UNIVERSITY of SOPRON

FACULTY OF WOOD ENGINEERING AND CREATIVE INDUSTRIES

Determination of the carbon footprint of FALCO Zrt., compared to other branches of industry in 2023/24 business year

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Authors:

Dr. Tibor L. Alpár
Dr. László Bejó
Dr. Zoltán Börcsök
Dr. Zoltán Kocsis
Dr. Gábor Németh
Dr. Zoltán Pásztory

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University of Sopron
Faculty of Wood Engineering and Creative Industry

Contents

Executive summary

This study is aimed at evaluating the carbon footprint of the FALCO Zrt. in Szombathely, Hungary in 2023/24 business year. The first four chapters establish the wider context of the study. After the introductory chapter, **Chapter 2** introduces the concept of Carbon Footprint in general, and the various approaches to its evaluation. **Chapter 3** summarizes the most important recent studies concerning the carbon footprint of panel product manufacturing. The chapter concludes that wood-based panel manufacturing typically has a negative carbon footprint as measured by most methodologies, which is usually enough even to offset the environmental impact throughout the product life cycle. **Chapter 4** compares the environmental impact of wood-based panels to other materials (mostly those used in the construction industry.) In this comparison, wood and wood-based products tend to fare much better than alternative building materials, partly because of the less energy intensive production processes, but mostly because of the carbon sink effect, leading to negative carbon footprint values.

The carbon footprint calculations of the various panel production processes at FALCO Zrt., based on detailed and rigorous calculations with a Cradle-to-Gate approach, are detailed in Chapters 5 through 10, as follows:

- Chapter 5-9 analyses the environmental impact of the raw material used in the production of FALCO Zrt.'s various products. According to generally accepted methodology, wood's carbon sequestration potential is counted as negative carbon footprint, but it is corrected to take energy use during the production, extraction and transportation of wood into account. The impact of adhesives, binders and paper, as well as simple additives is calculated based on international databases. Complex chemicals of unknown composition are present in miniscule quantities, and their CO_2eq value is estimated. Calculations show that the combined carbon footprint of all raw materials is mostly negative, due to the carbon sequestration of wood, except for CB particleboard, where it is slightly positive, due to the energy-intensive production processes of cement.
- Chapter 10 includes detailed calculations concerning the energy consumption related to the manufacturing and logistics processes at FALCO Zrt. The carbon footprint of electric energy consumption, heat generation from various sources, and that related to transportation are analysed separately. Since much of the heat generation involves wood combustion, different calculation scenarios are introduced, where wood is treated as completely carbon neutral, has net carbon neutrality (taking into account energy required for the extraction of the material and the efficiency of the furnaces), or not carbon neutral at all, respectively. Net carbon neutrality was considered the most realistic of the three approaches, and therefore was chosen for the final analysis.
- Chapter 11 integrates the data from chapters 5 – 10, to derive the unit carbon footprint values for the various products, as well as the total net annual carbon footprint value of FALCO. The single most important factor in the carbon footprint of organic bonded products is the negative footprint of the incorporated wood, which counterbalances the effect of other materials, as well as that of electric, heating, while the effect of internal and external transportation is almost negligible (see diagrams below). The calculations show that the unit carbon footprint values of raw particleboard, MF and MG particleboard production are still strongly negative, even after taking the energy costs into consideration. Cement-bonded particleboard production results in a positive

carbon footprint, due to the energy-intensive production processes of the inorganic binder.

Table A *Total net annual and unit carbon footprint of FALCO's production (2023/24)*

	Unit emissions (tCO_2eq / m^3)			Production m^3/a	Net annual emissions (tCO_2eq / a)		
	Raw material production[a]	On-site energy consumption[b]	Total		Raw material production[a]	On-site energy consumption[b]	Total
Raw PB	-1.149	0.057	**-1.092**	150 520	-172 920	8 579	**-164 341**
CB PB	0.155	0.109	**0.264**	28 282	4 711	3 082	**7 793**
MF	-1.115	0.016	**-1.099**	221 962	-247 320	3 551	**-243 769**
MG	-1.114	0.127	**-0.987**	14 637	-16 305	1 858	**-14 447**
Production, total					-432 191	17 070	-415 120

[a]Based on **Table 18**; [b]Based on **Figure 22**, Scenario II.

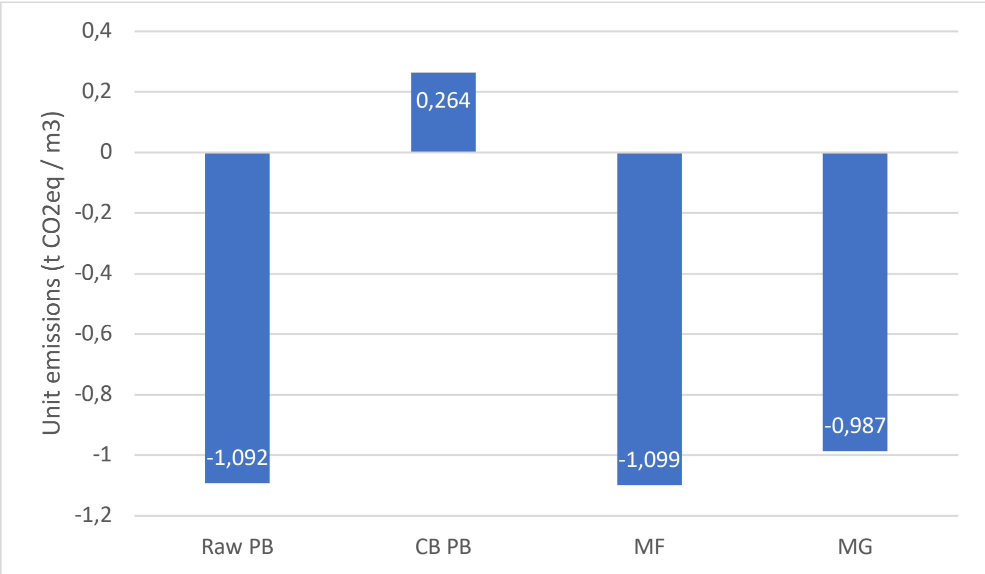

Figure A *Total net Unit carbon footprint of FALCO Zrt.'s products in 2023/24*

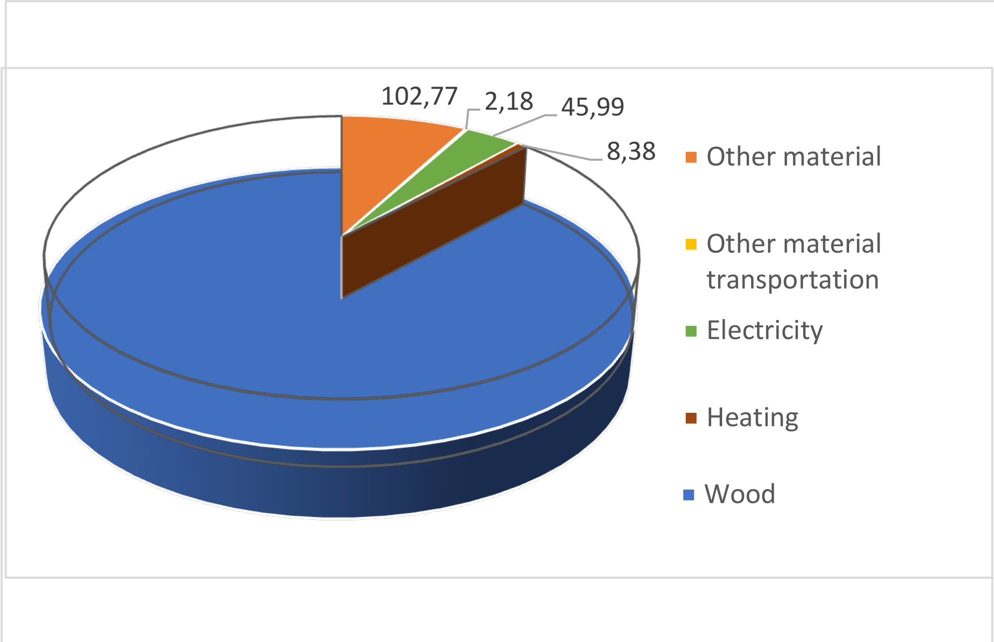

Figure B *The different components of the net emission calculations of raw particleboard (kgCO$_2$eq / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the top chart corresponds to the negative carbon footprint of raw PB.*

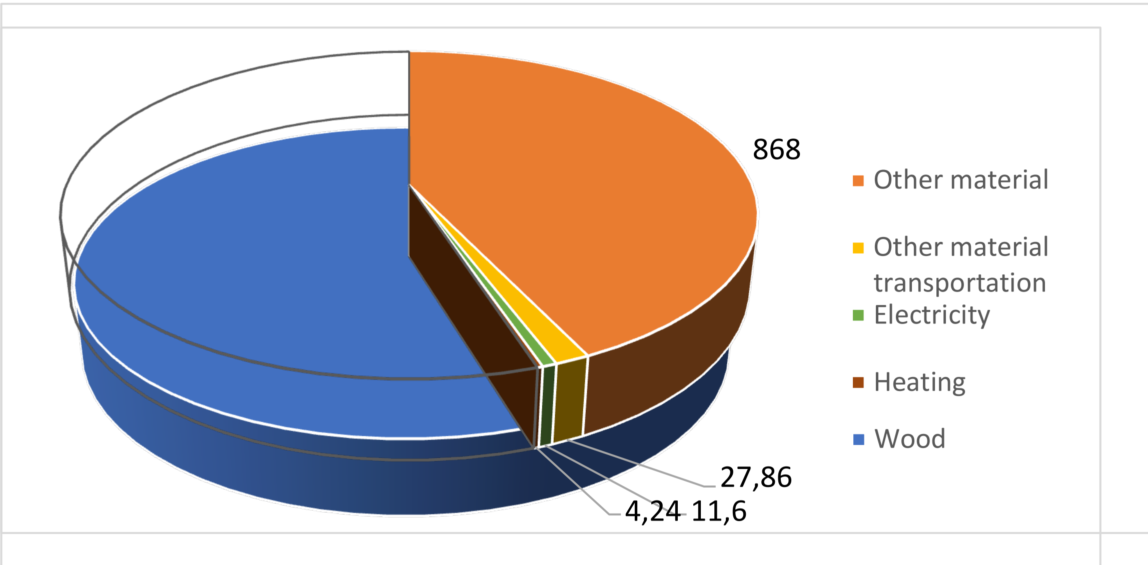

Figure C *The different components of the net emission calculations of melamine faced particleboard (kgCO$_2$eq/m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the top chart corresponds to the negative carbon footprint of MF PB.*

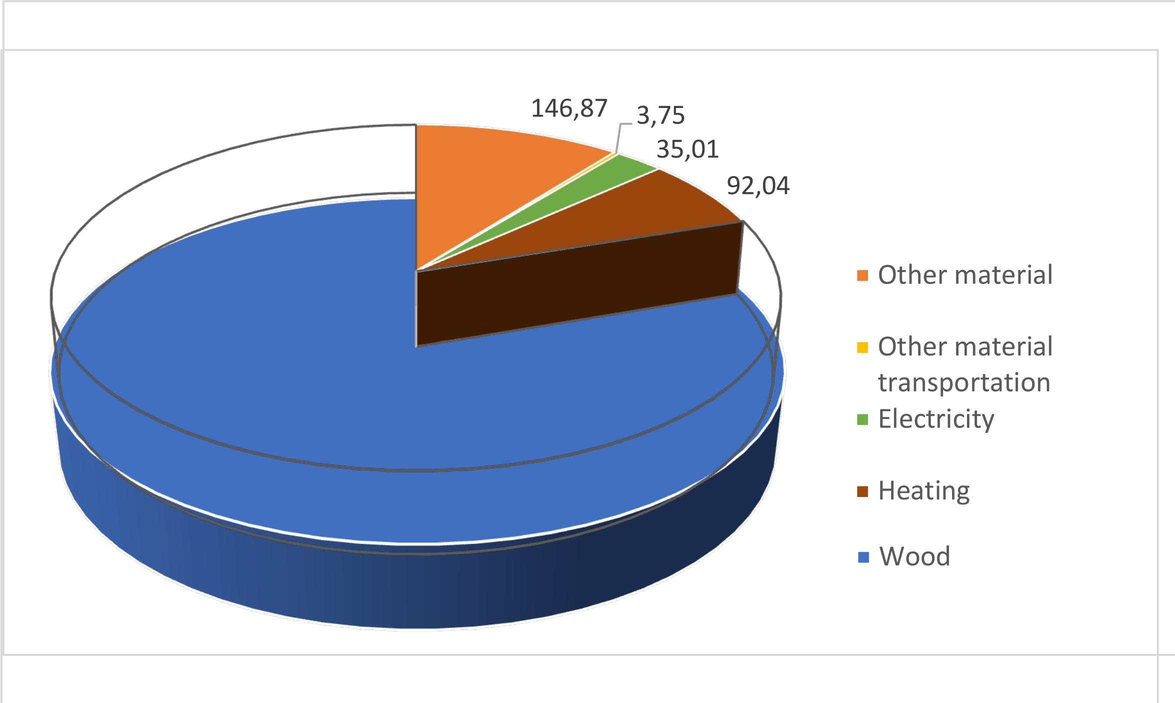

***Figure D** The different components of the net emission calculations of mirror gloss particleboard ($kgCO_2eq$ / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the top chart corresponds to the negative carbon footprint of MG PB.*

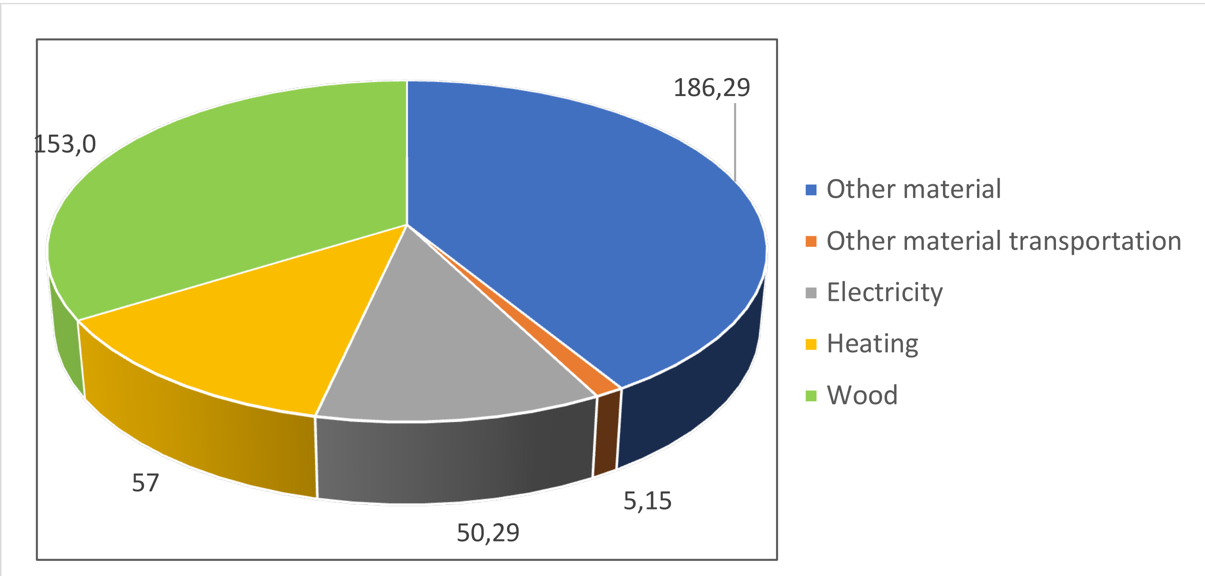

***Figure E** The different components of the net emission calculations of cement bonded particleboard ($kgCO_2eq$ / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the bottom chart corresponds to the carbon footprint of CB PB.*

Compared to other branches of the industry, FALCO Zrt.'s production has a much lower carbon footprint (even in the case of CBPB), mostly because of the carbon sink effect that makes the carbon footprint of raw and overlaid panels negative, and that of cement-bonded panels only slightly positive.

