DOI: 10.34101/ACTAAGRAR/1/15104

Estimating the amount and heating value of wood waste burned in households based on FICM HWP model output data

Éva Király[1*] – Gábor Kis-Kovács[2] – Zoltán Börcsök[3] – Zoltán Kocsis[3] – Péter Kottek[4] – Gábor Németh[3] – András Polgár[5] – Attila Borovics[1]

[1]Forest Research Institute, University of Sopron, Várkerület 30/A Sárvár, Hungary

[2]Hungarian Meteorological Service, Kitaibel Pál str. 1, Budapest, Hungary

[3]Faculty of Wood Engineering and Creative Industries, University of Sopron, Bajcsy-Zsilinszky E. str. 4, Sopron, Hungary

[4]Department of Forest Management Planning, Ministry of Agriculture, Frankel Leó str. 42-44., Budapest, Hungary

[5]Faculty of Forestry, University of Sopron, Bajcsy-Zsilinszky E. str. 4, Sopron, Hungary

*Correspondence: kiraly.eva.ilona@uni-sopron.hu

SUMMARY

A 2009 study published by the Regional Centre for Energy Policy Research (RCEPR) sparked significant debate within the Hungarian forestry and wood industry sectors. The study suggested a substantial shortfall in the balance of solid bioenergy biomass usage and sources, which it attributed to large-scale illegal logging. The Bio Screen CCE Project updated this analysis and quantified a 37.2 PJ (43%) deficit in the solid bioenergy biomass balance for 2019. This study investigates the extent to which household wood waste burning could account for this shortfall. Using the Forest Industry Carbon Model (FICM) HWP submodel, the authors estimate that over 1.2 million m³ of wood waste may be burned annually in households. The heating value of this burned wood waste for 2019 is estimated at 14 PJ, explaining 39% of the shortfall identified in the Bio Screen CCE Project's 2021 report.

Keywords: *energy statistics; energy balance; circular bioeconomy; climate change mitigation; waste management*

INTRODUCTION

A study published in 2009 by the Regional Centre for Energy Policy Research (RCEPR) generated numerous debates in the domestic forestry and wood industry sector. This study, analysing data from the National Forestry Database (NFD), the United Nations Food and Agriculture Organization (FAO), the Hungarian Central Statistical Office (HCSO), and the Hungarian Energy Office (HEO), concluded that there is a significant deficit between the data on biomass usage and sources. This deficit means that, according to the study, the solid biomass usage identifiable from HEO and HCSO statistical data exceeds the amount of firewood production reported by the NFD. The authors of the 2009 RCEPR study estimated this deficit to be between 3–3.5 million m^3 (net), concluding that this quantity of firewood used by households likely originates from illegal logging. They also concluded that the NFD's statistical data are unreliable.

The National Professional Association of the Wood Industry responded to the RCEPR study's claims with an eight-page opinion (Mőcsényi, 2009). It states that the RCEPR study is burdened with numerous methodological errors and uncertainties and fails to account for the phenomenon of natural mortality occurring in forests. Overall, it considers it unlikely that the deficit identified in the balance can be attributed to illegal logging. Furthermore, it points out that, due to the uncertainty in the methodology, the reported deficit could be 2 million m^3 less, which would mean it amounts to only 1–1.5 million m^3. The response also highlights the phenomenon that in final harvesting, forest managers do not fully utilise the opportunities outlined in their forest management plans, resulting in many overmature stands remaining uncut. It underlines that the volume of the overmature standing volume has been continuously increasing since the 1990s. This tendency also makes the existence of large-scale illegal logging unlikely. The amount of overmature wood stock is also analysed in detail by Borovics et al. (2023), who found that the standing volume of overmature stands continued to increase during the period after 2009, reaching 45.6 million m^3 by 2021.

The 2021 report of the Bio Screen CCE Project (Bódis et al., 2021) reopens the issue of the discrepancy between the demand and supply sides of the solid biomass balance. The report uses data from the HCSO and the Hungarian Energy and Public Utility Regulatory Authority (HEPURA) to quantify the demand side. The report examines the period from 2000 to 2019. It accounts for NFD firewood production data, firewood imports, provides estimates for logging from wooded areas not under forest management planning, accounts for the amount of slash, and includes the usage of straw and other non-woody biomass. Based on a comparison of supply and demand sides, the report quantifies a source-side deficit of 37.2 PJ (43%).

