounting for more than 600 PJ. Meanwhile, policy makers in the V4 countries seem to accept that they will lose significant forest carbon stocks. In the pessimistic case, the annual carbon sequestration rate of their forests falls from 20 million tonnes of CO_2 equivalents per year in 2020 to 12 million tonnes in 2030, a loss of 40%. Even under the most optimistic scenarios, the combined carbon sequestration of V4 forest lands will be no more than 19 million tonnes of CO_2eq by 2030. This is less than half of the combined V4 land use, land use change, and forestry (LULUCF) target for 2030 (–51.9 Mt CO_2eq) set in the EU LULUCF regulation.

Conclusions

Forest biomass is not an unlimited source of renewable energy. Recently, its limitations and scarcity have become even more apparent. The case of the V4 countries shows that a decline in the biomass capacity of forests, due to aging stocks and extreme losses caused by unusual weather patterns, accompanied by growing demand has resulted in increasing pressure on forest resources. This study explored the fundamental data uncertainty in biomass energy, with the findings implying that authorities struggle to monitor, control, and verify all sources and uses of PSB.

The growing demand for primary solid biomass as an energy fuel has been driven by a combination of policies. Here, the concepts of the renewability and climate neutrality of biomass energy need to be refined. Further, current government policies need to be reconsidered to protect the capacity of forests, and those households which rely on firewood as their only affordable fuel for space heating.

From a broader climate policy perspective, reassessing the integrity of biomass energy with climate policy is critical. For example, the V4 countries are losing their forest carbon stocks at an alarming rate, as well as the capacity of their forests to sequester carbon. While all V4 countries present ambitious biomass energy policies, very little is said about their policy plans to halt the declining trends in their forest carbon stocks and increase their annual forest carbon sequestration to meet their new LULUCF targets. Worryingly, the net balance of CO_2 removals and emissions for wood resources shifted from negative to positive in the V4 in 2010 and has continued to deteriorate thereafter. CO_2 emissions from biomass has increased from 1.8% to 14.2% of the total GHG emissions of the V4 group.

The most critical issue that energy and forest administrations should address is the significant uncertainty in the production and consumption data of primary solid biomass for energy. For example, the uncertainty in the V4 countries is such that 15% to 75% of the solid biofuel use reported in their national EBs cannot be justified by the wood resources reported in their JRC WRB for the 2009–2017 period, with the combined gap of the V4 group fluctuating between 33% and 56% over this period. Until this major administrative failure is corrected, no additional biomass energy support schemes (e.g. BECCS) should be introduced.

Many argue that biomass utilization should be focused more on agricultural biomass resources (Saleem 2022, Hellwinckel et al. 2024, and Rocha-Meneses et al. 2019).

Those involved in renewable energy statistics, in general, or biomass statistics, in particular, should take a precautionary approach, given that a significant part of PSB consumption in official EBs is not verified by official data on biomass sources. Designated authorities should establish working groups, including experts in forestry and energy statistics, to improve the reliability of national data publications. The JRC should continue and publish its WRB. Policy makers should develop a complex policy approach to the forest-biomass-energy-climate nexus to prevent unforeseen losses of their forests and keep fuelwood affordable for those households with no other options to meet their domestic energy needs.

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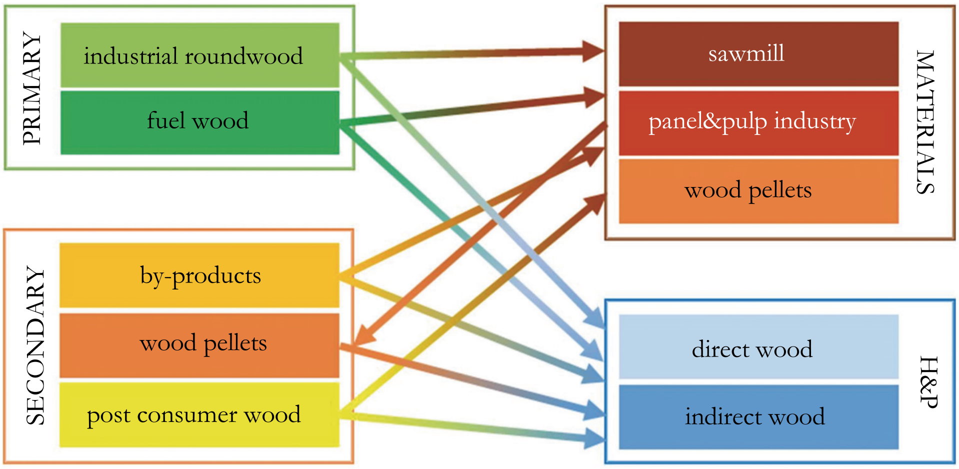
Appendix