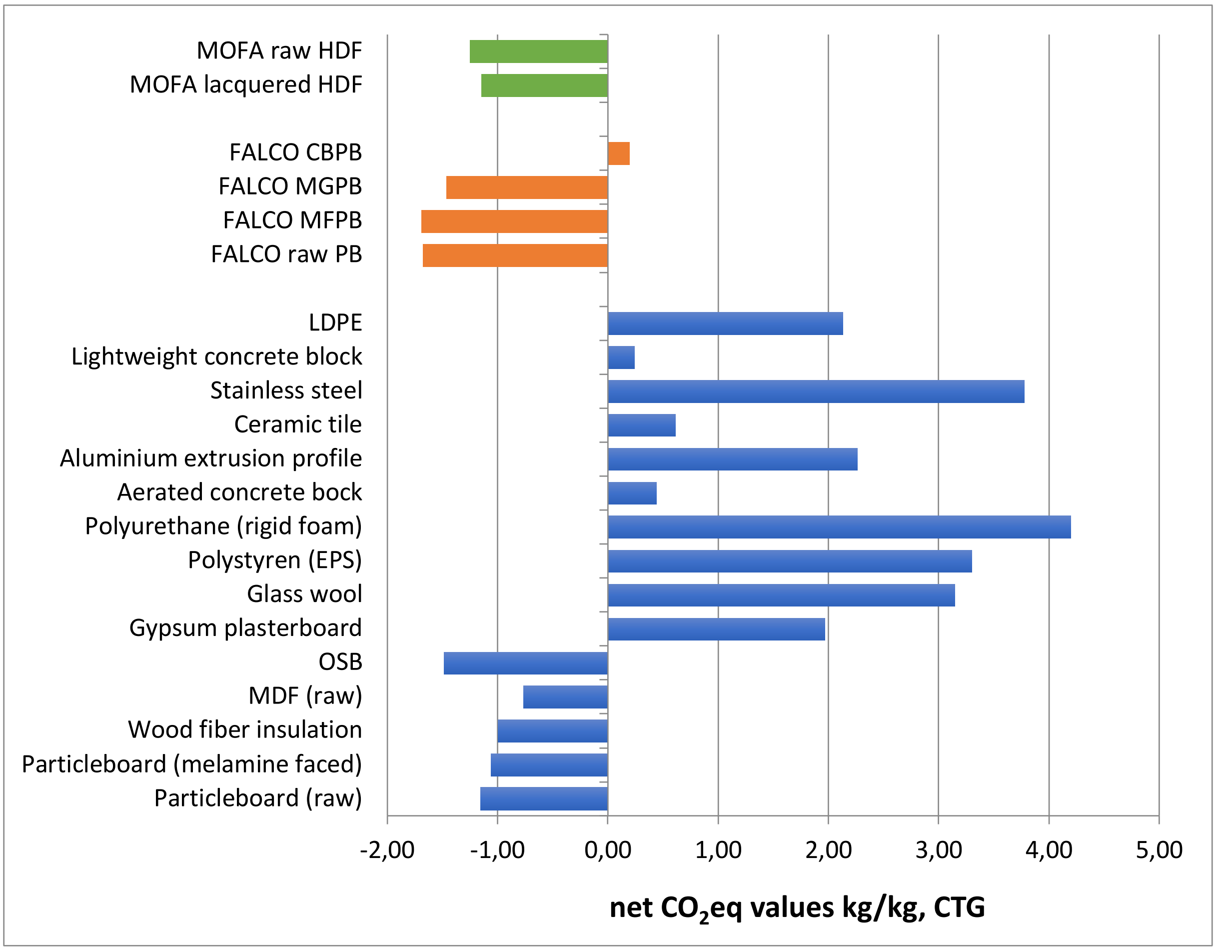

Figure F *FALCO's net unit carbon footprint values compared to other industrial branches (Cradle to Gate)*

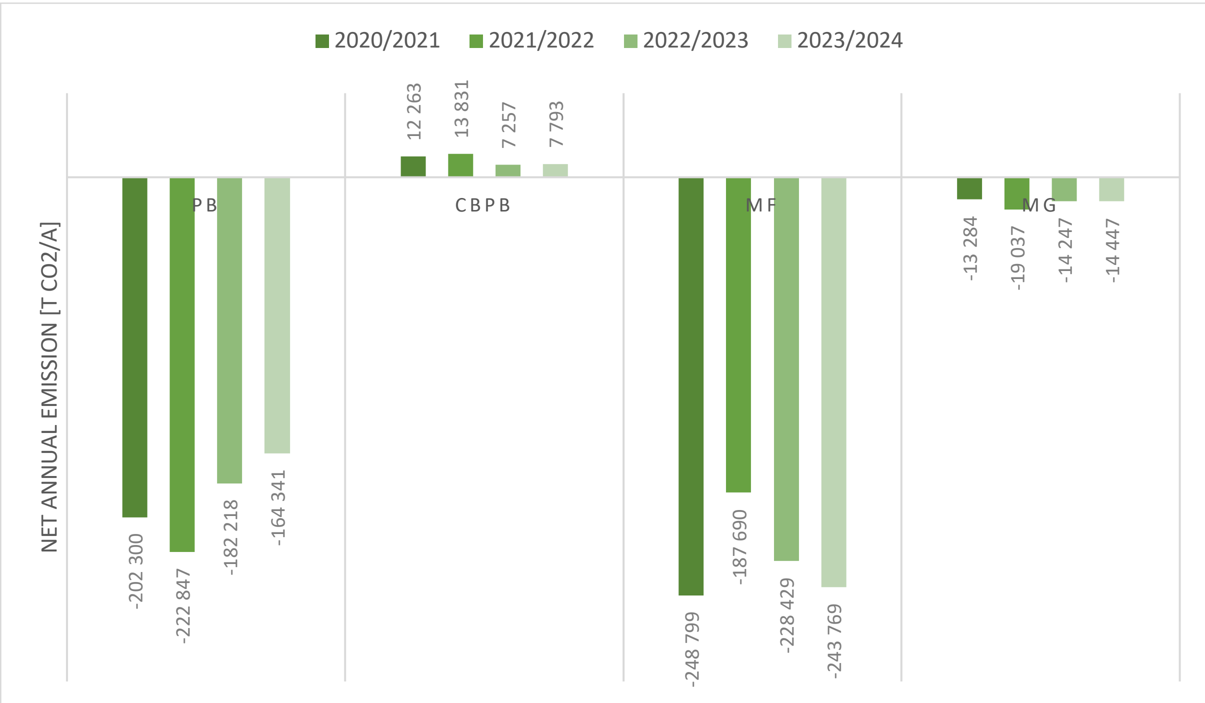

Figure G *Net annual emissions from 2020/21 to 2023/24*

1. Introduction

Carbon footprint refers to the amount of greenhouse gases (GHGs) produced due to human activities, measured in units of carbon dioxide. Carbon, as an element, is the basis of all living organisms that comprises all biopolymers in every single living organism. The term "carbon footprint" is generally taken to mean the impact of a product or process on the environment, expressed as CO_2 emission equivalent (tons of CO_2eq.). Carbon footprint is a measure of the exclusive, total amount of CO_2 emissions that is directly and indirectly released by an activity or is accumulated over the life stages of a product.

Considering the ever-stricter environmental regulations, it is becoming important to evaluate the carbon footprint of various products, technologies or branches of industry. FALCO Zrt. is an innovative, environment sensitive company processing wood into wood-based panels like particleboard or cement-bonded particleboard. As a company that strives for sustainability, FALCO Zrt. intended to measure and compare the carbon footprint of their technologies/products to others.

In this report, FALCO Zrt.'s production was evaluated based on the cradle-to-gate method. The carbon footprint of the raw materials and the on-site energy consumption in the production of various particleboard products was calculated, respectively, to a high level of accuracy. All of the input data was provided by FALCO Zrt.

Based on scientific reports and publications, the carbon footprint of other wood-based panel boards is introduced in chapter 3. Since FALCO Zrt.'s products are partially used in the construction or building industry, a comparison of panel-boards to alternative building materials are presented in chapter 4. This data is also derived from scientific reports and publications.

Both the reviewed reports and the evaluated data of FALCO shows wood processing has several environmental advantages compared to other building materials.

According to Wilson's (2010) summary:

- Wood-based composite panels are more environmentally friendly than alternate materials in most categories (compared e.g. to steel, cement, plastic and glass).
    - Panel board production consumes significantly less fossil fuel, feedstock, water and other materials.
    - Panel board production uses more renewable wood fuel, which is considered neutral to global-warming or climate-change, to displace fossil fuels.
- WBC panels have negative Global Warming Potential (GWP) values due to:
    - Sufficient carbon storage to offset additional CO_2 emissions from product use and disposal.
    - Offsetting some CO_2 in the atmosphere.

1.1. Terminology

When preparing this report, the authors made an effort to use a consistent terminology. Some of the most important terms used in the report are defined below:

Carbon dioxide equivalent or CO_2 equivalent (CO_2eq): a metric measure used to compare the emissions of various greenhouse gases on the basis of their global-warming potential (GWP) by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

Carbon footprint: the amount of GHGs produced due to human activities, measured in units of carbon dioxide equivalent.

Cascade material use: a process whereby materials (e.g. wood) is used and reused or recycled through several cycles, before being converted to energy.

Cradle-to-Gate Analysis: a carbon footprint analysis technique that considers all emissions related to the production of a material or product (including the generation and extraction of the raw materials), but not the emissions related to its use, maintenance and recycling/disposal (see Figure 4 for more detail).

Emission factor: the average emission rate of a greenhouse gas relative to the activity data of a source stream assuming complete oxidation for combustion and complete conversion for all other chemical reactions.

Fossil fuels: fuel formed by natural processes containing energy originating in ancient photosynthesis, typically having an age of millions of years.

Net calorific value (NCV): the specific amount of energy released as heat when a fuel or material undergoes complete combustion with oxygen under standard conditions less the heat of vaporisation of any water formed;

Oxidation factor: the ratio of carbon oxidised to CO_2 as a consequence of combustion to the total carbon contained in the fuel, expressed as a fraction, considering CO emitted to the atmosphere as the molar equivalent amount of CO_2;

Primary energy: the form of energy found in nature that has not been subjected to any human engineered conversion process. Proper accounting for the environmental footprint determination is based on primary energy.

Harvested wood product: Harvested Wood Products (HWPs) are wood-based materials harvested from forests, which are used for products such as furniture, plywood, paper and paper-like products, or for energy.

Intergovernmental Panel on Climate Change: The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. → https://www.ipcc.ch/

Green House Gas(es): A greenhouse gas is a gas that absorbs and emits radiant energy within the thermal infrared range and causes the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone.

1.2. Abbreviations

Abbreviations used in the report are defined, as follows:

BOD_5	Biological Oxygen Demand of breaking down organic matter in water
COD_k	Chemical Oxygen Demand of breaking down organic matter in water
CTG	Cradle-to-Gate
GHGs	Green House Gases
HHV	Higher Heating Value
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MC	Moisture Content
MDI	Methylenediphenyl Diisocyanate
PAS	Publicly Available Specification
UF	Urea Formaldehyde
HWP	Harvested wood product
IPCC	Intergovernmental Panel on Climate Change
GHG	Green House Gas(es)
$GtCO_2$	gigatonnes of carbon dioxide
CO_2eq	carbon dioxide equivalent
UF	Urea-formaldehyde resin
mUF	Melamine-urea-formaldehyde resin
SRF	Solid Recovered Fuel material

2. Carbon Footprint in General

Carbon footprint refers to the amount of greenhouse gases (GHGs) produced due to human activities, measured in units of carbon dioxide. Carbon, as an element, is the basis of all living organisms that comprises all biopolymers in every single living organism. On average, living organisms are comprised of ~40–50% of carbon on a dry weight basis. In general, the term "footprint" describes the area or ground impression of a building or other entity, and is characterized as global hectares, not local or actual hectares. In the case of carbon footprint, however, the term is used more figuratively, and is generally taken to mean the impact of a product or process on the environment, expressed as CO_2 emission equivalent (tons of CO_2-eq.)[1] Carbon footprint is a measure of the exclusive, total amount of CO_2 emissions that is directly and indirectly released by an activity or is accumulated over the life stages of a product.[2] Carbon footprint is commonly used as a general term, but other names, like climate footprint, GHG footprint, embodied carbon or carbon flow, are often used interchangeably.[3] [4]

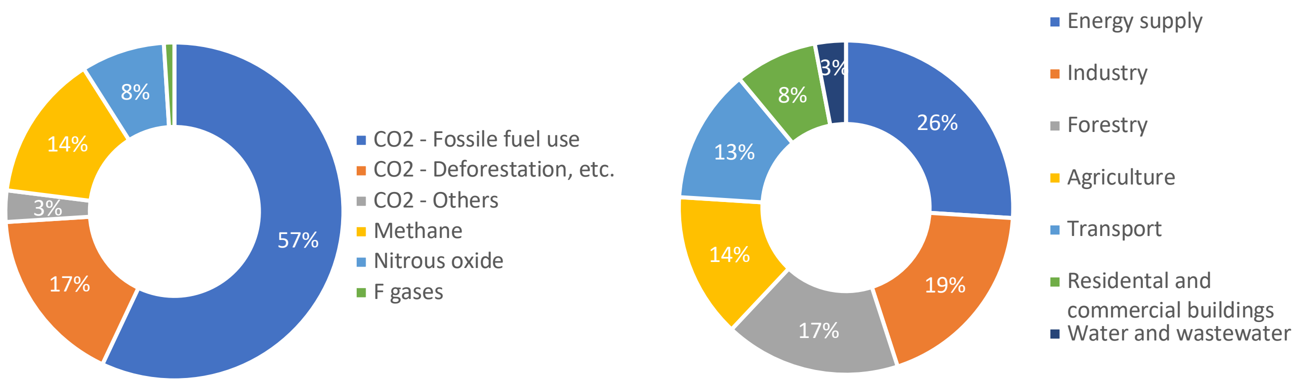

Figure 1 – (a) Global anthropogenic GHG emissions. (b) GHG emissions by sector.[6]

According to another publication, which used a somewhat different methodology, and classification, the building sector is responsible for 40% of the total energy use and for 30% of the total GHG emission worldwide[5]. Wood-based products and materials can play an important role in transitioning to a low-carbon and a resource-efficient society. They can act as energy source as well as physical and structural materials in various applications, e.g. in buildings (including wood-based construction materials, flooring, windows, furniture etc.). Several recent studies documented the potential of using sustainably produced wood-based materials to reduce energy use and carbon footprint of buildings as opposed to other materials like concrete, plastics or aluminium, etc.[6,7,8] Less energy input is needed to

1 S.S. Muthu 2015. The Carbon Footprint Handbook. 1st ed. CRC Press Taylor & Francis Group. ISBN 9781482262223
2 Wiedmann T, Minx J. 2007. A definition of carbon footprint. ISAUK Research Report 07-01, Durham.
3 Courchene TJ, Allan JR. 2008. Climate change: The case of carbon tariff/tax. *Policy Options* 3:59–64.
4 Edgar GH, Peters GP. 2009. Carbon footprint of nations: A global, trade linked analysis. *Environ Sci Technol* 43:6414 – 6420
5 UNEP (United Nations Environment Programme). 2007. Buildings and climate change status, challenges and opportunities. www.unep.org (September 20, 2011)
6 IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: Mitigation. Contribution of working Group III to the fourth assessment report. Cambridge, UK: Cambridge University Press.
7 Upton B, Miner R, Spinney M, Heath LS. 2008. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. *Biomass and Bioenergy* 32(1):1–10.
8 Dodoo A, Gustavsson L. 2013. Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply. *Applied Energy* 112:834–842.

manufacture wood products compared to alternative materials[9] (Figure 2). Wood-based building materials mainly use biomass residues (by-products) to produce the energy for industrial processes (like kiln drying) so they have lower carbon and primary energy balances compared to other materials[10].

According to life cycle assessment studies, wood buildings needs less energy from resource extraction through production, distribution, use and end of life disposal. Its GHG emissions is much less than of fossil fuel-intensive materials like concrete or steel. As example, building a wall with kiln-dried wood studs, oriented board (OSB) sheathings, and vinyl sidings instead of concrete can results 73.24 (kg/m^2) of avoided CO_2 emissions of wall surface. In addition, using OSB sub-floor joints rather than steel joints can decrease the CO_2 emission by 107.41 (kg/m^2)[11].

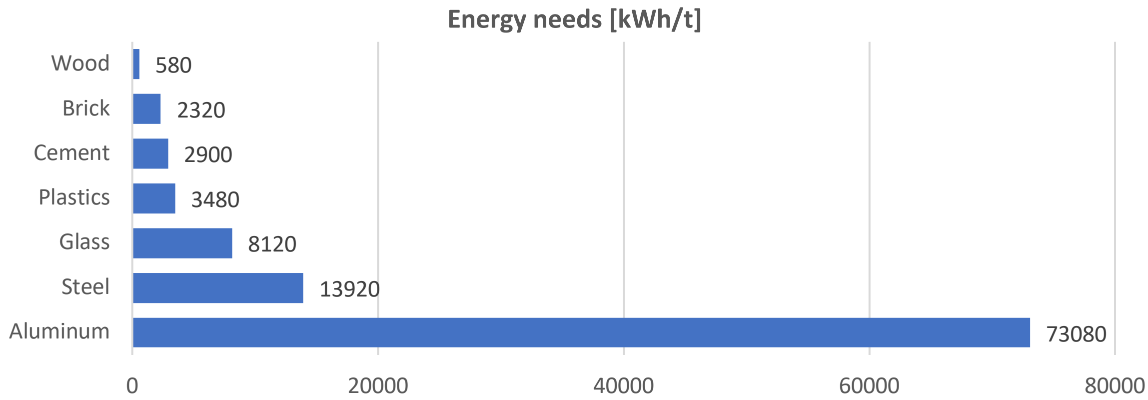

Figure 2 – The amount of energy required to produce a unit volume of building materials.12

Considerable quantities of biomass residues are produced from the total wood product chain and can be used to replace fossil fuels (Figure 3).

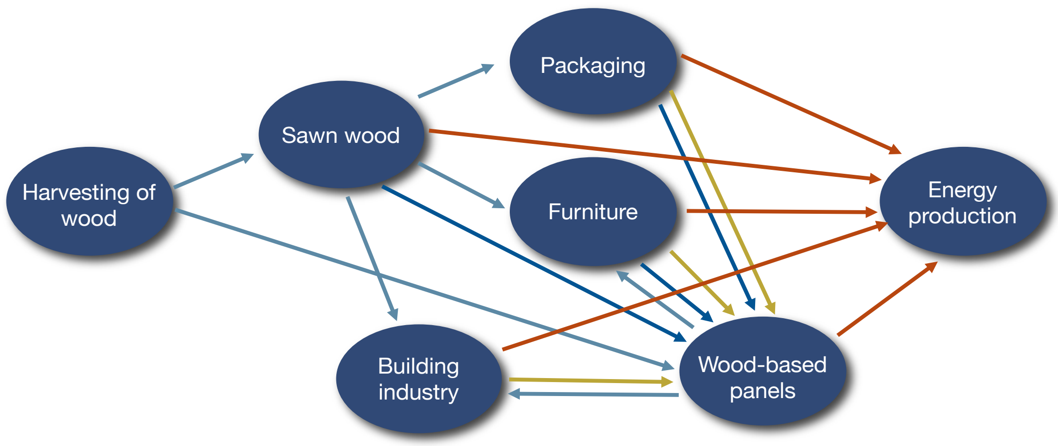

Figure 3 – Cascade use of wood (*legend: lt. blue: primary use, dk. blue: use as by-product (secondary use), yellow: recycling, red: energetic use*)[13]

9 Sathre R, O'Connor J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy* 13(2):104–114.
10 Ambrose Dodoo, Leif Gustavsson, and Roger Sathre: Modeling the Carbon Footprint of Wood-Based Products and Buildings. in: Subramanian Senthilkannan Muthu (2016): The Carbon Footprint Handbook. CRC Press Taylor & Francis Group.
11 American wood council. Wood and carbon Footprint.www.awc.org
12 *Birler: The Opportunity of Forest Plantation Investment and its Expected Impact to National Economy in Turkey.* http://www.fao.org/forestry/6290-0c1d5ed03982952a990db8117f2b0e9a7.pdf
13 Alpár T 2011. Újrahasznosítás, hulladékmentesség, a faanyag csodálsatos adottsága (Recyclable and Waste-Free, Some Wonderful Properties of Wood. In: Molnár, S (ed.) Örök társunk a fa (Wood, Our Eternal Companion). Sopron, Hungary: University of West Hungary (NYME), (2011) pp. 31-34.

Wood is a renewable material resource. Its applications in different aspects of human activities is the best solution to reduce the environmental impact associated with humankind activities[14] (Figure 4).