The report provides a detailed analysis of the potential uncertainties related to the calculations on the demand side. It explains that the estimation of household solid biomass consumption is based on the energy module results added to the Household Budget and Living Conditions Survey (HKÉF) conducted by the HCSO, as well as on building energy calculations carried out by the Hungarian Energy and Public Utility Regulatory Authority (HEPURA). This new methodology was introduced in 2016, in accordance with EU Regulation 431/2014. According to the report, the annual HKÉF survey asks households two questions regarding their biomass consumption: one about the quantity of biomass fuels used and another

DOI: 10.34101/ACTAAGRAR/1/15104

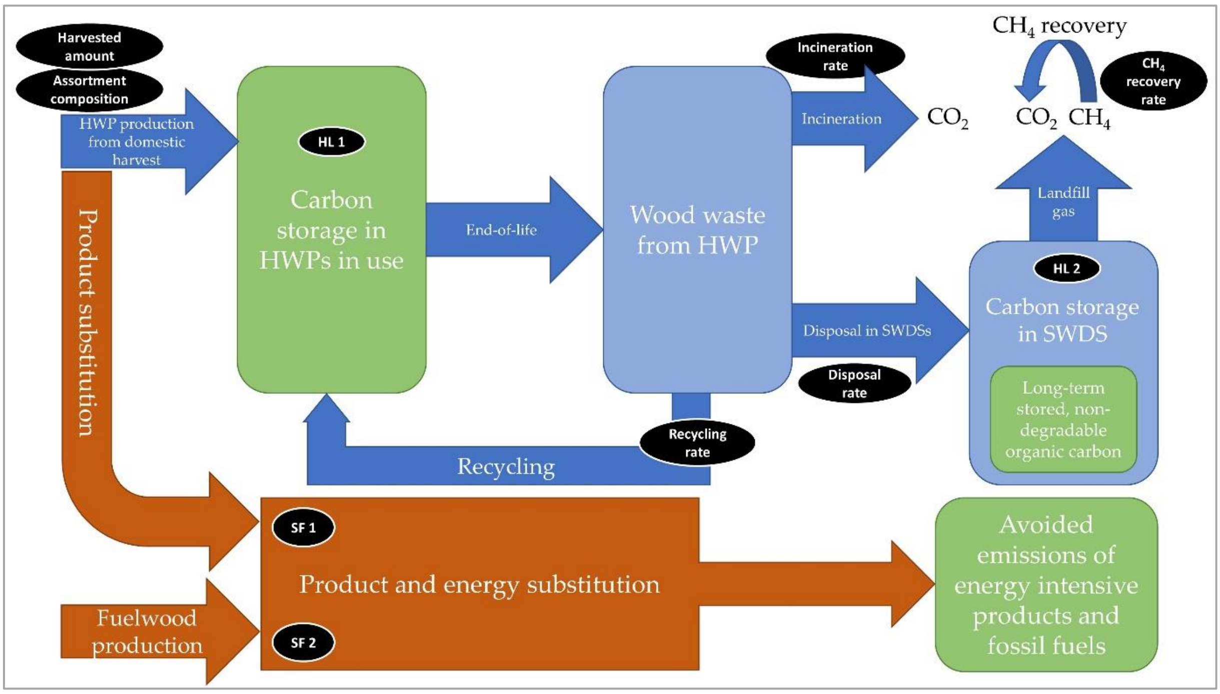
about the associated financial expenditures. The report identifies potential waste burning in households as a significant uncertainty factor. Although the HCSO survey included detailed questions about the type and source of solid biomass used, including wood waste, it is still assumed that waste burning is common in low-income rural areas. Also, it is very likely that respondents are unwilling to report the amount of waste and wood waste burned, as it is illegal to burn household waste due to its harmful effects on air quality, and violating this regulation can result in fines imposed by local governments or the Disaster Management Authority.

In this research, the authors investigated how much of the 37.2 PJ deficit estimated by the Bio Screen CCE Project could be attributed to the burning of household wood waste. For the analysis, the authors used the wood product (HWP) sub-model (Király et al., 2024) of the Forest Industry Carbon Model (Borovics et al., 2024).