Figure A1

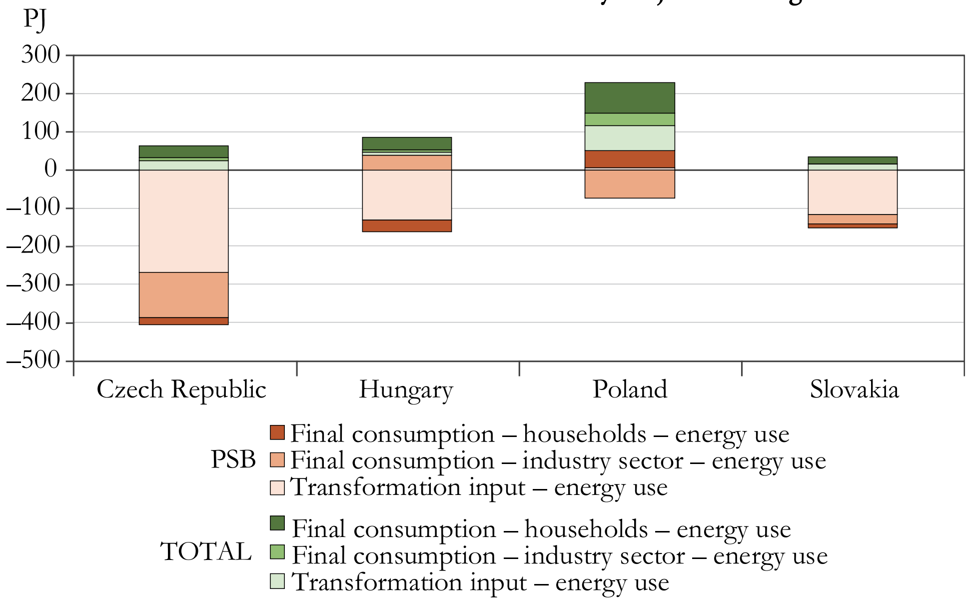
Flows of woody biomass among the different sectors in the Joint Research Centre wood resource balances



Source: Jonsson et al. (2021).

Figure A2

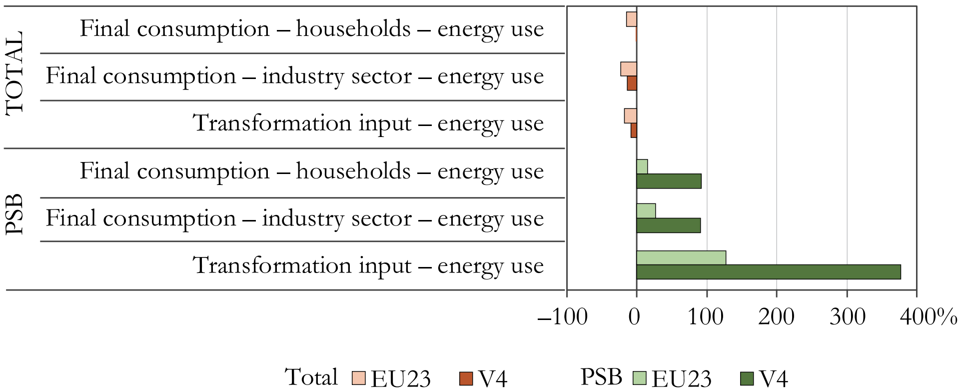
Absolute change in total and PSB use for energy in the V4 countries from 2004 to 2023 by major EB categories



Source: own chart based on Eurostat (2025).