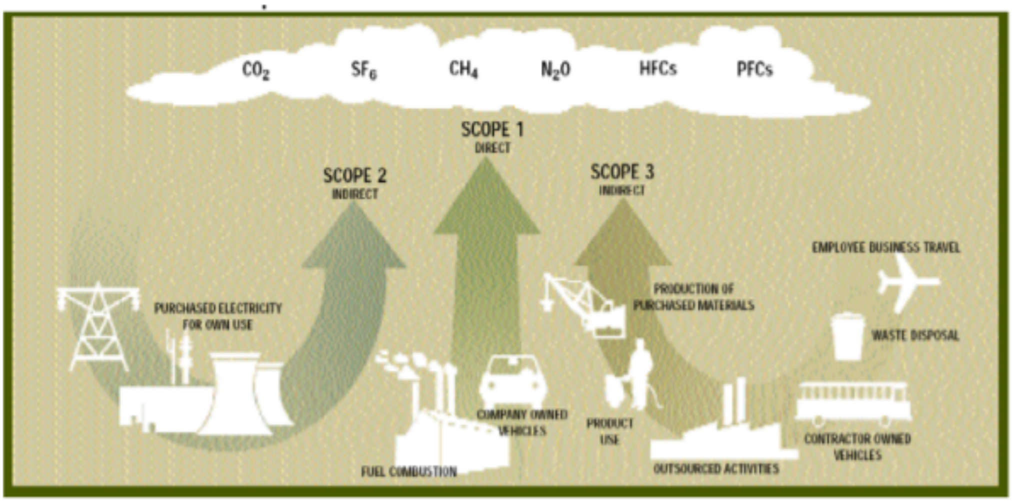

Figure 4 – Overview of the interrelationships of the different scoops the activities that generate direct and indirect emissions Source: World Resource Institute & World Business Council for Sustainable Development (2008)[15].

According to LCI data reported by (Taskhiri at al. 2019) wood waste have less environmental harm than fresh wood. (Table 1) summarised some global warming potential data for the procurement.

Table 1- global warming potential (GWP) data for the procurement[16].

Procurement	GWP
Industrial softwood	9.03 kg CO_2eq./m^3
Industrial hardwood	6.79 kg CO_2eq./m^3
Industrial residue softwood	3.18 kg CO_2eq./m^3
Industrial residue hardwood	2.04 kg CO_2eq./m^3
Waste wood class A-I	2.10 kg CO_2eq./t
Waste wood class A-II	4.90 kg CO_2eq./t
Waste paper	1 10 kg CO_2eq./t

Another research focused on evolution of carbon footprint at industrial park level, because energy consumption and dependence on fossil fuels made the industrial parks the main areas of GHG emissions. A sustainable industry growth can be achieved by properly grouping different types of industrial activities and costs of infrastructure and utilities can be reduced by concentrating activities in planned areas. Moreover, complementary industries and services can entail diversified effects on the surrounding region and finally stimulate regional development. Many carbon footprint calculators and international standard appeared in many organizations such as (WRI[17] and WBCSD[18], 2004, IPCC, 2006). Carbon footprint analysis

14 Andreja Kutnar and Callum Hill. Assessment of Carbon Foot printing in the Wood Industry Industrial Sectors, Volume 2, Eco Production, DOI: 10.1007/978-981-4585-75-0_6
15 DISCUSSION PAPER 1 VG08107: Vegetable Industry Carbon Footprint Scoping Study - Discussion Papers and Workshop 26 SEPTEMBER 2008 what is a Carbon Footprint? An overview of definitions and methodologies Andrew John East Growcom.
16 Mohammad Sadegh Taskhiri, Harish Jeswani, Jutta Geldermann, Adisa Azapagic. 2019. Optimising cascaded utilisation of wood resources considering economic and environmental aspects. Computers & Chemical Engineering. Volume 124, 302-316
17 World Resource Institute
18 World Business Council on Sustainable Development

could be divided into three categories: IPCC method, process analysis-based life cycle analysis (LCA) method, and input–output analysis (IOA) method. Each one of them have advantages and disadvantages.

- IPCC methods contain detailed calculations formulate and aspects for different emissions sources, However, it is only suitable for closed system and onsite emission, as a result it could not be used for indirect emissions.
- LCA method can give information that is more detailed to decision makers. Nevertheless, it is more time and labour consuming since it requires a huge detailed data.
- IOA method is more comprehensive top-down approach and has the ability to solve the major drawback of LCA method. Its advantage is decrease in time and work force once model in place. In other hand, its disadvantage is limitation in the suitability to assess micro systems such as products or processes[19].

Most of emissions are related with transport and fossil-based heat and electricity. Figure 5 represents values of for specific energy use for production of some selected building materials.

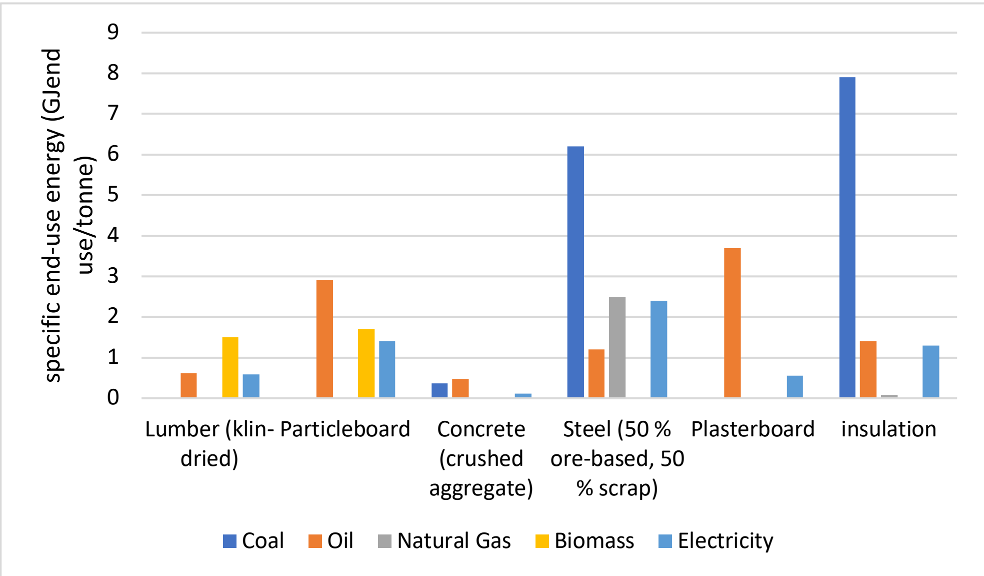

Figure 5 – Values of specific end-use energy (GJ and use/tonne) for production of selected building materials.[20]

19 Huijuan Dong Yong Geng Fengming Xi Tsuyoshi Fujita. 2013. Carbon footprint evaluation at industrial park level: A hybrid life cycle assessment approach. Energy Policy Volume 57.
20 Roger Sathre. 2007.Life cycle Energy and Carbon Implications of wood-based Products and Construction. mid sweden university doctoral thesis 34.

3. The carbon footprint of the panel board industry

In the following, we introduce some relevant scientific reports on the carbon footprint of the panel board industry. It is necessary to determine the system boundaries of LCI systems regarding panel board production (see Figure 6). Cradle-To-Gate boundary is typically used in the cited publications.

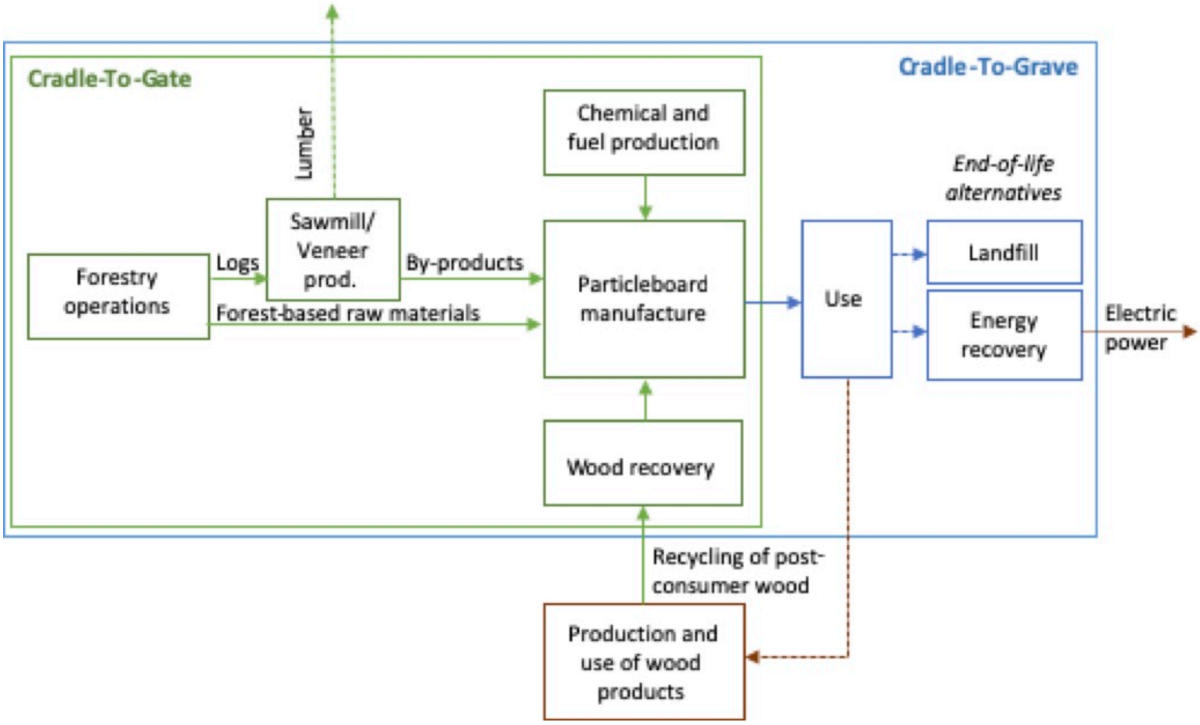

Figure 6 – System boundaries of panel board production

To deal with resources, carbon, energy, and emissions during particleboard production, the life cycle inventory (LCI) can provide solutions. Wilson (2010) studied the life-cycle of particleboard and its cradle-to-product gate LCI system boundary.[21] He collected the data of particleboard manufacturing by direct survey questionnaire, documenting all inputs of materials, fuels, and electricity and all outputs of products, co-products, and emissions to air, water, and land. Mass and energy balances were created, and the inputs and outputs were given as follows: wood on an oven-dry basis, chemicals like resin, catalysts, wax and formaldehyde scavenger as 100% solids. The end product was calculated in cubic meters. Energy balance was based on drying wood from an average moisture content (MC) of 25.7% to a target MC of 3-5%. The energy use per one kilogram of water removed was 7.81 MJ based on the fuel's higher heating value (HHV). The investigated mill produced 347,690 m^3 of particleboard annually, with an average density of 746 kg/m^3.

Wilson's survey resulted for carbon flux, storage, and footprint as follows.

Carbon storage:

- The wood carbon content of 1.0 m^3 of particleboard is 352 kg.
- The difference between the inputs and outputs is ~5% with more carbon flow out than in.

21 J.B. Wilson 2010. LIFE-CYCLE INVENTORY OF PARTICLEBOARD IN TERMS OF RESOURCES, EMISSIONS, ENERGY AND CARBON. Wood and Fiber Science, 42(CORRIM Special Issue), 2010, pp. 90–106

- The CO_2-equivalents of carbon storage in 1.0 m^3 of particleboard is -1290 kg based on 52.4% carbon component of wood
- Carbon stores of adhesive, hardener, wax and formaldehyde scavenger are not counted in the carbon flux values because they are derived from fossil feedstock of mineral oil or natural gas.
- The carbon stored remains in the particleboard for the life of its service for 10 – 80 years.

Carbon emission:

- CO_2 emission as a result of the combustion of wood is not included in the footprint because it is considered CO_2 neutral.
- The cradle-to-gate carbon footprint to produce particleboard is 392 kg CO_2 equivalent, and the on-site footprint is only 57.3 kg CO_2 eq.

The carbon storage of 1290 kg CO_2eq. for particleboard can be used to offset the carbon footprint of 392 kg CO_2 eq. to determine the net carbon flux of -898 kg CO_2eq. cradle-to-product gate (Figure 7).

Wilson concluded that:

> The embodied energy to produce 1.0 m^3 of particleboard comes from various fuels and electric energy used on-site, and from the fuels used cradle-to-gate including on-site as well as those fuels to generate and deliver wood, chemicals, fuels, and electricity to the mill.
> To produce 1.0 m^3 of particleboard, the CO_2 removed from the atmosphere due to carbon storage is 1290 kg-CO_2 eq., which can be used to offset the CO_2 eq. of the LCI output GHG emissions of 392 kg CO_2eq. – i.e. its carbon footprint – because of the combustion of fossil fuel. This results in a net carbon flux of -898 kg CO_2eq. This reduces its impact on global warming and climate change.

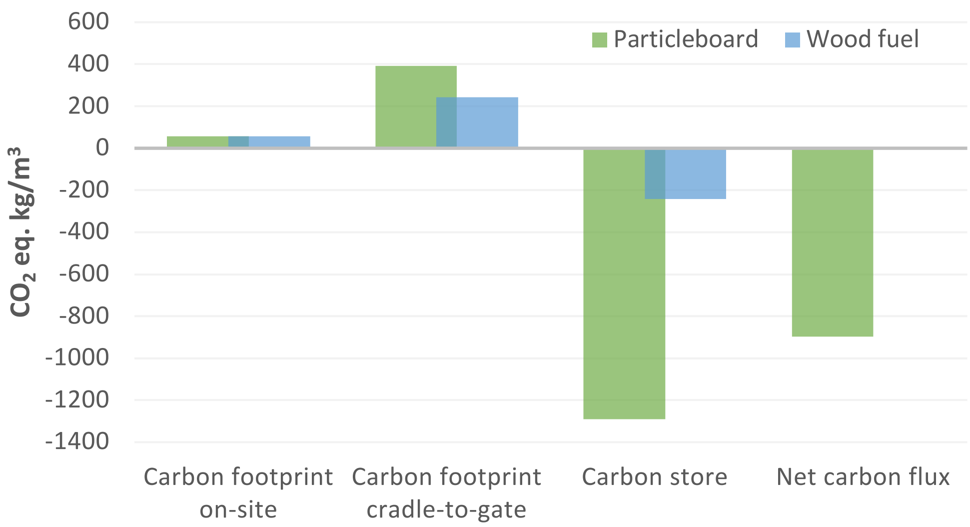

Figure 7 – The carbon footprint of particleboard. Wood fuel is considered carbon-neutral.[21]

Garcia and Freire (2013) made a comparison between various standardized methods analysing particleboard's carbon footprint. They compared ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. From our point of view, Cradle-to-Gate assessment results are relevant (Fig. 8)[22]. Results for ISO/TS 14067 and GHG Protocol are for mass allocation in the sawmill process. Others include energy inputs, transport of inputs and production of other chemicals.

22 R. Garcia, F. Freire 2014. Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. *Journal of Cleaner Production* (2014), doi: 10.1016/j.jclepro.2013.11.073.

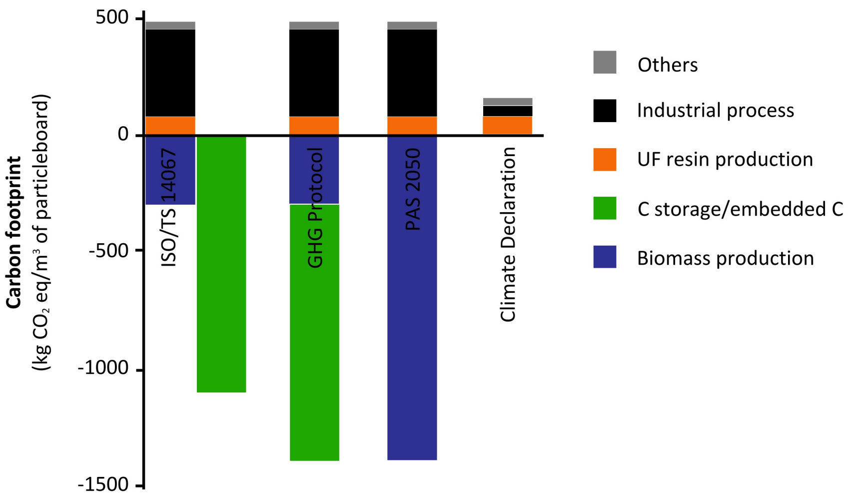

Figure 8 – Carbon footprint of particleboard (cradle-to-gate assessment)[22]

The report concluded, that there is a key difference in the carbon footprint between the methods that some include (GHG[23] Protocol, PAS[24] 2050) and others exclude (ISO/TS 14067, Climate Declaration) biogenic carbon storage. „The GHG Protocol (mass allocation, ma) and PAS 2050 calculated negative carbon footprints (-913 and -939 kg CO_2eq/m^3, respectively) while ISO/TS 14067[25] (ma) and the Climate Declaration calculated positive carbon footprints (188 and 168 kg CO_2eq/m^3). Carbon stored in particleboard (equivalent to 1098 kg CO_2/m^3) shall be reported separately in ISO/TS 14067 carbon footprint report and is shown in a separate column in Fig. 8."[26] In case of GHG Protocol counting the amount of carbon stored in the product is especially important in cradle-to-gate assessments in order to avoid misleading comparisons with other products, since the embodied carbon at gate may be released later during use or at the end-of-life phase.