MATERIALS AND METHODS

In this study, the authors applied the HWP sub-model of the Forest Industry Carbon Model developed within the framework of the ForestLab project (Borovics, 2022) (*Figure 1*).

Figure 1. **Flowchart of the FICM HWP sub-model.**



Source: Király et al., 2024

The HWP sub-model uses the methodology developed by the Intergovernmental Panel on Climate Change (IPCC) for calculating emissions, which is also employed in the preparation of the National Greenhouse Gas Inventory Report (NIR, 2023). It combines the IPCC model for landfills (IPCC, 2006) with IPCC equations describing carbon storage and emissions from wood products (IPCC, 2013, 2019), supplemented with a newly developed recycling and waste route selection module. The wood product module of the model simulates the carbon balance of wood products in use and the impact of recycling on the carbon balance. Additionally, it calculates emissions from the burning of firewood. The waste module estimates the amount of wood products that become waste and the carbon dioxide and methane emissions resulting from their incineration and disposal in landfills. It also accounts for the effect of methane recovery at landfills and changes in its extent. The substitution module quantifies the avoided emissions in the Industry and Energy sectors of the Greenhouse Gas Inventory through product and energy substitution. Thus, the HWP model covers and quantifies the entire lifecycle of wood material up to its disposal, considering all possible outcomes.

The country-specific parameterisation of the HWP sub-model was carried out based on the HCSO semi-finished wood product production and trade statistics (according to Király et al., 2022), the National Greenhouse Gas Inventory Report (NGHGI), the National Environmental Information System (NEIS), and the National Waste Management Plan (ITM 2021), as detailed by Király et al. (2023a,b, 2024).

The model quantifies the amount of wood products becoming waste (outflow) based on HCSO statistics and the wood product lifetimes defined by the IPCC, using the following equations:

DOI: 10.34101/ACTAAGRAR/1/15104

$$\Delta C(i) = C(i+1) - C(i) \quad (1)$$

$$C\ (i+1) = e^{-k} \cdot C(i) + \left[\frac{(1-e^{-k})}{k}\right] \cdot \text{inflow (i)} \quad (2)$$

$$\text{outflow (i)} = \left(1 - e^{-k}\right) \cdot C(i) + \left[1 - \frac{(1-e^{-k})}{k}\right] \cdot \text{inflow (i)} \quad (3)$$

where:

i: year;

C(i): the carbon stock in the particular HWP commodity class i at the beginning of the year i, kt C;

k: decay constant of first-order decay for each HWP commodity class i given in units yr^{-1} (k= ln(2)/HL, where HL is the half-life of the particular HWP commodity in the HWP pool in years);

inflow(i): the carbon inflow to the particular HWP commodity class i during the year i, kt C yr^{-1};

ΔC(i): carbon stock change in the HWP commodity class i during the year i, kt C yr^{-1};

outflow(i): the carbon content of the particular HWP commodity class i that goes out of use during the year i, kt C yr^{-1}.

The half-lives and conversion factors used are detailed in *Table 1*.

Table 1. **Default half-life values and conversion factors recommended by IPCC (2019)**

	Half-Life (Year)	**Density (Oven Dry Mass over Air Dry Volume) [Mg m^{-3}]**	**Carbon Fraction**	**C conversion Factor (Per Air Dry Volume) [Mg C m^{-3}]**
Coniferous sawnwood	35	0.45	0.5	0.28
Non-coniferous sawnwood	35	0.56	0.5	0.225
Veneer sheets	25	0.505	0.5	0.253
Plywood	25	0.542	0.493	0.267
Particle board	25	0.596	0.451	0.269
HDF	25	0.788	0.425	0.335
MDF	25	0.691	0.427	0.295
Fibreboard compressed	25	0.739	0.426	0.315
Other board	25	0.159	0.474	0.075
	Half-life (year)	**Relative dry mass (oven dry mass over air dry mass) [Mg Mg^{-1}]**		**C conversion factor (per air dry mass) [Mg C Mg^{-1}]**
Paper and paperboard (aggregate)	2	0.9	-	0.386

The outflow values calculated using the HWP sub-model were provided in units of m^3 and tons. From the outflow value, the authors estimated the quantity disposed of via landfill based on the NEIS and NGHGI data. Since, according to NEIS data, household wood waste is not disposed of through incineration, the authors assumed that the remaining quantity is either accumulated in households or burned in household heating appliances. The heating value of the waste quantity reduced by the landfilled amount was also calculated, using a heating value of 15 GJ t^{-1}.