Figure A3

Relative change in total and PSB use for energy in the V4 and EU23 countries from 2004 to 2023 by major EB categories



Source: own chart based on Eurostat (2025).

REFERENCES

ACHAT, D.–FORTIN, M.–LANDMANN, G.–RINGEVAL, B.–AUGOSTO, L. (2015): Forest soil carbon is threatened by intensive biomass harvesting *Scientific Reports* 5: 15991. https://doi.org/https://doi.org/10.1038/srep15991

AMACHER, G. S.–OLLIKAINEN, M.–KOSKELA, E. (2009): *Economics of forest resources* The MIT Press, Cambridge, Massachusetts.

AVITABILE, V.–BALDONI, E.–BARUTH, B.–BAUSANO, G.–BOYSEN-URBAN, K.–CALDEIRA, C.–CAMIA, A.–CAZZANIGA, N.–CECCHERINI, G.–DE LAURENTIIS, V.–DOERNER, H.–GIUNTOLI, J.–GRA, S. M.–GUILLEN GARCIA, J.–GURRIA, P.–HASSEGAWA, M.–JASINEVIČIUS, G.–JONSSON, R.–KONRAD, C.–KUPSCHUS, S.–LA NOTTE, A.–M'BAREK, R.–MANNINI, A.–MIGLIAVACCA, M.–MUBAREKA, S.–PATANI, S.–PILLI, R.–REBOURS, C.–RONCHETTI, G.–RONZON, T.–ROUGIEUX, P.–SALA, S.–SÁNCHEZ LOPEZ, J.–SANYE MENGUAL, E.–SINKKO, T.–STURM, V.–VAN LEEUWEN, M.–VASILAKOPOULOS, P.–VERKERK, P. J.–VIRTANEN, J.–WINKER, H.–ZULIAN, G. (2023): *Biomass production, supply, uses and flows in the European Union. Integrated assessment* Publications Office of the European Union, Luxemburg. https://doi.org/10.2760/811744

BERNDES, G.–ABT, B.–ASIKAINEN, A.–COWIE, A.–DALE, V.–EGNELL, G.–LINDNER, M.–MARELLI, L.–PARÉ, D.–PINGOUD, K.–YEH, S. (2016): *Forest biomass, carbon neutrality and climate change mitigation* European Forest Institute, Joensuu. https://doi.org/https://doi.org/10.36333/fs03

CAMIA, A.–GIUNTOLI, J.–JONSSON, R.–ROBERT, N.–CAZZANIGA, N.–JASINEVIČIUS, G.–AVITABILE, V.–GRASSI, G.–BARREDO, J. (2021): *The use of woody biomass for energy purposes in the EU* Publications Office of the European Union, Luxemburg. https://doi.org/10.2760/831621

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: 72–77. https://doi.org/https://doi.org/10.1038/s41586-020-2438-y

EUROPEAN COMMISSION [EC] (2013): *Manual for statistics on energy consumption in households* Publications Office of the European Union, Luxembourg. https://doi.org/10.2785/45686

FAVERO, A.–BAKER, J.–SOHNGEN, B.–DAIGNEAULT, A. (2023): Economic factors influence net carbon emissions of forest bioenergy expansion *Communications Earth & Environment* 4: 41. https://doi.org/10.1038/s43247-023-00698-5

GREGOR, K.–REYER, C.–NAGEL, T.–MÄKELÄ, A.–KRAUSE, A.–KNOKE, T.–RAMMIG, A. (2024): Reconciling the EU forest, biodiversity, and climate strategies *Global Change Biology* 30 (8): e17431. https://doi.org/doi: 10.1111/gcb.17431

HELLWINCKEL, C.–UGARTE, D. D.–FIELD, J. L.–LANGHOLTZ, M. (2024): Biomass from agriculture. In: LANGHOLTZ, M. H. (ed.): *2023 billion-ton report* Oak Ridge National Laboratory, Oak Ridge. https://doi.org/10.23720/BT2023/2316171