„For the ISO/TS 14067, GHG Protocol and PAS 2050 carbon footprint, the biomass production stage had a high contribution to GHG removals, due to the uptake of CO_2 from the atmosphere during tree growth." In case of Climate Declaration, emissions and removals of biogenic CO_2 are not included. „For the carbon footprint calculated using the Climate Declaration, the UF (urea formaldehyde) resin production had the largest contribution (40% of GHG emissions). The industrial process stage contributed 36% to the total. The main source of GHG emissions in the UF resin production was the production of urea (67%), due to ammonia production (47%). In the industrial process, the major contributor to the GHG emissions was the combustion of natural gas for wood drying. The other LC stages individually contributed to less than 10% of the total carbon footprint."[14]
Hussain et al. (2017), calculated carbon footprint in particle board manufacturing by using a cradle to gate life cycle assessment approach. The system boundary included raw material acquisition, particleboard production, finished product distribution and transportation. Based on the total emissions of 1 m^3 of particleboard, 52 % of emissions represents the GHG emissions from off-site industrial operations of the particleboard industry, while the other 48 % was caused the onsite industrial operations creates direct GHG emission. The operations included energy consumption in stationary sources, the company vehicle fleet and the

23 GHG = Green House Gas
24 PAS = Publicly Available Specification
25 standard IDO/TS 14067 - Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication
26 Andreja Kutnar and Callum Hill. Assessment of Carbon Foot printing in the Wood Industry Industrial Sectors, Volume 2, Eco Production, DOI: 10.1007/978-981-4585-75-0_6

distribution and marketing of the finished product. The use of natural gas combustion in the stationary and mobile sources, raw materials, transport and urea-formaldehyde resin production chain accounted for the highest emissions from particleboard production[27].
Another study reported the LCA study of particleboard produced from sugarcane bagasse residues. The cradle to gate assessment was used as method for 1 m^3 of particle board. In general, three main sub-systems were introduced (bagasse generation, bagasse distribution and particleboard sugarcane bagasse production). Two scenarios were analysed to evaluate the influence of the allocation criteria and the sugarcane bagasse consumption. Results indicated that sugarcane bagasse particleboard have the potentials to replace the conventional particleboard due to its better sustainability[28].
In sawn wood and wood chip production, the main contributor of the overall emissions is the forest operations and timber transportation. GHG emission in wood processing including sawn wood, wood chips, wood pellet and OSB production mainly occurred because of chains and electricity usage from the national grid. The integration of CHP plants with sawmills and pellet plants found to be the best solution to reduce the GHG emission in sawmilling and wood pellet manufacture. Synthetic resin utilisation in wood-based panel board production has a direct impact on GHG emissions. For a large proportion of emissions in both MDF and OSB manufacture, wood energy products considered advantageous in compare with other sources of biomass and with fossil fuel (Table 2).

Table 2- Global warming potential of products 2012 versus 2020[29]

	Product	2012	2020
		GWP (kg CO_2eq)	
Scenario 1	Sawn wood (m^3)	40.2	36.3
	Chip (odt)	86.7	78.5
Scenario 2	Powered by CHP	-	-
Scenario 3	Sawn wood (m^3)	31.7	29.4
	Chip (odt)	68.6	63.6
	Wood pellet (odt)	327.8	266.1
Scenario 4	Powered by CHP	-	-
Scenario 5	Wood pellet (odt)	1102.5	881.5
Scenario 6	MDF (m^3)	896.7	856.8
Scenario 7	OSB (m^3)	235.6	217.4

Padilla-Rivera et al. (2017) conducted LCA, which is divided into four low carbon strategies that include: low carbon materials, material minimization, reuse, and recycle materials and adoption of local sources. The use of biofuels were evaluated, it was found that the reuse of wood waste in the particleboard production has huge advantage on environment benefit when considering temporary carbon storage[30].
The amount of GHG emissions created in the production stage of selected products were compared in (Table 3).

27 Majid Hussain, Riffat Naseem Malik , Adam Taylor. 2017.Carbon footprint as an environmental sustainability indicator for the particleboard produced in Pakistan. Environmental Research 155385–393.
28 Diogo Aparecido Lopes Silva & Francisco Antonio Rocco Lahr & Ana Laura Raymundo Pavan & Yovana M. B. Saavedra & Natalia Crespo Mendes & Sabrina Rodrigues Sousa & Roberta Sanches & Aldo Roberto Ometto. 2014. Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particle board manufacturing. Int J Life Cycle Assess 19:1767–1778 DOI 10.1007/s11367-014-0776-4
29 Fionnuala Murphy, Ger Devlin, Kevin McDonnell.2015. Greenhouse gas and energy based life cycle analysis of products from the Irish wood processing industry. Journal of Cleaner Production.
30 Alejandro Padilla-Rivera, Pierre Balnchet. 2017. Carbon footprint of pre-fabricated wood buildings. SIMPÓSIO BRASILEIRO DE DESIGN SUSTENTÁVEL + INTERNATIONAL SYMPOSIUM ON SUSTAINABLE DESIGN Belo Horizonte

Table 3- LCI results of selected wood-based products (kg CO_2eq; a-years); functional unit -1 m^3. [31]

Method	Glulam	SST	DT	OSB	PB	HDF	MDF	LDF
CML-IA	235.78	180.76	67.87	376.00	365.09	1163.15	761.90	87.80
EDIP	234.93	180.37	67.66	376.69	361.42	1152.98	757.06	87.42
EF	241.40	184.75	69.36	389.83	375.75	1198.10	781.96	89.69
EPD	235.78	180.76	67.87	376.00	365.09	1163.15	761.90	87.80
ILCD	-1341.70	-1199.10	-1186.27	-837.24	-642.98	-249.60	340.51	0.96
IMPACT 2002+	227.36	175.32	66.44	351.39	343.74	1100.59	727.72	84.72
ReCiPe	239.85	183.44	68.74	386.66	373.87	1190.92	778.06	89.23
BEES	233.43	179.28	67.35	373.96	358.54	1143.93	751.90	86.87
TRACI	234.93	180.37	67.66	376.69	361.42	1152.98	757.06	87.42
IPCC 100a	236.76	181.34	68.10	378.16	366.98	1170.04	766.41	88.14
Ipcc 20 a	260.65	196.08	73.37	427.02	427.32	1355.77	869.66	96.90
IPCC uptake	-1339.89	-1198.15	-1185.83	-835.82	-637.55	-232.62	349.73	1.66

Based on (Table 3). Some methods led to equal results of GHG emissions such as CML-IA and EPD or EDIP and TRACI. Only ILCD and IPCC methods included carbon dioxide uptake. Considering carbon dioxide in the air as a raw material stored in biological matter resulted negative CO_2 values indicating carbon removals.
By comparing the distribution of CO_2 emissions and removal according to IPCC uptake method it is clear that sequestrated carbon played a substantial role in overall assessment. In other hand, emissions from land transformation were negligible. See (Table 4).

Table 4- Assessment of selected wood/based products using IPCC including CO_2 uptake method (emissions to soil were assigned to fossil carbon); kg CO2eq / 1 m^3.[31]

Impact category	Carbon emissions and removals				
	Fossil	Biogenic	Uptake	LT	Total
Glulam	234.62	330.97	-1906.50	1.02	-1339.89
SST	179.33	335.14	-1713.57	0.95	-1198.15
DT	67.51	4.53	-1258.36	0.48	-1185.83
OSB	376.35	374.75	-1587.96	1.04	-835.82
PB	357.22	394.01	-1389.83	1.06	-637.55
HDF	1137.78	553.40	-1940.37	16.57	-232.62
MDF	762.89	544.11	-958.69	1.43	349.73
LDF	86.94	152.09	-237.94	0.57	1.66

In methods that did not consider carbon uptake, the fossil carbon emissions replicate CO_2 emissions. Reflecting emissions related with transport and fossil-based heat and electricity.
IPCC uptake and CML-IA were selected to determine the magnitude of production impact. See (Table 5). For IPCC uptake, glulam was found the best product followed by SST and DT. During manufacture of LDF and MDF fossil carbon prevailed that resulted positive signs indicated environmental burden. For CML-IA, DT had the lowest impact on the climate change while MDF and HDF ranked the worst. In both methods, only PB stayed at the same rank.

31 Rozália Vaňová. 2021. INFLUENCE OF CARBON ACCOUNTING ON ASSESSMENT OF WOOD-BASED PRODUCTS. ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 63(2): 143−152.

Table 5- Ranking of selected wood-based products according to different carbon accounting (products were sorted from the most beneficial to the most burdensome); kg CO2eq / 1 m^3.[31]

Rank		IPCC uptake		CML-IA
1	Glulam	-1339.89	DT	67.87
2	SST	-1198.15	LDF	87.80
3	DT	-1185.83	SST	180.76
4	OSB	-835.82	Glulam	235.78
5	PB	-637.55	PB	365.09
6	HDF	-232.62	OSB	376.00
7	LDF	1.66	MDF	761.90
8	MDF	349.73	HDF	1163,15

4. Environmental comparison of panel-boards to alternative materials

Wilson (2010) and Garcia and Freire (2013) [13,14] describes Cradle-To-Gate (CTG) analysis as the effect of all materials, processes and actions that have some kind of environmental impact for their production, use and disposal. LCI data can be used to compare various material options, e.g. for construction materials. Comparison can be made on a volume (m^3) or weight (kg) basis.

Wilson makes the following comparison:

- Wood-based composite panels are more environmentally friendly than alternate materials in most categories (compared e.g. to steel, cement, plastic and glass).
    - Panel board production consumes significantly less fossil fuel, feedstock, water and other materials.
    - Panel board production uses more renewable wood fuel, which is considered neutral to global-warming or climate-change, to displace fossil fuel.
- WBC panels have negative Global Warming Potential (GWP) values:
    - Sufficient carbon storage to offset additional CO_2 emissions from product use and disposal.
    - Offsets some additional CO_2 in the atmosphere.

Plastics also incorporate carbon, but that is not considered an offset against GHG emissions, since it comes from fossil resources, whose carbon cycle is millions of years long, unlike that of wood. Plastic is made from a non-renewable resource since it is based on fossil-fuel feedstock.

Wood-based panels have less acidification and smog contribution than any of alternative materials. Wood-based composites also have the lowest emissions to water (BOD[32], COD[33]).

In general, particleboard and MDF have the lowest environmental impact for the resource use and emission factors determined. They should be considered green materials that are friendlier to the environment.[13, 14]

In Table 6., several alternative materials are compared to wood-based panels in terms of their environmental impact.

- Of these materials, only wood panels are made mostly of renewable and sustainable raw materials.
- All but cement can be made from recycled material.
- Only wood panels and plastics can be used as fuel to further displace the use of fossil fuels. However, plastic is only a transformed form of fossil fuels.

As Wilson demonstrates, composite panels:

- generate almost no waste during their production:
    - 97% of all wood residues go to product and fuel,
    - 3% or less goes to landfill;
- are "better than climate neutral" based on GHG emissions:
    - Carbon pool properties,
    - Offset CO_2 emissions due to delivery, use, disposal, and even some atmospheric CO_2;
- make significant use of woody biomass for fuel;

32 BOD = Biological Oxygen Demand of breaking down of organic matter in water

33 COD = Chemical Oxygen Demand of breaking down of chemicals in water

- outperform other materials in terms of in-ground resource, fossil fuel, feedstock, water use, and GWP;
- in most cases perform better in terms of acidification, eutrophication and smog environmental impact indices; [34]
- fulfil the principle on substitution – use less environmentally affecting materials and processes if possible.

Table 6 – Environmental comparison of particleboard (PB) to alternative materials[34]

Cradle-to-Gate	Unit	PB Unit/m³	MDF Unit/m³	Steel Unit/m³	Cement Unit/m3	Plastic Unit/m3	Glass Unit/m³
In-Ground resources							
Fossil fuel & feedstock	MJ	8.153	12.052	229.357	16.245	80.634	30.679
Wood fuel	MJ	2.410	8.204	12	0	13	431
Materials	kg	4	22	13.824	5.070	39	3.202
Water	kg	906	2.205	NA	2.621	23.655	22.521
Emissions							
Air							
Carbon footprint	kg CO_2eq	392	621	18.055	4.273	2.413	660
Carbon sequestered	kg CO_2eq	1.360	1.343	52	0	1.391	0
Net carbon	kg CO_2eq	-968	-722	18.003	4.273	2.413	660
Acidification (TRACI)	H+moles eq	370	547	3.310	1.145	1.013	1.143
Eutrophication (TRACI)	kg N eq	0.16	0.24	-72	0.49	0.34	1.06
Smog (TRACI)	kg CO_2eq	2.6	4.5	26	12	37	10
Water							
BOD & COD	kg	0.09	0.27	15.7	0.09	1.09	5.29
Landfill							
Waste	kg	41	68	2.954	NA	NA	NA

In a report called *Zukunkft Holz (The future of wood)* [35], there are already a large number of studies and characteristics on the basis of life cycle assessment, etc., for construction wood.[36] It is clear that wood as a building material does not only require significantly less energy compared to other building materials in its production (and thus releases less CO_2), but that using wood in buildings, and keeping it built in for as long as possible represents an effective carbon sink (Figs. 9., 10.).

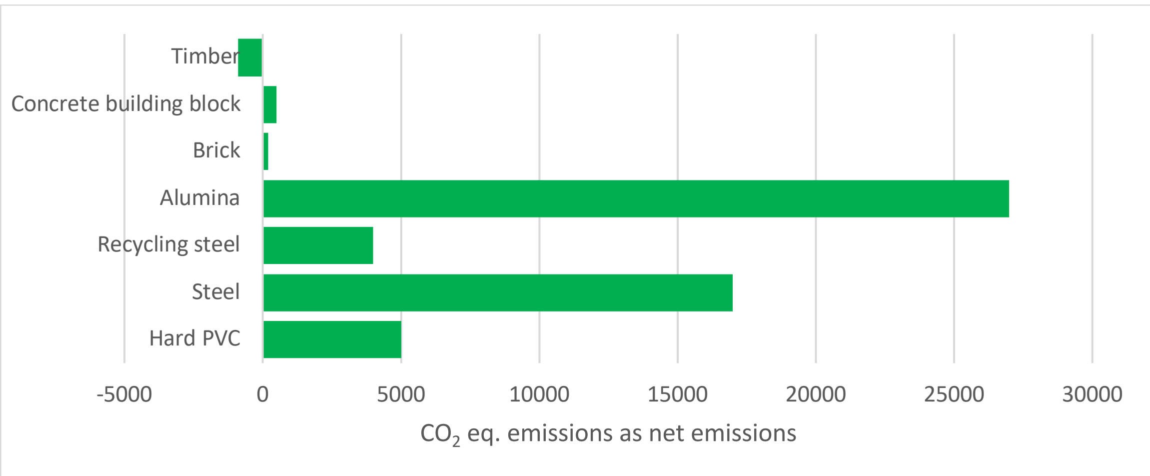

Figure 9 – Comparison of the CO_2 emissions of different materials as net emissions (CO_2 equivalent emissions) including the carbon sink effect. Based on[36]

[34] Newsweek Online, April 3, 2009 Jim Wilson White Paper CPA Resources in: www.surfaceandpanel.com
[35] Dem Klimawandel mit Holz entgegnen. CEI Bois, Brüssel. www.cei-bois.org
[36] K. Schwaner ed. (2009): Zukunft Holz. 8 Vollholz – 8.1 Holz im Vergleich mit anderen Werkstoffen. Institut für Holzbau Hochschule Biberach pp. 541-542

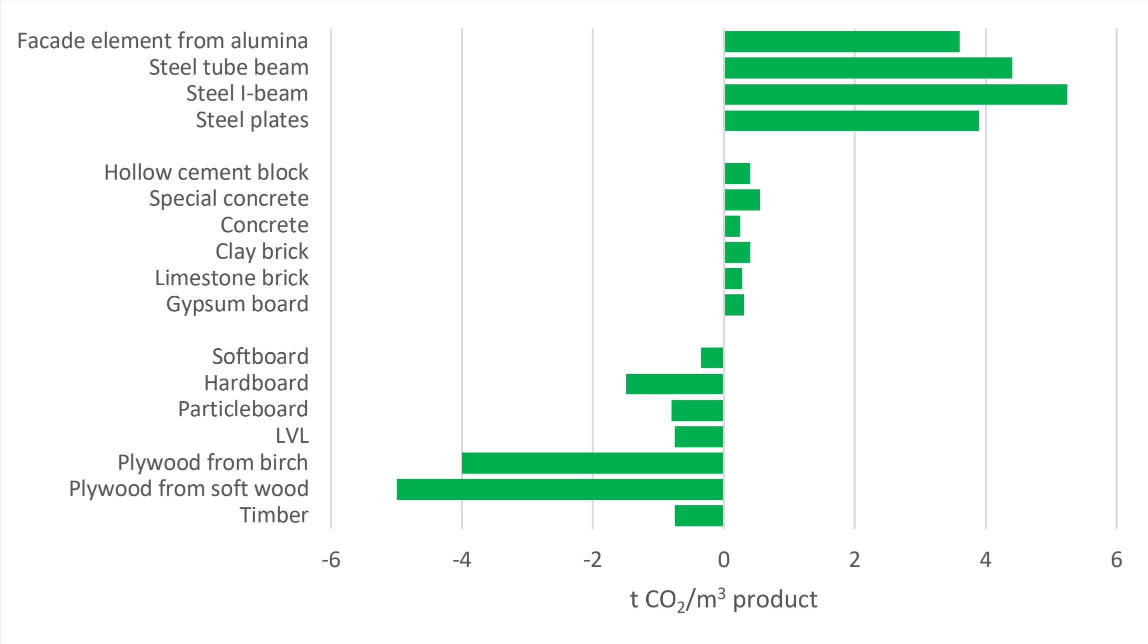

Figure 10– Net CO_2 emissions of building materials during the entire service life. Based on[36]

Antti Ruuska reports the carbon footprint and carbon uptake of 50 building products.[37] In addition to some wood-based panels, we will also cite data on non-wood products in Table 7. The data is based on cradle-to-gate assessment.

Table 7. Carbon footprint and carbon uptake of various building products. Based on[37]

Material	CO_2eq. [g/kg]	CO_2 uptake eq. [g/kg]
Particleboard (raw)	409	1564
Particleboard (melamine faced)	467	1527
Wood fibre insulation	243	1240
MDF (raw)	652	1418
OSB	208	1692
Gypsum plasterboard	1967	-
Glass wool	3148	-
Polystyrene (EPS)	3300	-
Polyurethane (rigid foam)	4200	-
Aerated concrete bock	442	-
Aluminium extrusion profile	2264	-
Ceramic tile	613	-
Stainless steel	3778	-
Lightweight concrete block	240	-
LDPE	2130	-

All of the studies above were based on the assumption that wood, as a fuel source, is carbon-neutral, since the CO_2 released in the atmosphere gets recycled when trees are replanted and start photosynthesizing. While this is essentially true and fair, the extraction, transportation and processing of fuelwood does require some energy. This energy is usually not accounted

37 A. Ruuska 2013. Carbon footprint for building products. VTT Technology 115. VTT Technical Research Centre of Finland

for. In our study, we strived for a more balanced approach that takes this energy into consideration.

Pandey et al 2011, mentioned that the use of wood-based panels products as building material release less carbon footprint than the other construction materials. This research work showed that more than 25 tonnes of GHG could be saved if wood products were used instead of the usual alternatives. (Figure 11) represents the GHG emissions from manufacture of different building components in family house. Production as well has positive impact on reducing carbon emissions by being part of the short term carbon cycle that consider trees absorbing carbon dioxide from the air, relaxing oxygen and storing the carbon in the wood [38].