RESULTS AND DISCUSSION

According to the obtained results, the amount of wood waste generated in households ranged between 1.1 and 1.4 million m^3 during the period from 1980 to 2020, with the amount in 2019 being 1,378,126 m^3 (*Figure 2).* On average, 10% of the household wood waste generated during the examined period ended up in landfills (*Figure 3*). In 2019, the amount deposited in landfills accounted for 8% of the total generated quantity. There is no registered information on the fate of the remaining 92%, as this amount does not appear in the NEIS records. The HWP sub-model of the FICM model assumes that this waste quantity is incinerated, resulting in the release of carbon dioxide. This is significant for the NGHGI carbon balance, as this amount represents a substantial source of emissions. Therefore, the conservative estimation according to IPCC requirements necessitates calculating and accounting for this emission.

However, it is possible that this waste quantity is not completely incinerated in households, as wood waste might be stored in yards or cellars for a longer term. Additionally, it is theoretically possible that the lifespan of wood products in Hungary is much higher than the default values provided by the IPCC. On the other hand, if neither of these conditions applies, we must assume that this wood waste is incinerated in households.

DOI: 10.34101/ACTAAGRAR/1/15104

Figure 2. **HWPs reaching their end of life and becoming waste at households (amounts expressed in m^3)**

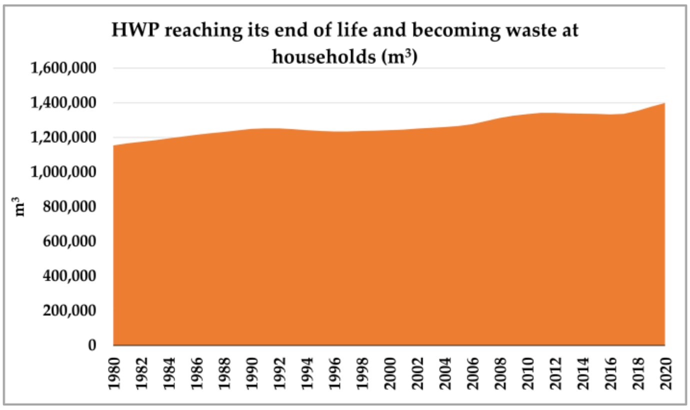
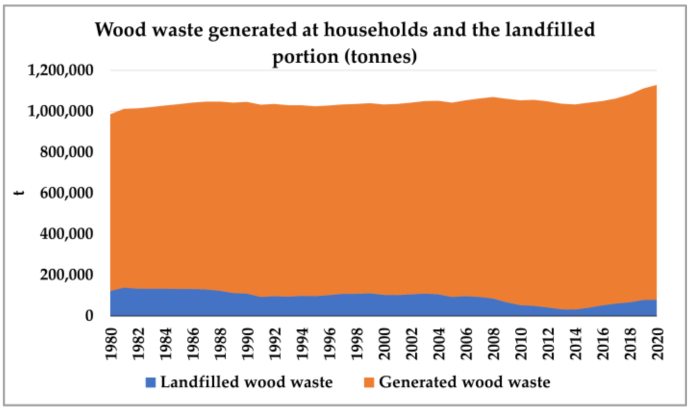
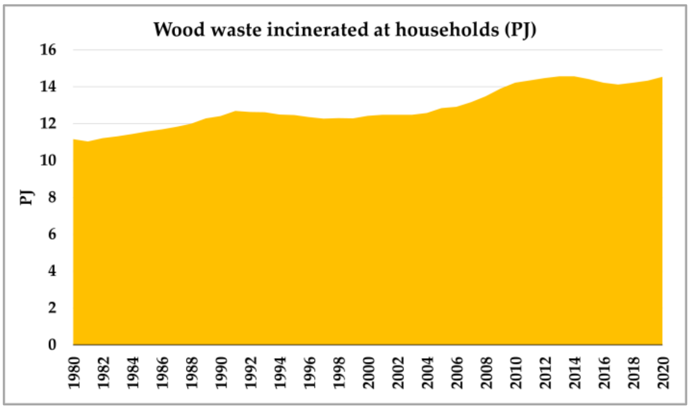