JONSSON, R.–CAZZANIGA, N.–CAMIA, A.–MUBAREKA, S. (2021): *Analysis of wood resource balance gaps for the EU* Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/417678

KALLIO, A. M.–SOLBERG, B. (2018): On the reliability of international forest sector statistics: problems and needs for improvements *Forests* 9 (7): 407. https://doi.org/doi:10.3390/f9070407

KOROSUO, A.–PILLI, R.–ABAD VIÑAS, R.–BLUJDEA, V.–COLDITZ, R.–FIORESE, G.–ROSSI, S.–VIZZARRI, M.–GRASSI, G. (2023): The role of forests in the EU climate policy: are we on the right track? *Carbon Balance Management* 18: 15. https://doi.org/10.1186/s13021-023-00234-0

LIU, S.–BRANDT, T. –NORD-LARSEN, T.–CHAVE, J.–REINER, F.–LANG, N.–TONG, X.–CIAIS, P.–IGEL, C.–PASCUAL, A.–GUERRA-HERNANDEZ, J.–LI, S.–MUGABOWINDEKWE, M.–SAATCHI, S.–YUE, Y.–CHEN, Z.–FENSHOLT, R. (2023): The overlooked contribution of trees outside forests to tree cover and woody biomass across Europe. *Science Advance* 9 (37): eadh4097. https://doi.org/10.1126/sciadv.adh4097

NGUYEN, T. Q.–LUU, L. Q.–MARTÍNEZ-RAMON, N.–LONGO, S.–CELLURA, M.–DUFOUR, J. (2024): Sustainability and circularity assessment of biomass-based energy supply chain *Heliyon* 10 (19): e38557. https://doi.org/10.1016/j.heliyon.2024.e38557

PALAHÍ, M.–VALBUENA, R.–SENF, C.–ACIL, N.–PUGH, T. A. M.–SADLER, J.–SEIDL, R.–POTAPOV, P.–GARDINER, B.–HETEMÄKI, L.–CHIRICI, G.–FRANCINI, S.–HLÁSNY, T.– LERINK, B. J. W.–OLSSON, H.– OLABARRIA, J. R. G.–ASCOLI, D.–ASIKAINEN, A.–BAUHUS, J.–BERNDES, G.–DONIS, J.–FRIDMAN, J.–HANEWINKEL, M.–JACTEL, H.–LINDNER, M.–MARCHETTI, M.–MARUŠÁK, R.–SHEIL, D.–TOMÉ, M.–TRASOBARES, A.–VERKERK, P. J.–KORHONEN M.–NABUURS, G-J. (2021): Concerns about reported harvests in European forests *Nature* 592: E15–E17. https://doi.org/10.1038/s41586-021-03292-x

PILLI, R.–FIORESE, G.–GRASSI, G. (2015): EU mitigation potential of harvested wood products *Carbon Balance and Management* 10: 6. https://doi.org/10.1186/s13021-015-0016-7

ROCHA-MENESES, L.–BERGAMO, T. F.–KIKAS, T. (2019): Potential of cereal-based agricultural residues available for bioenergy production *Data in brief* V 23: 103829. https://doi.org/10.1016/j.dib.2019.103829

SALEEM, M. (2022): Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source *Helyion* 8 (2): e08905. https://doi.org/10.1016/j.heliyon.2022.e08905

SCHNELL, S.–ALTRELL, D.–STÅHL, G.–KLEINN, C. (2015): The contribution of trees outside forests to national tree biomass and carbon stocks – a comparative study across three continents *Environmental Monitoring Assessment* 187: 4197. https://doi.org/10.1007/s10661-014-4197-4

TIETENBERG, T.–LEWIS, L. (2018): *Environmental and natural resource economics* Routledge.