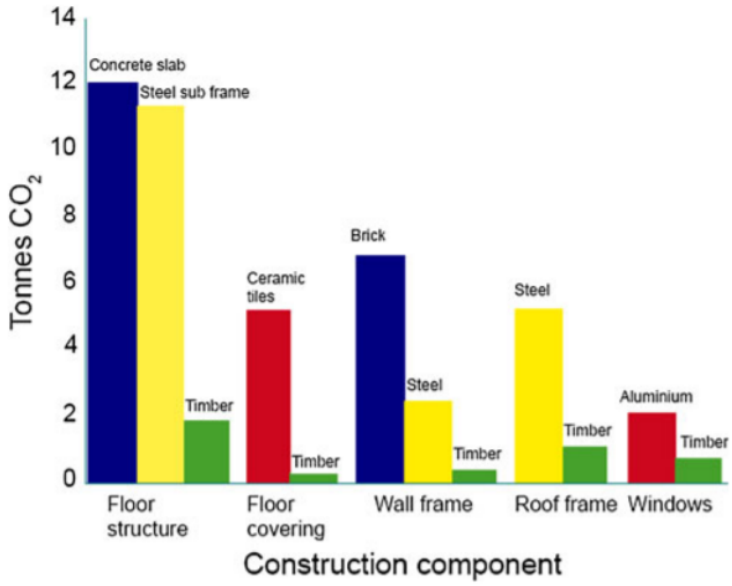

Figure- 11 Greenhouse gas emissions from the manufacture of different building components in a family home[39].

In another publication, the primary energy input (mainly fossil fuels) in the production of building materials was found to be about 60–80% higher when concrete frames were considered instead of wood frames. The way that the wood would be handled after demolition of the building can determine the net greenhouse gas (GHG) balance for wood. If all the demolition wood is used to replace fossil fuels, the net GHG balance will be slightly positive, however, if part of the demolition wood is re-used it will be slightly negative, and clearly positive if all wood is deposited in landfills, due to the production of CH_4[40].

Houses with wood-based wall systems needs 15–16% less total energy for non-heating/cooling applications than thermally comparable houses using alternative steel- or concrete-based building systems. Results for non-renewable energy consumption are essentially the same as those for total energy, reflecting the fact that most of the displaced energy is in fossil fuels. Over the last decade, net GHG emissions related to wood-based houses are 20–50% lower than emissions related with thermally comparable houses using steel- or concrete-based building materials[41].

38 C. N. Pandey, S. K. Nath, D. Sujatha. 2011. Wood based panel products: technology road map. J Indian Acad Wood Sci (December 2011) 8(2):62–67 DOI 10.1007/s13196-012-0047-6.
39 CRC for greenhouse accounting www.timber.net.au
40 Pål Börjesson, Leif Gustavsson. 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy. Volume 28, Issue 9, 31. 575-588
41 Brad Upton, Reid Miner, Mike Spinney, Linda S.Heath. 2008. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass and Bioenergy. Volume 32, Issue 1, 1-10

5. Carbon sequestration in raw material wood

5.1. Introduction

The wood contributes to climate change mitigation in 3 different ways: (i) wood can storage carbon in harvested wood products (HWP), even for a long time. This period can be significantly increased by cascading (Dammer et al. 2016; Vis et al. 2016; Risse et al. 2017; Brunet-Navarro et al. 2018); (ii) wood can substitute other sources of energy (Smyth et al. 2017), mainly fossil fuels (the carbon neutrality of biomass combustion and energy substitution potential is a subject of serious disputes, for details, see e.g. Bracks 2017a, 2017b) and (iii) wood products can substitute functionally equivalent more emission-intensive materials and product (Rüter et al. 2016). From the carbon storage effect, material substitution effect and energy substitution effect the total mitigation potential of wood is in the range of 0.08-1.9 t-CO_2 eq/m^3, depending on the frame of the study (Kayo and Noda 2018).

5.2. Carbon sequestration in wood in general

The wood products are belonging to the forest sector's carbon cycle, and they are managed as a part of the distinct land-uses, including forests (IPCC 2006). However, wood products themselves are important both in aspect of a country and globally. Researches have shown that the carbon content of wood in most cases is between 46 and 55% (Ragland, Aerts 1991, Birdsey 1992; Francis 2000, Gifford 2000; Sampson 2002; Lamlom, Savidge 2003, Telmo et al. 2010). In some cases, there are much different opinions (40%), which are not based on measurements, but the calculation of elemental composition the main components of the cell wall (Jaakko 1999). The softwoods generally have slightly higher carbon content, usually above 50%, while the hardwoods (angiosperms) have somewhat lower, usually below 50%. Therefore, in the different calculations usually 50% carbon content is used, that this value is used if you want to calculate carbon content of wood (e.g. Barson 1989, Dias et al. 2005, Hassan et al 2005, IPCC 2014). According to the latest research, this needs to be refined in the future, because "the ubiquitous 50% generic wood C fraction introduces a systematic error in forest C accounting that can range from a mere 0.1% underestimate in conifer-dominated temperate forests, to 8.9% overestimates in angiosperm-dominated tropical forests" (Martin et al. 2018). Since there is no consensus based on the new results, the currently accepted 50% carbon content was used in the calculations.

Based on statistical data, the IPCC also calculated the carbon content per cubic meter, for both wood and wood-based products (Table 8).

Table 8. Default conversion factors for the default HWP categories and their subcategories (IPCC 2014)

HWP categories	Density (oven dry mass over air dry volume) [Mg/m^3]	Carbon fraction	conversion factor (per air dry volume) [Mg C/m^3]
Sawn wood	0.458	0.500	0.229
coniferous sawn wood	0.450	0.500	0.225
non-coniferous sawn wood	0.560	0.500	0.280
Wood-based panels	0.595	0.454	0.269
HDF	0.788	0.425	0.335
Insulating boards	0.159	0.474	0.075
Fiberboards compressed	0.739	0.426	0.315
MDF	0.691	0.427	0.295
Particleboard	0.596	0.451	0.269
Plywood	0.542	0.493	0.267
Veneer sheets	0.505	0.500	0.253

5.3. Materials and methods

The calculations were based on the data received from FALCO Zrt. The data shows how much wood was shipped into the plant during the period under investigation (Table 9).

Table 9. Transported wood types in the period of 01.10.2023-30.09.2024

	Rm	tA	kgA/Rm	Fm	tL	kgL/Fm
Soft Roundwood CK	34 904	10 642	305	21 465	17 268	804
Soft Roundwood	111 720	32 635	292	66 923	51 815	774
Hard Roundwood (Hard)	74 846	27 047	361	44 159	41 743	945
Hard Roundwood (Soft)	45 602	13 648	299	27 361	22 229	812
Chips with bark	99 285	23 934	241	31 771	33 887	1 067
Chips without bark	6 899	827	120	2 212	1 677	758
Shavings / Sawdust	183 042	26 247	143	54 613	46 613	854
Edgings	65 988	15 386	233	28 498	21 461	753
Recycling	113 687	17 623	155	36 734	23 056	628
Construction waste chips	361 044	63 138	175	130 128	82 250	632
Recycling chips	334 727	60 881	182	126 753	79 114	624
Waste chipboard	12 814	4 371	341	9 752	4 856	498
Fuel Wood / Bark	58 536	12 341	211	18 946	17 747	937
Total:	1 503 095	308 719	3 059	599 314	443 716	10 086
Where: Rm – stacked cubic meter; tA – atro tons (absolutely dry mass); Fm – solid cubic meter; tL – lutro tons (air dry mass (12%))						

Since the absolute dry weight of all the wood delivered is known, Equation (1) can be used to calculate the carbon content.

$$m_c = tA \cdot 0.5 \quad (1)$$

If we want to know that this carbon quantity is how much carbon dioxide, we need to convert it. Since the molar mass of carbon is 12 g and the molar mass of carbon dioxide is 44 g, the conversion factor is 3.67 (see Equation 2).

$$m_{CO_2} = m_c \cdot 3.67 = tA \cdot 0.5 \cdot 3.67 = tA \cdot 1.83 \quad (2)$$

In the case of panels, the carbon content is below 50%, as the composition of the panel contains other materials than wood. Known data do not detail the types of panels, so in this case the conversion factor (0.454) of Table 2 for wood-based panels in general is used (Equation 3).

$$m_{c_{panel}} = tA \cdot 0.454 \quad (3)$$

5.4. Results

The results are shown in Table 10.

Table 10. Carbon content and carbon dioxide equivalence of supplied wood types.

	tA	m_C [t]	m_{CO2} [t]
Soft Roundwood CK	10 642	5 321	19 528
Soft Roundwood	32 635	16 318	59 886
Hard Roundwood (Hard)	27 047	13 523	49 630
Hard Roundwood (Soft)	13 648	6 824	25 043
Chips with bark	23 934	11 967	43 920
Chips without bark	827	413	1 517
Shavings / Sawdust	26 247	13 124	48 164
Edgings	15 386	7 693	28 233
Recycling	17 623	8 812	32 338
Construction waste chips	63 138	31 569	115 858
Recycling chips	60 881	30 441	111 717
Waste chipboard	4 371	1 984	7 283
Fuel Wood / Bark	12 341	6 170	22 645
Total:	308 719	154 360	566 500

The amount of wood shipped contains 154,360tons of carbon, which equivalent to 566,500 tons of stored carbon dioxide.

In the following, we did not investigate what happens to the wood at this point. Obviously, it has to be judged differently if it is burned or used in panel production.

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6. Environmental effect of transportation

6.1. Introduction

The GHG emission from transport sector has more than doubled since 1970. The rate of the increase is more than any other sector. The transport sector produced 7.0 $GtCO_2eq$ of direct GHG emissions in 2010 and hence was responsible for approximately 23% of total energy-related CO_2 emissions globally (Sims et al. 2014). In the EU this rate is even higher (Figure 1 and Figure). Recognizing the importance of this, many countries and the EU have set targets for reducing CO_2 emissions from transport (Faber Mainsell 2008; Ricardo-AEA 2015; DT 2017; ICCT 2018; Markovich and Dobrescu 2018). Calculation systems have been developed to estimate and monitor this (e.g. van den Broek et al. 2014; Sims et al. 2014; Klein et al. 2018; TNO 2018).

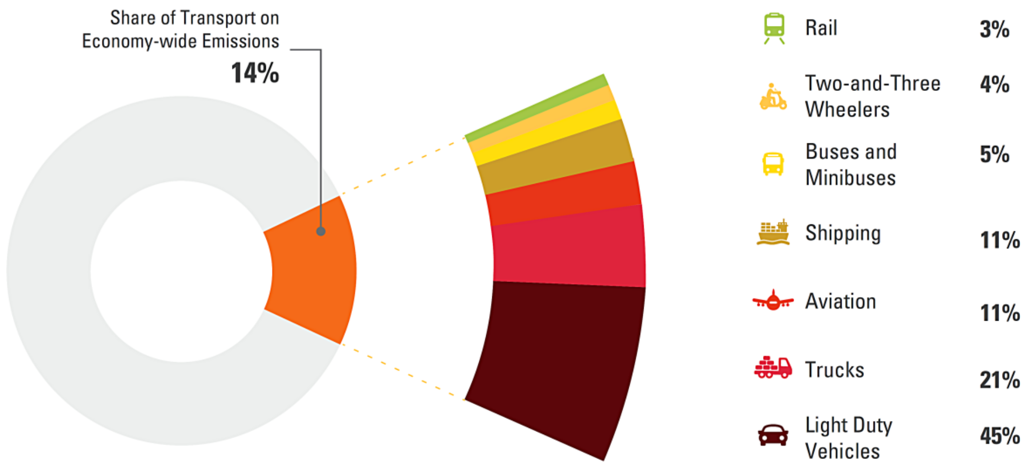

Figure 12. Share of Transport Sector GHG Emissions by Mode (2015) (SLoCaT 2018):

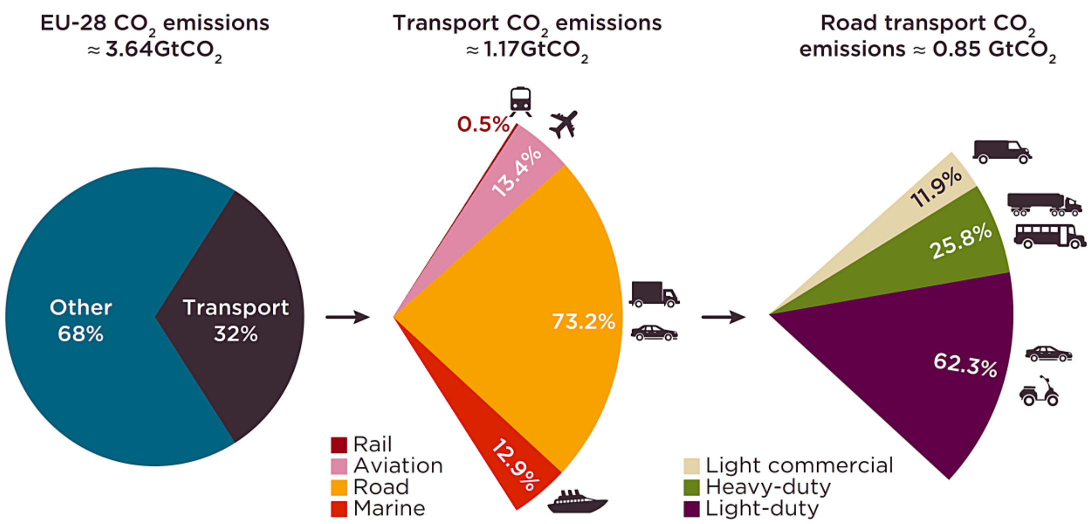

Figure 13. Distribution of total direct CO_2 emissions in the European Union in 2015. (ICTT 2018)

The environmental impact of transport can thus significantly increase the ecological footprint of a product or service, depending on the boundaries of the system under investigation (see. Börcsök et al. 2016).

Since we do not know how the timber was transported, we count on truck delivery. There have been more studies on the consumption of trucks, and the range of consumption varies

considerably depending on the circumstances under consideration and the type of car (for details see https://www.hbefa.net/e/index.html and http://www.theicct.org/). According to the IPCC (2014), the emissions of heavy duty vehicles are between 76 and 178 gCO_2eq/tkm. The Network for Transport Measures database (NTM Calc 4.0; www.transportmeasures.org) contains more details, where depending on the vehicle type, the emissions are between 64 and 812 gCO_2eq/tkm. McKinnon et al. (2015) said the emissions are in the range of 84-584 gCO_2eq/t-km. Measurements show that the specific emissions of larger vehicles are lower. The situation can be complicated by considering how much the car is loaded. McKinnon and Piecyk (2010) examined 40-44 tonne truck with varying payloads and levels of empty running in their work and the emissions were found between 39.7 and 151.1 gCO_2eq/tkm. It raises additional problems when we consider that timber transported takes place at least partly on forest roads, not on public roads, which increases vehicle fuel consumption and thus emissions. Moreover as the terrain becomes more „extreme‟, fuel consumption increases for both public and forest roads. Comparing loaded vehicles on flat public roads with „flat‟, „rolling‟ and „mountainous‟ forest roads requires 6%, 70% and 196% more fuel, respectively (Whittaker et al. 2010).
According to the latest information from the European Environment Agency (2021)[42], the environmental impact of the various modes of transport has hardly changed in recent times. Thus, in 2018, the environmental impact of freight transport by truck is 137 g CO_2eq/tkm, while in the case of rail transport the mean is 24 g CO_2eq/tkm (Figure 14-15).

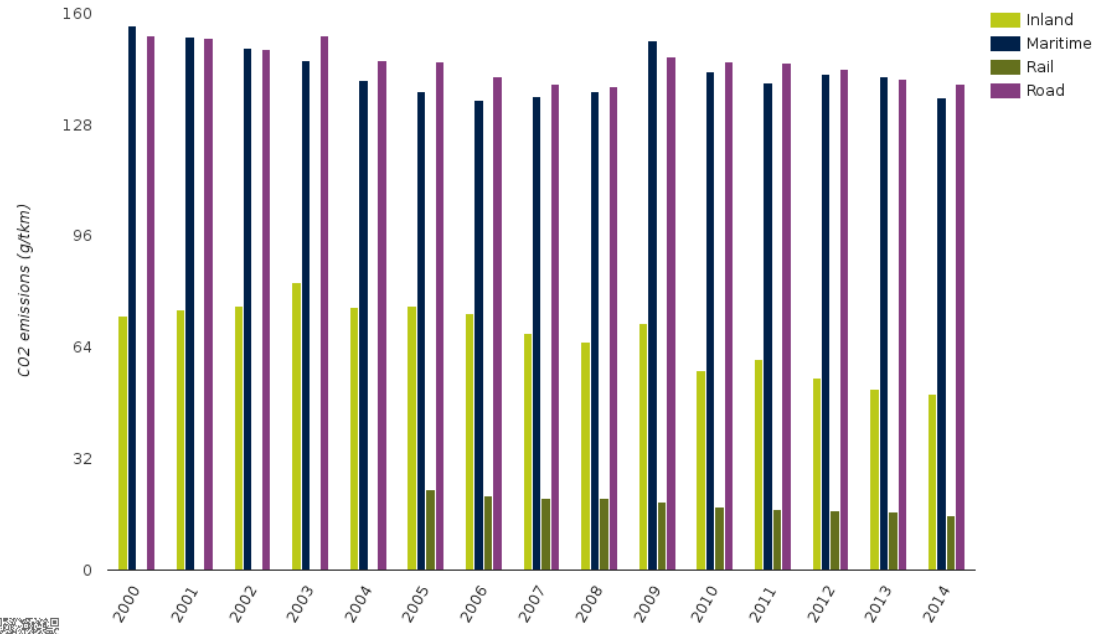

Figure 14 – Specific CO_2 emissions per ton-km and per mode of transport in Europe (EEA 2017)[43]

42 https://www.eea.europa.eu/publications/rail-and-waterborne-transport/rail-and-waterborne-best
43 https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-used-in-indicators

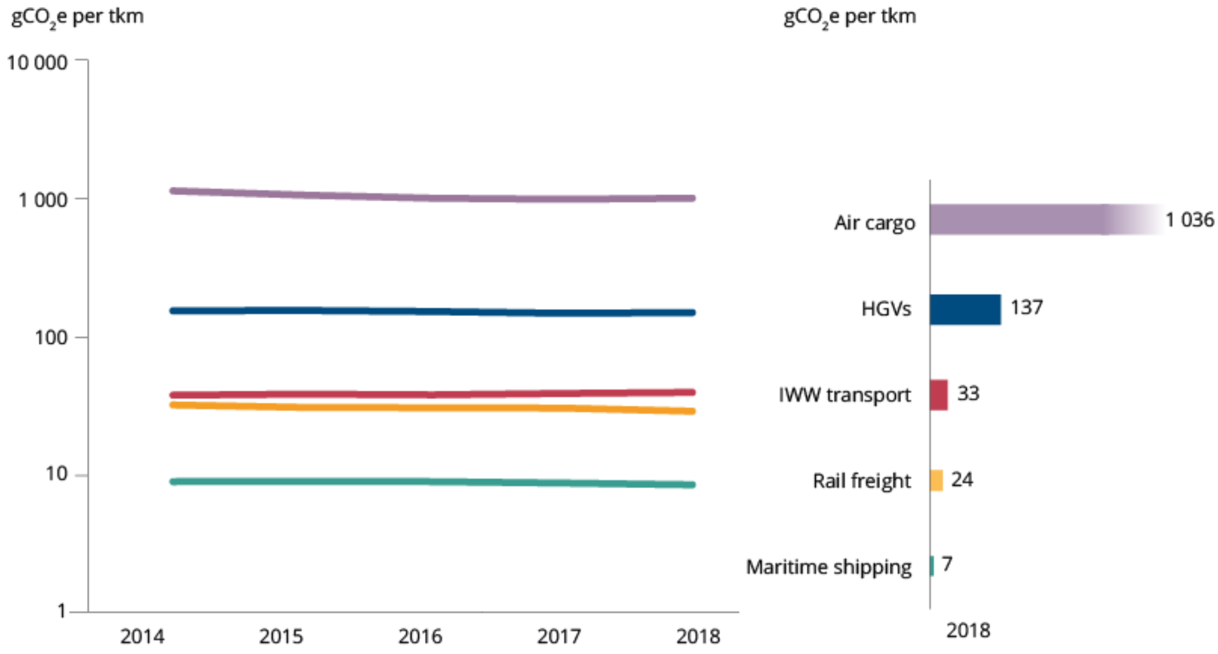

Figure 15 – Specific CO_2 emissions per ton-km and per mode of transport in Europe (EEA 2017)[44]

The calculations were based on the data received from FALCO Zrt. It is known that all the transports arrived by trucks. The total wet weight of the transports (tL) and the distance are known, so the total ton-km can be calculated. The exact kind of vehicle used for transportation is also unknown. The Hungarian truck park is not the most up-to-date, **we accepted the European average of 137 and 24 gCO_2eq/t-km for our calculations**.