Figure 3. **Wood waste generated at households and its landfilled portion (expressed in tonnes)**



The calorific value of the waste quantity not disposed of in landfills, expressed in PJ units, is shown in *Figure 4.* During the examined period, the calorific value of the wood waste presumably burned in households is estimated to average 13 PJ per year. The calorific value ranges between 11 and 15 PJ, and it amounts to 14 PJ for 2019 and 15 PJ for 2020.

Figure 4. **Wood waste incinerated at households expressed in heating value (PJ)**



The obtained results suggest that 39% of the 37.2 PJ deficit reported for 2019 in the Bio Screen CCE Project 2021 report (Bódis et al., 2021) could be attributed to the incineration of household wood waste. This means that only 23 PJ of the reported deficit value (equivalent to 26% of total demand-side solid biomass use) would require further explanation. However, given that both the estimates of demand-side biomass use, and the outflow values calculated using the FICM HWP model are subject to significant uncertainty, this 26% deficit might fall within the margin of error.

DOI: 10.34101/ACTAAGRAR/1/15104

Additionally, it is important to note that if such a high proportion of wood waste is indeed being incinerated in Hungarian households, one might assume that other non-wood waste materials could also be burned. Hoffer et al. (2024) estimated the type and amount of household waste incinerated in Hungary and Romania based on the analysis of PM10 samples. According to their results, the burning of packaging materials and clothing containing polyethylene-terephthalate (PET) was the most typical in the examined areas. According to their estimate, the population burns 8–13% of the total amount of household waste generated in Hungary, i.e. approximately half a million tons of waste is burned annually in household stoves as calculated based on the waste generation data of the HCSO (2024). Hoffer et al. (2024) point out that this high level of waste incineration is responsible for a significant amount of PM10 concentration, which poses a serious environmental and public health risk.

Based on the above, it can be concluded that the discrepancies between the demand and supply sides of the solid biomass balance do not result from illegal logging.

The authors' estimate suggests that more than 1.2 million m^3 of wood waste are incinerated in households annually. This quantity accounts for 38% of the average annual net firewood removal for the years 2017–2021, highlighting its substantial size. Wood is a crucial raw material in the circular bioeconomy, offering significant climate change mitigation potential through both long-term carbon storage and the avoidance of emissions from fossil fuels by providing alternative energy sources (Borovics et al., 2023). Therefore, it is especially important to find and maintain an optimal balance between different uses of wood (Verkerk et al., 2022). Landfilling wood waste is the least preferable disposal method, as it leads to substantial methane emissions, which are far more detrimental to global warming compared to carbon dioxide (Király et al., 2023).

In line with the principles of the circular bioeconomy, the best approach for managing wood waste is through reuse or material recycling. Contaminants such as coatings, wood preservatives, binding agents, and flameproofing agents determine the applicability of recycling technologies (Kharazipour & Kües, 2007; Harms & Flamme, 1999). Untreated solid wood products, as well as wood products and composites free from organic halogen compounds and other harmful substances, are suitable to be converted into wood chips for wood composite production (Kharazipour & Kües, 2007). Furniture coated and painted with halogenated organic compounds can only be recycled after the removal of coatings and varnishes (Kharazipour & Kües, 2007). Wood products treated with harmful chemicals or those with high levels of contamination are only suitable for energy recovery. Hazardous PCB-containing wood waste must be treated and disposed of separately (Kharazipour & Kües, 2007).

One key limitation of this study lies in the assumptions made regarding the final fate of wood waste. While the amount of wood waste generated is estimated using the FICM HWP model based on national wood product production and trade data, and first-order decay functions, the subsequent assumption that the non-landfilled and non-publicly incinerated fraction is burned in households introduces uncertainty. This residual method does not account for other potential fates of wood waste–most notably, the possibility that a portion may simply be stored in backyards or otherwise stockpiled without immediate combustion. As such, while household incineration is a plausible and likely major pathway, especially in rural areas, the exact proportion of wood waste actually burned remains uncertain. Future research should aim to refine this estimate through empirical data collection, including surveys and localized studies on household waste handling practices.