INTERNET SOURCES

CAZZANIGA, N.–JASINEVIČIUS, G.–JONSSON, K.–MUBAREKA, S. (2021): *Wood resource balances of European Union and member states* Publications Office of the European Union, Luxembourg. https://publications.jrc.ec.europa.eu/repository/handle/JRC126552 (downloaded: February 2025)

EUROPEAN ACADEMIES SCIENCES ADVISORY COUNCIL [EASAC] (2018): *Commentary on forest bioenergy and carbon neutrality* European Academies Science Advisory Council, Vienna. https://easac.eu/fileadmin/PDF_s/reports_statements/Carbon_Neutrality/EASAC_commentary_on_Carbon_Neutrality_15_June_2018.pdf (downloaded: November 2024)

EUROPEAN COMMISSION [EC] (2009): *Commission Decision of 30 June 2009 establishing a template for National Renewable Energy Action Plans under Directive 2009/28/EC of the European Parliament and of the Council* EUR-Lex, Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009D0548 (downloaded: November 2024)

EUROPEAN COMMISSION [EC] (2018): *Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework* EUR-Lex, Bruxelles. Regulation (EU) 2018/841. https://eur-lex.europa.eu/eli/reg/2018/841/oj (downloaded: November 2024)

EUROPEAN COMMISSION [EC] (2021): *Biomass peporting under Annex IX, Part 1 (m) to Regulation (EU) 2018/1999 of the EU Parliament and of the Council of 11 December 2018 on the governance of the energy union and climate action* EUR-Lex, Brussels. https://ec.europa.eu/eurostat/documents/38154/13437164/Biomass-questionnaire-instructions-2020.pdf/c26a8d10-e490-fbed-e76c-b87855bdc84a?t=1634715494028 (downloaded: November 2024)

EUROPEAN COMMISSION [EC] (2024a): *Regulation (EU) 2024/3012 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products* EUR-Lex, Bruxelles. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202403012 (downloaded: November 2024)

EUROPEAN COMMISSION [EC] (2024b): C*ommunication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions towards an ambitious industrial carbon management for the EU* EUR-Lex, Bruxelles. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A62%3AFIN&qid=1707312980822 (downloaded: November 2024)

EUROPEAN COMMISSION JOINT RESEARCH CENTRE [EC JRC] (2021): *Wood resource balances of EU and member states, years 2009–2017*. https://knowledge4policy.ec.europa.eu/publication/wood-resource-balances_en (downloaded: November 2024)

EUROPEAN UNION [EU] (2003): *ETS directive* EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02003L0087-20230605 (downloaded: November 2024)

EUROSTAT (2025): *Complete energy balances: nrg_bal_c*. https://doi.org/10.2908/NRG_BAL_C (downloaded: March 2025)

FOOD AND AGRICULTURE ORGANIZATION [FAO] (2009): Forest product conversion factors for the UNECE region *Discussion Paper* 49., Geneva Timber and Forest, Geneva. https://www.researchgate.net/publication/261212246_FOREST_PRODUCT_CONVERSION_FACTORS_FOR_THE_UNECE_REGION (downloaded: January 2025)

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE [IPCC] (2006): *2006 IPCC guidelines for national greenhouse gas inventories* IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (downloaded: December 2024)

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE [IPCC] (2023): *National inventory submissions* UNFCCC, Bonn. https://unfccc.int/ghg-inventories-annex-i-parties/2023 (downloaded: May 2025)

MANTAU, U. E. (2010): *EUwood – real potential for changes in growth and use of EU forests* University of Hamburg, Hamburg. https://ecopedia.s3.eu-central-1.amazonaws.com/pdfs/108.pdf (downloaded: March 2025)

NECP-CZ (2024): *National energy and climate plan of Czechia* EU COM, Bruxelles. https://commission.europa.eu/publications/czech-draft-updated-necp-2021-2030_en (downloaded: November 2024)

NECP-HU (2024): *National energy and climate plan of Hungary* EU COM, Bruxelles. https://commission.europa.eu/publications/hungary-final-updated-necp-2021-2030-submitted-2024_en (downloaded: November 2024)

NECP-PL (2024): *National energy and climate plan of Poland* EU COM, Bruxelles. https://commission.europa.eu/publications/poland-draft-updated-necp-2021-2030_en (downloaded: November 2024)

NECP-SK (2024): *National energy and climate plan of Slovakia* EU COM, Bruxelles. https://commission.europa.eu/publications/slovakia-draft-updated-necp-2021-2030_en (downloaded: November 2024)