From the average distance (s_A) and the wet mass (tL) the total ton-km (T) can be calculated:

$$T = tL \cdot s_A \tag{4}$$

from which emissions can be calculated:

$$GHG = T \cdot 137 = tL \cdot s_A \cdot 137 \tag{5}$$

44 https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-used-in-indicators

6.2. Results

The results are shown in Table 11.

Table 11. Calculated GHG emissions from wood transportation

	Avergae distance [km]	tL	T [tkm]	GHG [tCO_2eq]
Soft Roundwood CK	49	17 268	849 508	116
Soft Roundwood	48	51 815	2 466 626	338
Hard Roundwood (Hard)	54	41 743	2 255 543	309
Hard Roundwood (Soft)	76	22 229	1 698 531	233
Chips with bark	88	33 887	2 969 684	407
Chips without bark	69	1 677	116 151	16
Shavings / Sawdust	283	46 613	13 206 433	1 809
Edgings	120	21 461	2 579 796	353
Recycling	119	23 056	2 736 056	375
Construction waste chips	406	82 250	33 366 902	4 571
Recycling chips	260	79 114	20 578 656	2 819
Waste chipboard	144	4 856	697 285	96
Fuel Wood / Bark	90	17 747	1 605 065	220
Total:		443 716	85 126 236	11 662
Where: tL – lutro tons (=air dry mass (12%))				

The transportation of the wood shipped caused 11,662 tons/a of carbon dioxide emission.

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[15] https://www.hbefa.net/e/index.html

[16] http://www.theicct.org/

[17] www.transportmeasures.org

[18] https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-used-in-indicators

7. Carbon stored in transported wood reduced by the environmental impact of transport

From the amount of the carbon-dioxide stored and the carbon dioxide emitted by the trucks, a reduced amount of carbon dioxide (m_{CO2} *[t]) can be calculated (Table 12.).

Table 12. Calculated reduced amount of carbon dioxide (m_{CO2} *[t])

	m_{CO2} [t]	GHG [tCO_2eq]	m_{CO2} *[t]
Soft Roundwood CK	19 528	116	19 412
Soft Roundwood	59 886	338	59 548
Hard Roundwood (Hard)	49 630	309	49 321
Hard Roundwood (Soft)	25 043	233	24 811
Chips with bark	43 920	407	43 513
Chips without bark	1 517	16	1 501
Shavings / Sawdust	48 164	1 809	46 354
Edgings	28 233	353	27 879
Recycling	32 338	375	31 963
Construction waste chips	115 858	4571	111 287
Recycling chips	111 717	2 819	108 898
Waste chipboard	7 283	96	7 187
Fuel Wood / Bark	22 645	220	22 426
Total:	566 500	11 662	554 838

On the basis of the table, it can be seen that the transported wood still has a significant carbon storage potential. The amount of CO_2 emitted by transport is only about 1.9% of the amount of stored carbon dioxide.

The wood shipped stores as much carbon as equivalent to 554,838tons/a of stored carbon dioxide.

8. Calculation of the amount of carbon stored in the output panels

8.1. Introduction

Among different wood products, fibreboards and particleboards can have significant carbon storage (Wilson 2010; Garcia and Freire 2013) for example within an apartment (Bergman et al. 2015; Negro and Bergman 2019). Wood-based panels also contribute to the national CO_2 emissions and sequestrations (Wang et al. 2017).

8.2. Materials and methods

Calculation based on Safety Data Sheets, literature and factory data. Based on factory data, in the 2023/24 business year 408.239 m^3 particleboard (PB) was manufactured, from which 223,209 m^3 was laminated in 'traditional' way (MF-PB), and from which 16,549 m^3 Mirror Gloss (MG) was prepared (Figure 16). The remaining was sold as plain particle board (PB2 on the Figure 16).

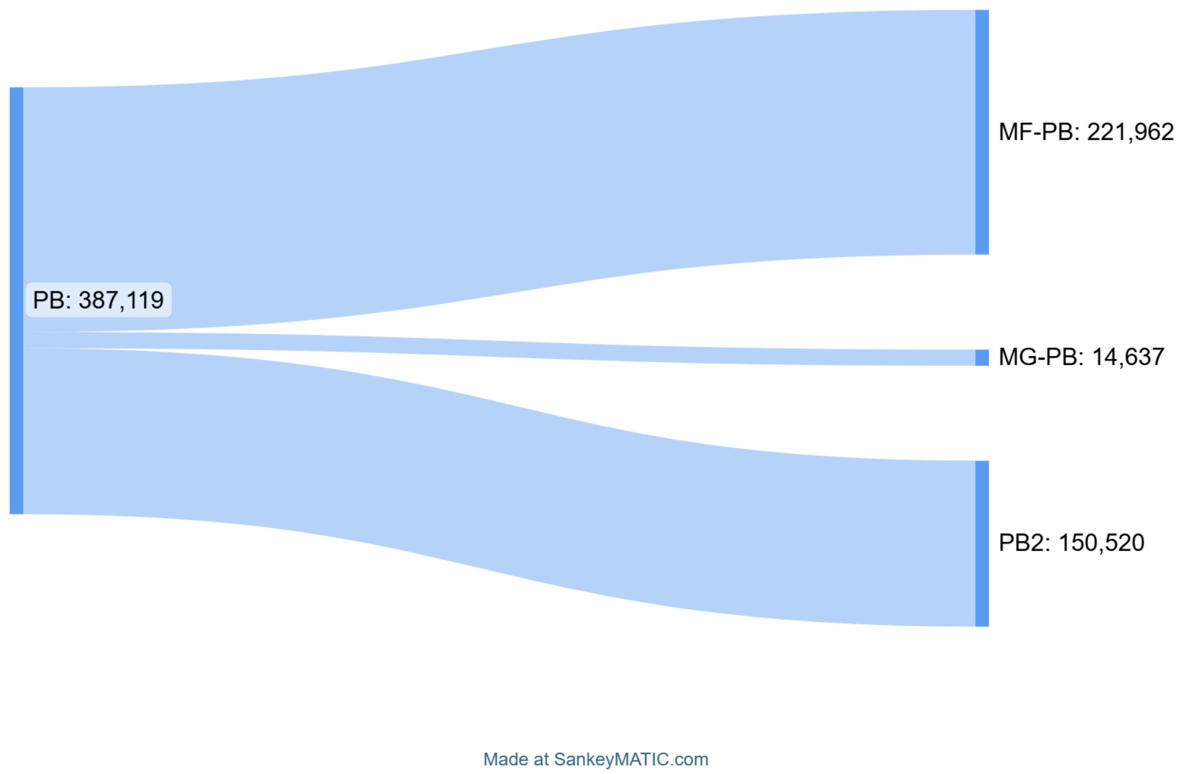

Figure 16. Products in m^3

According to the factory data the fraction of the wood (f; [tA/m^3]) and the total amount of the particleboards (V; [m^3]) are known, from which the used amount (oven dry mass) of the wood [tA] can be calculated.

$$tA = V \cdot f \tag{6}$$

From the tA, the carbon content of the panels can be calculated, by using the Equation 1. From which the stored carbon dioxide also can be calculated by the Equation 2. Based on the factory data the atro tons of wood in one cubic meter cement bonded can be calculated (tA/m^3). From the produced 26,971 m^3 cement bonded chipboard 1800 m^3 is rejected (Table 14).

Based on the factory suggestions, a total of 2,427 tons of paper was used in the 2023/24 business year. The 1% (24,401 kg) of the used paper became waste. 415.5 tons of paper went to Mirror Gloss preparation and 2,011 tons is used for 'normal' lamination. With calculation of 0.9 dry matter content and 0.386 t C/Mg conversion factor (F_C), the carbon content of the used papers can be calculated (Table 14). The carbon content was calculated as Equation 7 shows. From the carbon content the carbon dioxide equivalent value can be calculated (Equation 8).

$$m_c = tA \cdot F_C \tag{7}$$

$$m_{CO_2} = m_c \cdot 3.67 = \rho \cdot F_C \cdot 3.67 \tag{8}$$

8.3. Results

The gross amount of stored carbon and CO_2 in panels and papers were calculated (Table 12-13). A part of the shipped wood and some of the waste wood materials is used as fuel. In the business year 2023/24 51 046 t biomass was used as fuel, which is equivalent to 93 671 tons of carbon dioxide. In this business year 26 646 tons of unused waste (dust, metal, foil etc.).

Table 12. Carbon stored in products' wood content

	V [m³]	f [tA/m³]	wood [tA]	C [t]	CO_2eq [t]
PB sum	387 119	0.699	270 596	**135 298**	**496 544**
MF-PB	221 962	0.699	155 151	**77 576**	**284 703**
MG-PB	14 637	0.699	10 231	**5 116**	**18 774**
PB without coating	150 520	0.699	105 213	**52 607**	**193 067**
CC	26 749	0.414	11 074	**5 537**	**20 321**
CC rejected	1 042	0.414	431	**216**	**792**

Table 13. The carbon content of used and unused fraction of the impregnating paper

	m [kg]	dry matter content*	f conversion factor [t C/Mg]	C [t]	CO_2eq [t]
$IMP_{MF\ used\ (net)}$	1 951 746	0.9	0.386	672	2 465
$IMP_{MF\ waste}$	18 549	0.9	0.386	6	24
$IMP_{MG\ used\ (net)}$	600 202	0.9	0.386	207	759
$IMP_{MG\ waste}$	4 993	0.9	0.386	2	6

*based on IPCC 2014

The gross amount of stored CO_2 were reduced with the emissions of the transportation and a net value was created. The emissions from transport were distributed proportionally between the panel types, because it is not always possible to determine which wood transported belongs to which panel type. All carbon dioxide emitted during transport will burden the manufactured panels even if not all of the wood supplied has been used in panel manufacturing.

Table 14. Transport emission

<table>
<tr><th></th><th>V [m³]</th><th>stored gross CO₂eq [t] with paper</th><th>transport emission CO₂eq [t]</th><th>net stored CO₂eq [t]</th><th>net stored CO₂eq [t/m³]</th></tr>
<tr><td>MF-PB</td><td>221 962</td><td>287 144</td><td>6414</td><td>280 730</td><td>1.265</td></tr>
<tr><td>MG-PB</td><td>14 637</td><td>19 527</td><td>423</td><td>19 104</td><td>1.305</td></tr>
<tr><td>PB without coating</td><td>150 520</td><td>193 067</td><td>4350</td><td>188 717</td><td>1.254</td></tr>
<tr><td>CC</td><td>26 749</td><td>20 321</td><td>458</td><td>19 863</td><td rowspan="2">0.743</td></tr>
<tr><td>CC rejected</td><td>1 042</td><td>792</td><td>18</td><td>774</td></tr>
</table>

Based on the calculations, it can be said that, based on both estimation modes, approx. 509 188 tons of carbon dioxide are stored in various panel products.

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Conclusions of Transport

In the following, we assumed that wood and paper that had not been used in the panels had been burned. Based on these, the following summary can be made:

(1) 605,909 tons of carbon dioxide is stored in the wood transported into the factory.

(2) 3063 tons of carbon dioxide is stored in the paper used in the factory.

(3) Net 536,516 tons of carbon dioxide is sequestered in the panels made in the factory.

(4) 11,809 tons of carbon dioxide is emitted from the transportation of wood into the factory.

(5) The stored carbon dioxide pro m^3 respectively:

   a. MF-PB: 1.265 t CO_2eq./m^3
   b. MG-PB: 1.305t CO_2eq./m^3
   c. PB: 1.254 t CO_2eq./m^3
   d. CC: 0.743 t CO_2eq./m^3.

9. The environmental impact of adhesives and additives

In addition to wood in various forms (roundwood, edgings, sawdust and shavings, etc.) and other materials (e.g. communal waste wood and wood-based materials) used as fibre stock, other materials are also present in wood-based panels. These include binders (adhesives), catalysts, modifiers (e.g. moisture repellents and formaldehyde scavengers), release agents, paper for the melamine and mirror gloss surface treatments, as well as cement and waterglass for cement bonded particleboard production. There was also some purchased décor paper in the examined period.

Adhesives are typically organic materials (except in the case of the inorganic binder in cement bonded chipboard), and constitute a significant portion of the end product. Unfortunately, these adhesives are typically produced from fossil fuels. Thus, their carbon storage potential may not be taken into account. Their production, on the other hand, is an energy intensive process, which contributes to GHG emissions significantly. There has been much research in this area, and the general consensus is that adhesives can significantly increase (even multiply) the environmental impact of wood-based panels, compared to solid wood[45, 46, 47].

Other chemicals used in panel production are present in relatively minor quantities. Some of these materials (like paraffin, often used as a moisture repellent additive) are simple, one-component materials, whose carbon footprint is easily calculated. Other materials, like catalysts and release agents, are typically complex chemicals with many compounds, and their exact composition is often unknown. For these materials, sometimes the best option is using simplifying assumptions or even rough estimates. This introduces a level of uncertainty in the carbon footprint determination, but, because of the miniscule quantities, this has little influence on the overall carbon footprint of the products in consideration.

The determination of the effect of adhesives and additives was calculated based on data provided by FALCO Zrt. The amount of each material was broken down to product types. Carbon equivalent values came from various sources, as follows:

- The CO_2eq values for urea-formaldehyde and melamine-formaldehyde (UF and MF) resins and cement used in CB panels were taken from the Bath University database[48]
- In the case of paper, the CO_2eq value was taken from the 2018 British governmental guidelines[49] (Section: material use). **<u>Note:</u>** paper also contains wood fibres from renewable sources, i.e. it has a negative carbon footprint due to carbon sequestration. This has been taken into account in Chapter 5. This chapter accounts for the emissions due to its production and transportation.
- CO_2eq values for simple chemicals, including paraffin, ammonium nitrate, sodium silicate, urea and butanediol were taken from the Eco Invent 2.2 database (accessed through carbonfootprint.com).

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- The chemical composition of other materials – including catalysts, release agents and one modifying agent is unknown. Therefore, for these materials, the CO_2eq value for "Plastics: average plastics" was used from the 2018 British governmental guidelines[49] (Section: material use). This relatively high value is likely to be a conservative estimate for the effect of these materials.

Table 15 shows the total and unit cradle-to-gate CO_2eq emissions related to the binders and additives used in the different products of FALCO Zrt. This does not include the emissions originating from the transportation of these materials to the production site. **Table 16** comprises the transportation-related emissions. The determination of average transportation distances was based on sample data of origin countries and quantities provided by FALCO Zrt., and the CO_2eq emission values for transportation used in Chapter 6. (137 g CO_2eq/tkm).

Table 15 – Annual and unit cradle-to-gate carbon footprint values of the adhesives and additives used in manufacturing panel products at FALCO Zrt. (2023.10-2024.09, calculated on a dry matter basis, wherever applicable.)