CONCLUSIONS AND RECOMMENDATIONS

This study estimated the amount of wood waste incinerated in Hungarian households using a model-based approach. Domestic harvested wood product production was calculated based on national production and trade data. The quantity of HWP going out of use was derived using first-order decay functions, and landfilled wood waste was estimated from national environmental statistics. The remaining amount was attributed to household incineration. According to the obtained results, approximately 1.2 million m^3 of wood waste is burned annually in households, equivalent to 38% of the average annual net firewood removal. This highlights the substantial role of wood waste in household energy use and its potential to fill existing gaps in biomass energy statistics.

To improve the accuracy of future estimates, the authors recommend the collection of more granular, location-specific data on household waste management practices, with special attention to differences between rural and urban areas. Given the illegality and underreporting of waste burning, traditional surveys should be supplemented with anonymised questionnaires, indirect assessment methods (e.g., atmospheric monitoring), and targeted field studies.

Furthermore, to reduce the environmental and health impacts of uncontrolled household waste incineration, the development of a cascading wood waste management system is strongly advised. This would involve improving the infrastructure for the separate collection, recycling, and energy recovery of wood waste. To ensure that households – particularly in rural areas – continue to have access to affordable heating, these efforts should be accompanied by a social firewood support program and the promotion of short-rotation energy plantations. Together, these measures would support both climate and public health objectives while contributing to a more sustainable, circular bioeconomy.

DOI: 10.34101/ACTAAGRAR/1/15104

ACKNOWLEDGEMENTS

This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

REFERENCES

Bódis, P.; Gálhidy, L.; Harmat, Á.; Szajkó, G.; Varga, K. (2021): Van-e elég fenntartható biomassza Magyarországon? – Országjelentés a szilárd biomassza keresleti és kínálati oldaláról. Magyarország. Bio Screen CEE projekt. 79. p. [Is there enough sustainable biomass in Hungary? – National report on the demand and supply side of solid biomass. Hungary. Bio Screen CEE Project.] https://rekk.hu/downloads/projects/Country_report_Hungary_HU_FINAL.pdf

Borovics, A. (2022): ErdőLab: a Soproni Egyetem erdészeti és faipari projektje: Fókuszban az éghajlatváltozás mérséklése *Erdészeti Lapok, 157*: 4 pp. 114–115. [ForestLab: The forestry and wood industry project of the University of Sopron: Focusing on climate change mitigation]

Borovics, A.; Király, É.; Kottek, P. (2024): Projection of the Carbon Balance of the Hungarian Forestry and Wood Industry Sector Using the Forest Industry Carbon Model. *Forests, 15*: 4 Paper: 600, 13 p. https://doi.org/10.3390/f15040600

Borovics, A.; Mertl, T.; Király, É.; Kottek, P. (2023): Estimation of the Overmature Wood Stock and the Projection of the Maximum Wood Mobilization Potential up to 2100 in Hungary. *Forests, 14*: 8 Paper: 1516, 22 p. https://doi.org/10.3390/f14081516

Borovics, A.; Kottek P.; Király, É. (2023): Az erdészeti bioenergia hozzájárul a karbonsemlegességhez: Klímavédelmi szempontból valóban jobb gázzal vagy szénnel fűteni, mint fával? *Erdészeti Lapok, 158*: 6 pp. 223–226. [Forest bioenergy contribution to carbon neutrality: From a climate protection perspective, is it really better to heat with gas or coal than with wood?]

HCSO (2024): Az egyes hulladékfajták mennyisége a kezelés módja szerint. [The amount of different waste types and their disposal.] https://www.ksh.hu/stadat_files/kor/hu/kor0029.html.

Harms, S.; Flamme, S. (1999): Wood waste recycling in Germany. R'99 Congress (Recovery, Recycling, Re-integration), February 1999. Available online: https://www.environmental-expert.com/articles/article434/article434.htm.

Hoffer, A.; Meiramova, A.; Tóth, Á.; Jancsek-Turóczi, B.; Kiss, G.; Rostási, Á.; Levei, E.A.; Marmureanu, L.; Machon, A.; Gelencsér, A. (2024): Assessment of the contribution of residential waste burning to ambient PM10 concentrations in Hungary and Romania, Atmos. *Chem. Phys., 24,* 1659–1671, https://doi.org/10.5194/acp-24-1659-2024.

IPCC (2006): IPCC Guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).

IPCC (2013): Revised supplementary methods and good practice guidance arising from the Kyoto protocol. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Pp. 268.

IPCC (2019): Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Calvo Buendia, E., Tanabe, K., Kranjc, A.; Baasansuren, J.; Fukuda, M.; Ngarize, S.; Osako, A.; Pyrozhenko, Y.; Shermanau, P. and Federici, S. (eds).

ITM (2021): Országos Hulladékgazdálkodási Terv (2021–2027) Innovációs és Technológiai Minisztérium 2021. [National Waste Management Plan (2021–2027) Ministry of Innovation and Technology 2021.] https://kormany.hu/dokumentumtar/orszagos-hulladekgazdalkodasi-terv-2021-2027.

Kharazipour, A.; Kües, U. (2007): Chapter: Recycling of Wood Composites and Solid Wood Products. In *Wood Production, Wood Technology, and Biotechnological Impacts*; Kües, U., Ed.; Universitätsverlag Göttingen: Göttingen, Germany, 2007; pp. 509–533.

Király, É.; Börcsök, Z.; Kocsis, Z.; Németh, G.; Polgár, A.; Borovics, A. (2022): Carbon Sequestration in Harvested Wood Products in Hungary an Estimation Based on the IPCC 2019 Refinement. *Forests, 13*: 11 Paper: 1809, 15 p. https://doi.org/10.3390/f13111809

Király, É.; Börcsök, Z.; Kocsis, Z.; Németh, G.; Polgár, A.; Borovics, A. (2023): A new model for predicting carbon storage dynamics and emissions related to the waste management of wood products: introduction of the HWP-RIAL model. *Acta Agraria Debreceniensis/Agrártudományi Közlemények 2023: 1.*75–81., https://doi.org/10.34101/actaagrar/1/12495

Király, É.; Börcsök, Z. Kocsis, Z.; Németh, G.; Polgár, A.; Borovics, A. (2024): Climate Change Mitigation Through Carbon Storage and Product Substitution in the Hungarian Wood Industry. *Wood Research, 69*: 1.. 72–86. https://doi.org/10.37763/wr.1336-/69.1.7286

Király, É.; Kis-Kovács, G.; Börcsök, Z.; Kocsis, Z.; Németh, G.; Polgár, A.; Borovics, A. (2023): Modelling Carbon Storage Dynamics of Wood Products with the HWP-RIAL Model—Projection of Particleboard End-of-Life Emissions under Different Climate Mitigation Measures. *Sustainability, 15*: 7 Paper: 6322, 17 p. https://doi.org/10.3390/su15076322

Mőcsényi, M. (2009): Vélemény a REKK illegális fakitermelést taglaló tanulmányáról. [Opinion on the RCEPR study discussing illegal logging.] https://rekk.hu/downloads/projects/fagosz-reakcio.pdf.

NIR (2023): National Inventory Report for 1985–2021. Hungary. Chapter: Land-Use, Land-Use Change and Forestry; Somogyi, Z., Tobisch, T., Király É., Hungarian Meteorological Service: Budapest, Hungary, 486 p.

RCEPR (2009): Erdészeti és ültetvény eredetű fás szárú energetikai biomassza Magyarországon, Regionális Energiagazdasági Kutatóközpont. [Forestry and plantation-based wood biomass for energy in Hungary, Regional Energy Economics Research Centre.] https://rekk.hu/downloads/projects/wp2009_5.pdf.

Verkerk, P.J.; Delacote, P.; Hurmekoski, E.; Kunttu, J.; Matthews, R.; Mäkipää, R.; Mosley, F.; Perugini, L.; Reyer, C.P.O.; Roe, S. et al. (2022): *Forest-Based Climate Change Mitigation and Adaptation in Europe*. From Science to Policy 14; European Forest Institute: Joensuu, Finland, ISBN 978-952-7426-22-7.