	Quantities					CO_2eq value (kg/kg)	Emissions, CO_2eq			
	All OB PB	**Raw PB**	**CB PB**	**MF**	**MG**		**Raw PB**	**CB PB**	**MF**	**MG**
Annual production (m^3/a):	**387 119**	**150 520**	**28 282**	**221 962**	**14 637**					
Annual consumption/ emission (kg/a):										
PBM2470 MUF adhesive	5 358 070	2 083 330	0	3 072 151	202 589	2.805 [a]	5 843 439	0	8 616 937	568 233
CB1639 UF adhesive	6 757 384	2 627 413	0	3 874 474	255 497	2.760 [a]	7 251 660	0	10 693 549	705 172
Paraffin Emulsion	550 019	213 859	0	315 364	20 796	0.829 [c]	177 289	0	261 436	17 240
Ammonium Nitrate	309 494	120 338	0	177 454	11 702	8.553 [c]	1 029 249	0	1 517 766	100 087
Release Agent	16 646	6 472	0	9 544	629	3.119 [b]	20 187	0	29 769	1 963
Urea	891 535	346 648	0	511 178	33 709	3.310 [c]	1 147 403	0	1 692 001	111 577
Portland cement	0	0	24 570 751	0	0	0.950 [b]	0	23 342 214	0	0
Waterglass	0	0	1 109 899	0	0	1.097 [c]	0	1 217 559	0	0
UF resin	0	0	0	861 704	107 606	2.760 [a]	0	0	2 378 304	296 992
MF resin	0	0	0	822 663	102 730	4.190 [a]	0	0	3 446 956	430 440
UF hardener	0	0	0	14 154	1 768	3.119 [b]	0	0	44 147	5 513
MF hardener	0	0	0	9 807	1 225	3.119 [b]	0	0	30 589	3 820
Cross-linking agent	0	0	0	32 664	4 079	3.119 [b]	0	0	101 879	12 722
Modificator	0	0	0	108 556	13 556	3.119 [b]	0	0	338 585	42 281
Craft paper	0	0	0	2 015 019	251 626	0.955 [b]	0	0	1 924 343	240 303
Purchased décor	0	0	0	248 430	31 023	6.136 [d]	0	0	1 524 367	190 356
Annual emission, total (kg CO_2eq/a):							**15 469 227**	**24 559 773**	**32 600 628**	**2 726 699**
Unit emissions (kg CO_2eq/m^3)							**102,77**	**868,39**	**146,87**	**186,29**

CO_2eq value sources: [a]Bath University Database (in the case of PBM2470, calculated as a weighted average of UF and MF); [b]2018 British governmental guidelines (for complex chemicals of unknown composition, the "Plastics: average plastics" value was used); [c]Ecoinvent 2.2 database; [d]Calculated from the company's own data for impregnation, including raw material usage, energy consumption and carbon stored in paper.

Table 16 – Annual and unit transportation emission values related to adhesives and additives used in manufacturing panel products at FALCO Zrt. (2023.10-2024.09)

	Quantities					Transport distances (km)	Transport emissions*, CO_2eq			
	All OB PB	Raw PB	CB PB	MF	MG		Raw PB	CB PB	MF	MG
Annual production (m^3/a):	**387 119**	**150 520**	**28 282**	**221 962**	**14 637**					
Annual consumption/ emission (kg/a):										
PBM2470 MUF adhesive	5 358 070	2 083 330	0	3 072 151	202 589	402	114 643	0	169 057	11 148
CB1639 UF adhesive	6 757 384	2 627 413	0	3 874 474	255 497	402	144 583	0	213 208	14 060
Paraffin Emulsion	550 019	213 859	0	315 364	20 796	800	23 424	0	34 543	2 278
Ammonium Nitrate	309 494	120 338	0	177 454	11 702	400	6 591	0	9 720	641
Release Agent	16 646	6 472	0	9 544	629	676	600	0	884	58
Urea	891 535	346 648	0	511 178	33 709	799	37 944	0	55 953	3 690
Portland cement	0	0	24 570 751	0	0	204	0	685 324	0	0
Waterglass	0	0	1 109 899	0	0	675	0	102 694	0	0
UF resin	0	0	0	861 704	107 606	401	0	0	47 330	5 910
MF resin	0	0	0	822 663	102 730	402	0	0	45 270	5 653
UF hardener	0	0	0	14 154	1 768	420	0	0	814	102
MF hardener	0	0	0	9 807	1 225	420	0	0	564	70
Cross-linking agent	0	0	0	32 664	4 079	400	0	0	1 789	223
Modificator	0	0	0	108 556	13 556	400	0	0	5 946	743
Craft paper	0	0	0	2 015 019	251 626	812	0	0	224 033	27 976
Purchased décor	0	0	0	248 430	31 023	673	0	0	22 889	2 858
Annual emission, total (kg/a):							**327 786**	**788 018**	**831 999**	**75 411**
Unit emissions (kg/m^3)							**2,18**	**27,86**	**3,75**	**5,15**

*Calculated as the quantity in tons (solutions, wherever applicable), multiplied by the distance, multiplied by the transport emission equivalent value of 137 gCO_2eq/t-km.

Table 17 shows the total annual and unit CO_2eq emissions related to the adhesives and additives used by FALCO Zrt in 2023/24. Based on the results, transportation emissions of these materials is relatively low, and has very little influence on the carbon footprint of these materials (and, indeed, on the total carbon footprint of the panel products.)

Figure 17 compares the emissions related to adhesives and additives used by FALCO Zrt between business years 2017/18 through 2023/24. Total emissions show considerable variability between the examined periods. This is mostly due to the change in produced quantities. Decrease in the total emission of raw particleboard production, in particular, is mostly due to reduced production quantities, since unit emissions did not change significantly.

Results are more consistent in terms of unit emissions. There is some variation between 2017/18 and later years. The main reason for this is the fact that our 2018 calculations did not take the dry matter content into account in the case of some materials (Resins, Paraffin, Ammonium Nitrate), which provided a conservative estimate for the emissions originating from these materials. In our newer calculations, production-related emissions were computed on a dry matter basis, which provided more accurate (lower) emission values for these materials (and, since resins are a major source of emission, overall production-related emission values.) 2020/21 through 2023/24 unit emission values are remarkably consistent, except for Mirror Gloss particleboard, where there is a significant reduction. This is because material flows were altered compared to earlier yiers, and some amount of lower-impact décor paper (Impregnat I) is now used for MG, as well as MF panel production. Other than this, there was no change in the calculation methodology (nor indeed in the ratios of materials used) throughout this four-year period and therefore unit emission values are unchanged.

Figure 17 also shows that transportation contributed very little to the carbon footprints of adhesives and additives. More accurate transportation distance estimates resulted in somewhat higher transport-related emissions, compared to the 2017/18 values, but this had negligible effect on the carbon footprint of the adhesives and additives used, let alone on that of the products overall.

Table 17 – Annual and unit carbon footprint of additives and adhesives used in manufacturing panel products at FALCO Zrt. (2023.10-2024.09): 2023/24 business year

	Annual emissions (kg CO_2eq / a)			**Unit emissions (kg CO_2eq / m^3)**		
	Materials[a]	Transport[b]	Total	Materials[a]	Transport[b]	Total
Raw PB	15 469 227	327 786	15 797 013	102.77	2.18	104.95
CB PB	24 559 773	788 018	25 347 790	868	27.86	896.25
MF	32 600 628	831 999	33 432 627	146.87	3.75	150.62
MG	2 726 699	75 411	2 802 110	186.29	5.15	191.44
Production, total	**85 386 814**	**2 168 858**	**87 538 939**			

[a] see Table 15, [b] see Table 16

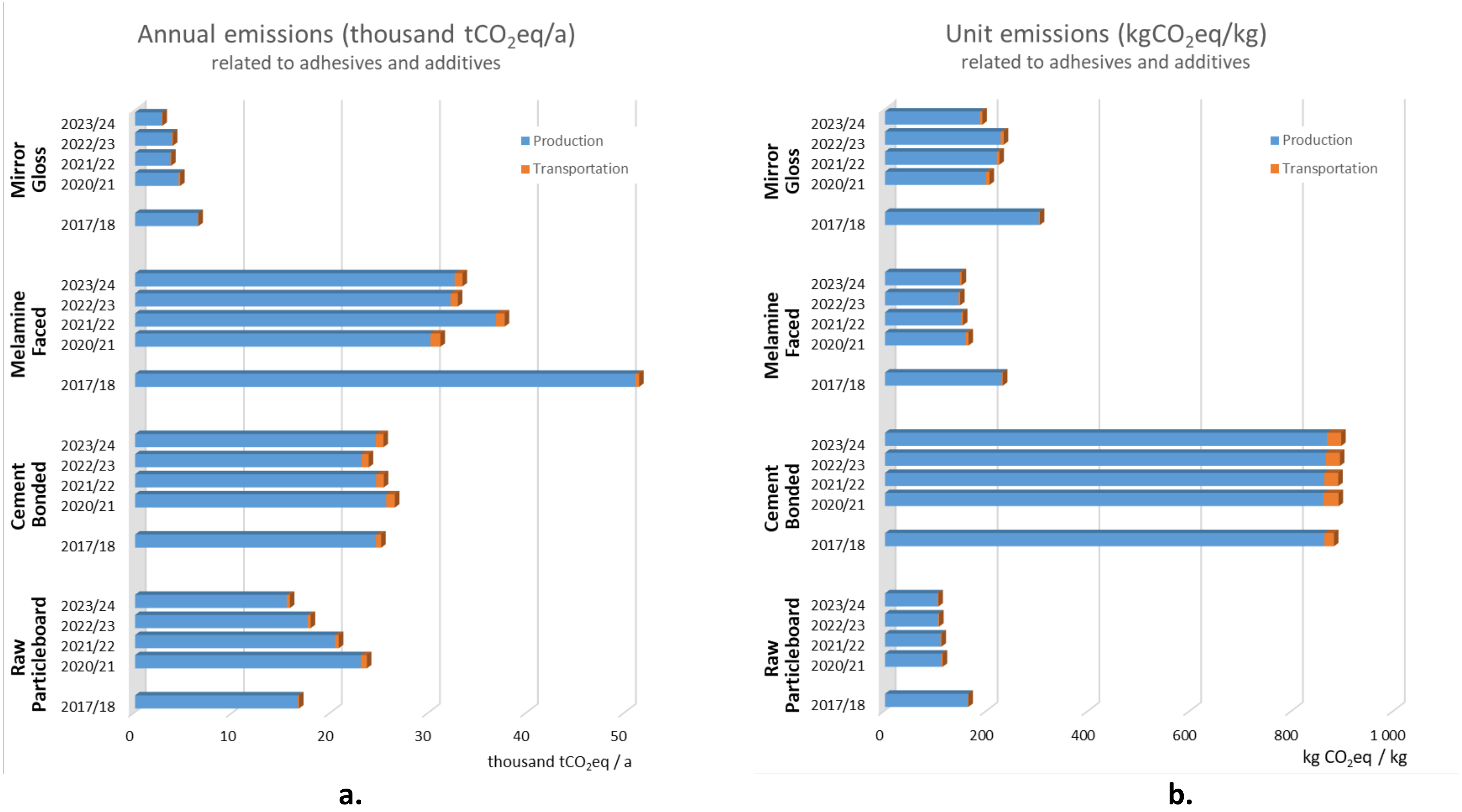

Figure 17. Total annual (a) and unit (b) emissions related to the adhesives used in business years 2017/18 through 2023/24 in Falco Zrt, allocated to different products.

Table 18 – Annual and unit carbon footprint of all raw materials incorporated in FALCO Zrt's products (2023.10-2024.09): 2023/24 business year

	Net annual emissions (t CO_2eq)			**Unit emissions (t CO_2eq / m^3)**		
	Wood and paper*	Other materials	Total	Wood and paper*	Other materials	Total
Raw PB	-188 717	15 797	-172 920	-1.254	0.105	-1.149
CB PB	-20 637	25 348	4 711	-0.743	0.896	0.153
MF	-280 730	33 433	-247 297	-1.265	0.151	-1.114
MG	-19 104	2 802	-16 302	-1.305	0.191	-1.114
Production, total	**-509 188**	**77 380**	**-431 808**			

* Since the carbon sequestration potential of wood outweighs the extraction and transportation emissions, its carbon footprint is negative.

Finally, **Table 18** summarizes the total environmental impact of all raw materials, including wood, paper, adhesives and additives, based on **Tables 14** and **17**. As seen in the table, materials incorporated in all of the organic bonded panels have a massively negative total environmental impact, while the cement used for producing cement bonded particleboards offsets the (relatively low) negative carbon footprint of the wood used for its production; thus the overall carbon footprint of the materials used in cement bonded particleboard is positive, albeit moderate.

10. Carbon dioxide emissions from energy used in the panel board industry

Environmental pollution is an increasing problem all over the world, including Hungary. Intensive agriculture, industry and human activity in general emit more and more pollutants. This is why the analysis and determination of the environmental impact of various products is crucially important. One of the most significant components of the environmental impact is usually the energy required for industrial production.

Forest management and wood industry, including panel production, is renowned for supporting sustainable development, due to the so-called carbon sequestration. Thus, these products contribute significantly to the reduction of CO_2 in the atmosphere, which is one of the most important greenhouse gases.

One of the most important components of carbon footprint is related to energetics, namely, heat generation and electricity consumption. Some studies in this area also often include fuel consumption due to logistics, while others treat this separately. When analysing the energy consumption, we used the data for 2020/21,2021/22 and 2022/23 as a basis for comparison.

10.1. Energy consumption in panel production

Panel production involves electricity, heat and fuel consumption. The following table includes the various quantities used annually by FALCO Zrt.

Table 19 – Total energy consumption of FALCO Zrt. during panel production (2020/21; 2021/22; 2022/23; 2023/24 based on FALCO data)

		2020/21		
		Amount of energy [kWh]	**Amount of energy [MJ]**	**Other unit**
Electricity	Electricity	**93 376 270**	336 154 573	-
Heat	Natural gas	30 886 600	111 191 760	**3 191 468 Sgm³**
	Biomass	234 484 284	844 143 425	**51 047 tons**
Internal transport, transportation	Diesel	3 835 131	13 806 473	**321 081 kg**
	LPG 11 kg	302	1 088	**23 kg**
	LPG (tank)	0	0	**0 litre**
Total		**362 582 587**	**1 305 297 319**	
Total produced board product [m³] (PB+CBPB)		**450 810**		

		2021/22		
		Amount of energy [kWh]	**Amount of energy [MJ]**	**Other unit**
Electricity	Electricity	**92 371 342**	332 536 831	-
Heat	Natural gas	29 075 660	104 672 376	**2 997 386 Sgm³**
	Biomass	254 441 441	915 989 190	**53 664 tons**
Internal transport, transportation	Diesel	5 066 522	18 239 480	**424 174 kg**
	LPG 11 kg	0	0	**0 kg**
	LPG (tank)	0	0	**0 litre**
Total		**380 954 965**	**1 371 437 877**	
Total produced board product [m³] (PB+CBPB)		**478 619**		

		2022/23		
		Amount of energy [kWh]	**Amount of energy [MJ]**	**Other unit**
Electricity	Electricity	85 729 331	308 625 591	-
Heat	Natural gas	28 910 383	104 077 381	**2 931 765 Sgm³**
	Biomass	223 790 371	805 645 335	**48 827 tons**
Internal transport, transportation	Diesel	3 895 241	14 022 868	**326 113 kg**
	LPG 11 kg	0	0	**0 kg**
	LPG (tank)	0	0	**0 litre**
Total		**342 325 326**	**1 232 371 174**	
Total produced board product [m³] (PB+CBPB)		**434 905**		

		2023/24		
		Amount of energy [kWh]	**Amount of energy [MJ]**	**Other unit**
Electricity	Electricity	87 162 757	313 785 924	-
Heat	Natural gas	28 315 328	101 935 181	**2 885 097 Sgm³**
	Biomass	218 423 810	786 325 716	**47 947 tons**
Internal transport, transportation	Diesel	3 820 162	13 752 582	**319 827 kg**
	LPG 11 kg	0	0	**0 kg**
	LPG (tank)	0	0	**0 litre**
Total		**337 722 056**	**1 215 799 403**	
Total produced board product [m³] (PB+CBPB)		**415 401**		

In general, literature provides various energetics data, e.g. in the BAT reference document (BREF)[50]. Unfortunately, based on this data we cannot get an accurate overall picture concerning the actual energy consumption of panel product manufacturing. This requires a separate, company-specific analysis.

10.2. Methodology for the determination of energy-related CO_2 emission

For the accurate determination of the emission, energy consumption values related to the various panel products were collected. Since in many cases, values were available for the whole production process only, the company's own estimations were used to break this down and calculate the unit consumption values for each product.

The ***emission factors***[51] belonging to each form of energy were determined based on national and international guidelines and national emission data. This corresponds to the so-called 1st determination level.[52]

Net calorific values[53] belonging to various forms of energy were determined based on the available test reports. This corresponds to the 1st determination level, or the 3rd determination level in case of biomass.[52]

[50] **Stubdrup, K. R., Karlis, P., Roudier, S., & Sancho, L. D. (2016).** *Best Available Techniques (BAT) Reference Document for the Production of Wood-based Panels.* Retrieved from http://publications.jrc.ec.europa.eu/repository/bitstream/JRC100269/wbp_bref_2016.pdf

[51] ***emission factor*** means the average emission rate of a greenhouse gas relative to the activity data of a source stream assuming complete oxidation for combustion and complete conversion for all other chemical reactions;

[52] **European Commission. (2012).** *Commission Regulation (EU) No 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council (Text with EEA relevance).* Retrieved from https://eur-lex.europa.eu/legalcontent/EN/TXT/PDF/?uri=CELEX:32012R0601&from=EN

[53] ***net calorific value (NCV)*** means the specific amount of energy released as heat when a fuel or material undergoes complete combustion with oxygen under standard conditions less the heat of vaporisation of any water formed;

Oxidation factors[54] were determined using the 1st determination level.[52]

Taking all of these into account, the uncertainty of the heat generation data was taken as ± 7,5 % and ± 2,5 % (1st and 3rd determination level, respectively.)

Our goal is to determine the full CO_2 emission of the company as precisely as possible. In addition to direct CO_2 emission, this includes other GHG emissions that are converted into CO_2 equivalent (CO_2eq) values, using appropriate conversion factors. Data required for the calculations originated from estimations, measurements, and literature sources.

Emission factors for CH_4 and N_2O were calculated using the same methodology as for the CO_2 per kWh, using the Tier 1 methodology and the default emission factors of the *2006 IPCC Guidelines*, including also emissions from biofuels in this case (as opposed to CO_2 only emissions). The emission factors are converted from g CH_4 and g N_2O to g CO_2eq using the 100-year Global Warming Potential (GWP) given below. For the purpose of comparability with international data submission guidelines, the factors from the 4th Assessment of the IPCC are used. [55]

[54] ***oxidation factor*** means the ratio of carbon oxidised to CO_2 as a consequence of combustion to the total carbon contained in the fuel, expressed as a fraction, considering CO emitted to the atmosphere as the molar equivalent amount of CO2;

[55] **International Energy Agency. (2018).** *Emission factors 2018.* Retrieved from http://wds.iea.org/wds/pdf/CO2KWH_Methodology.pdf

Table 20 – CH_4 and N_2O emissions for electricity generation[55]

GHG	100-year global warming potentials (GWP) – SAR (IPCC Second Assessment Report)	100-year global warming potentials (GWP) – AR4 (Fourth Assessment Report)
Carbon dioxide (CO_2)	1	1
Methane (CH_4)	21	25
Nitrogen dioxide (N_2O)	310	298

Values are determined as carbon-dioxide mass-equivalent, for a given time period (usually 100 years). Carbon-dioxide's GWP is, by definition, 1.

10.3. CO_2 emissions related to electric energy consumption

FALCO Zrt. uses about 85-93 GWh of electric energy (so-called secondary energy source) annually for producing wood-based panels. Related CO_2 emissions do not occur directly at the company. Indirect emissions from this source can be calculated using an emission factor specific to Hungary.

Electric energy emission factors differ from country to country. For our calculations, we used an emission factor relevant to Hungary. Various reports and calculations published in recent years yielded many different values, some of which are collected below:

1. The technical supplement to the guidelines for the "Form related to the sustainable energy action plan (SEAP)" published in 2010 contains the following values:
   - Standard emission factor: 0.566 tCO_2/MWh
   - LCA (Life Cycle Assessment) emission factor: 0.678 tCO_2eq/MWh (CO_2eq= equivalent CO_2 emission[56])
2. The IEE 2013 document[57] also contains the above 0.566 tCO_2/MWh value.
3. Many Hungarian energetics consultation reports between 2017 and 2020 typically use values of 0.32 … 0.35 tCO_2eq/MWh_e for their calculations.
4. One international publication from 2018[58] used 0.304 tCO_2eq/MWh.
5. The report prepared for FALCO Zrt. by Get-Energy Hungary PLC in 2019 uses 0.369 tCO_2eq/MWh for the calculations.[59]
6. The 2019 Carbon Footprint report recommends 0.314 $kgCO_2eq/kWh$ for electricity.[60]
7. Interactive online calculators offer 0.196 … 0.288 kg CO_2eq/kWh based on real time monitoring, but this refers to gross production values[61]
8. According to some of the newest reports published in June 2024, the equivalent emission factor for electric energy production was 0.181 tCO_2eq/MWh in 2022.[62]

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[56] A ***carbon dioxide equivalent*** or ***CO_2 equivalent***. abbreviated as ***CO_2eq*** is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP). by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

[57] **Intelligent Energy Europe. (2013, March).** *Guidelines for the calculation of the IEE Common Performance Indicators (CPIs).* Retrieved from https://ec.europa.eu/easme/sites/easme-site/files/guidelines-iee-common-performance-indicators.pdf

[58] Carbon Footprint Ltd. (2018) Country specific electricity factors. https://www.carbonfootprint.com/docs/2018_8_electricity_factors_august_2018_-_online_sources.pdf

[59] Get-Energy Magyarország Kft. (2019) FALCO Zrt. 9700 Szombathely, Zanati út 26. 9700 Puskás Tivadar utca 12., 2641 Tárnok, Állomás utca 2. telephelyek komplex energiahatékonysági auditja. (Complex energy efficiency audit of the Szombathely sites of FALCO)

[60] https://www.carbonfootprint.com/docs/2019_06_emissions_factors_sources_for_2019_electricity.pdf

[61] https://app.electricitymap.org/zone/HU (10. 2023 - 09. 2024 average: 0.239 kgCO2e/kWh); https://www.nowtricity.com/country/hungary/ (2023: 0.206 kgCO2e/kWh)

[62] https://www.eea.europa.eu/en/analysis/maps-and-charts/co2-emission-intensity-15

As shown above, emissions factors from various sources show considerable differences. Discrepancies of this magnitude cannot be justified solely based on the penetration of renewable energy within the energy sector.

Because of the uncertainties in the above values, **we created our own calculations based on 2022 data.**

1st calculation method:

Total electric energy production was 35 648 GWh[63] in Hungary in 2022. Of this, 26 405 GWh was produced in large power plants (>50MWe). These large power plants produced a total of 6.89 million tons of CO_2[6363]. This means that, on average, these plants produced 0.261 kg of carbon dioxide for each kWh of electric energy produced. Taking the ratio of gross to net production into account (due to the consumption of the power plant itself) we get 0.276 $kgCO_2/kWh$, but in terms of the net consumption value (which includes network transportation losses to the consumer), the actual emission value is closer to 0.294 $kgCO_2/kWh$.

At present, these data, provided by MAVIR, is considered most up-to-date. Based on earlier MAVIR data, the emission in large power plants ranged form 0.29 to 0.4 $kgCO_2/kWh$, however, in the last year, the CO_2 emission data for large power plant emissions showed a significant decrease of about 15%.

The fact that the ratio of used and imported electric energy in Hungary was 26.5%[63] in 2022, as well as the fact that there is no MAVIR emissions data published for power plants smaller than 50 MWe influences the results significantly. Electric energy-related emissions vary between countries of origin, which causes further uncertainty. Since there is no reliable information for this, we assumed that, on average, the energy imported from other countries have similar emission values. Among others, small power plants (units below 50 MWe of output, but larger than household units, with the combined production of 9243 GWh of energy) include renewable energy sources. Since renewables allow for the use of lower emission values to be used[63], thus, based on technical estimates and the proportion of renewables, a base value of approx. 0.23 $kgCO_2/kWh$ may be used as the emission factor for Hungarian electric energy consumption (this can primarily be attributed to the continuously expanding solar panel systems).

Since official statistics do not specify if this is equivalent CO_2 emission, thus the equivalency increment may be calculated based on the ratio provided in a document mentioned earlier ("Form related to the sustainable energy action plan (SEAP)") Using the ratio of 0,678/0,566, based on the base value of 0.239 $kgCO_2/kWh$, as well as the power plants' own consumption (difference between gross and net production) and network losses (difference between production and consumption), the equivalent emission factor is calculated as 0.276 tCO_2eq/MWh. This figure fits literature and official reporting values well.

2nd calculation method:

Using MEKH data[64] we can calculate the emissions based on the energy sources used for our gross electric energy production. (We should note that there is a small difference in the totals published in MEKH and MAVIR documents, due to the final accounting.)

[63] MAVIR Zrt: Magyar Villamosenergia-rendszer (VER) 2022. évi adatai alapján (Data of The Hungarian Electricity System 2022)
[64] http://mekh.hu/eves-adatok

Table 21. CO_2eq values determined from gross electric energy production.

Energy sources	Gross electric energy production, 2022	LCA-based emission values	Source
	GWh	gCO_2eq/kWh	
Nuclear	15812	12	IPCC 2014
Carbon and carbon products	3064	820	IPCC 2014
Natural gass	8846	490	IPCC 2014
Crude oil products	59	650	UK POST 2014
Biomass	1693	230	IPCC 2014
Biogas	315	230	IPCC 2014
Renewable portion of communal waste	130	700	https://app.electricitymap.org/zone/HU
Water	178	24	IPCC 2014
Wind	610	11	IPCC 2014
Solar	4732	45	IPCC 2014
Geothermal	4	38	IPCC 2014
Other	331	700	https://app.electricitymap.org/zone/HU
Total	35774	-	
Weighted average	-	**226**	

Based on the above 0.226 tCO_2eq/MWh value, also considering the gross/net emissions ratio and network losses, the resulting equivalent emission factor is 0.255 tCO_2eq/MWh.

Conclusions concerning the calculation methods:

Apparently, calculated values may be very different, which is caused by uncertainties in the input parameters and energetics and environmental parameters.

Accordingly, the best way to handle the situation is to use the average of the two calculated values in subsequent calculations. Thus, we will use **0.265 tCO_2eq/MWh as the equivalent emissions factor** for electric energy.

The following two tables show the electric energy consumption values and the related CO_2 emissions at FALCO Zrt.

Table 22 – Annual electric energy consumption and related CO_2 emissions in total, and broken down per product (2020/21; 2021/22; 2022/23; 2023/24)

	Consumption [kWh/year]	Consumption [MJ/year]	Emission factors [kgCO_2eq/kWh]	CO_2 emissions [tons/year] TOTAL	CO_2 emissions [tons/year] PB	CO_2 emissions [tons/year] CBPB	CO_2 emissions [tons/year] MF-PB (lamination only)	CO_2 emissions [tons/year] MG (lamination only)	CO_2 emissions [tons/year] IMP (impregnation only)
Electricity - based on data received (2020/21)	93 376 270	336 154 573	0.326	30 441	23 633	2 006	3 129	843	829
Electricity - based on data received (2021/22)	92 371 342	332 536 831	0.313	28 912	22 390	1 808	3 149	616	949
Electricity - based on data received (2022/23)	85 729 331	308 625 591	0.275	23 576	18 176	1 408	2 649	505	839
Electricity - based on data received (2023/24)	87 162 757	313 785 924	0.265	23 098	17 805	1 422	2 576	512	783

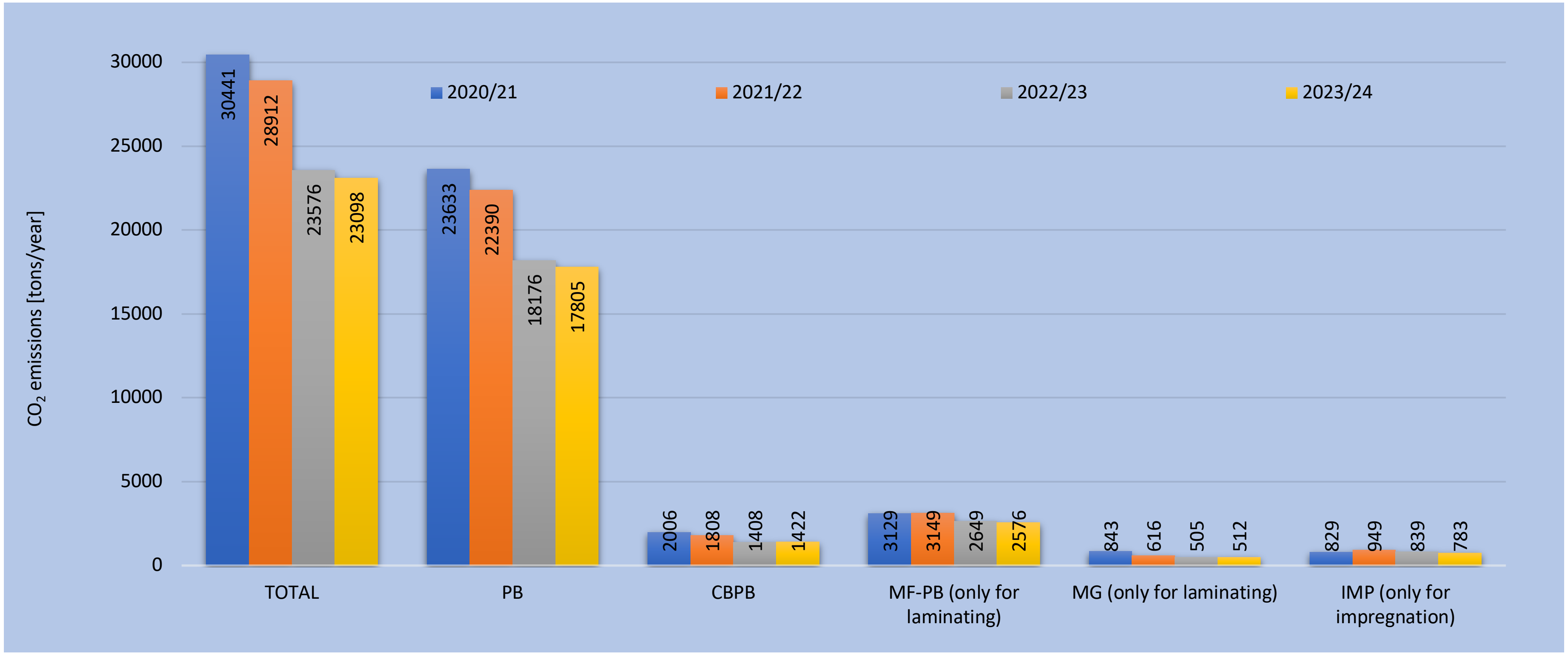

Figure 18. - Annual electric energy consumption and related CO_2 emissions in total, and broken down per product (2020/21; 2021/22; 2022/23; 2023/24)

Table 23 – Unit CO_2 emissions from electric energy consumption related to various products (2020/21; 2021/22; 2022/23; 2023/24)

		Total raw material production PB+CBPB	Production of particle board PB	Production of CBPB CBPB	Laminating of particle board MF-PB	Laminating of particle board MG	Impregnating of paper for MF IMP	Impregnating of paper for MG IMP
		A	B	C	D	E	F	G
2020/21	Produced, processed material [m³]	**450 810**	**421 065**	**29 745**	**189 970**	**22 371**	**26 203 764 [m2]**	**6 647 392 [m2]**
	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	67.52	56.13	67.45	16.47	37.69	3.48	7.50
2021/22	Produced, processed material [m³]	**478 619**	**450 121**	**28 498**	**246 380**	**16 401**	**29 067 504 [m2]**	**6 115 587 [m2]**
	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	60.41	49.74	63.45	12.78	37.55	3.18	10.06
2022/23	Produced, processed material [m³]	**434 905**	**408 239**	**26 666**	**223 209**	**16 549**	**23 102 991 [m2]**	**6 829 341 [m2]**
	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	54.21	44.52	52.79	11.87	30.49	2.90	11.56
2023/24	Produced, processed material [m³]	**415 401**	**387 119**	**28 282**	**221 962**	**14 637**	**28 625 250 [m2]**	**3 574 591 [m2]**
	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	55.60	45.99	50.29	11.60	35.01	3.13	5.94

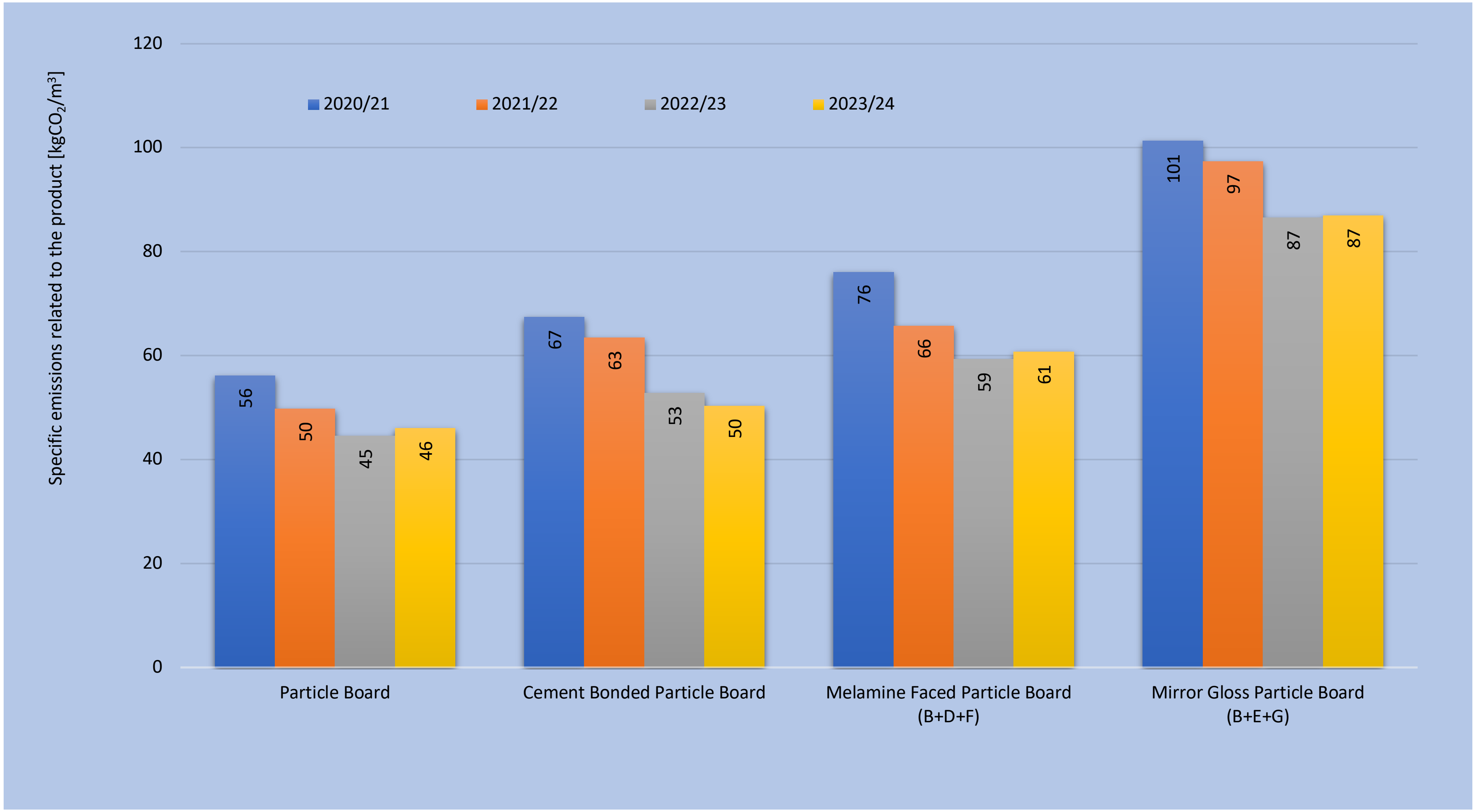

Figure 19. Unit CO_2 emissions from electric energy consumption related to various products (2020/21; 2021/22; 2022/23; 2023/24)[65]

[65] Column A in the table above shows average emissions including all raw panels produced (PB+CPB). It does not reflect any specific product, and is therefore emmitted from this and all subsequent diagrams.

10.4. CO_2 emission related to heat generation

Technological (e.g. drying, pressing) and infrastructural (e.g. heating production halls and offices) heat is generated from natural gas and dendromass-based energy sources. These are turned into thermal energy at the production site.

Significant heat is being produced on site, due to technological requirements. Most of the heat is used for drying wood. The so-called UTWS system includes a mixed-operation natural gas/wood dust combustion chamber with a 90 MW_{th} nominal output. Heat from the hot flue gas is transported to the wood chip dryer drum via a (gas/gas) heat exchanger, and the condensed steam is used for cooling the burners. For fire safety reasons, wood drying occurs in a low-oxygen environment. Since the drying and combustion cycles are separated, flue gas does not get mixed in with the raw material, and the released flue gas is much cleaner than in earlier technologies. Before releasing, the separately handled flue gas passes through a dry elektrofilter for maximum purity. On ignition, the UTWS burns gas only. Wood dust burning starts later, because sustaining the burn requires a high temperature chamber.

The second most important heat generator on site is a bark combustion Wiesloch boiler with a 15 MW_{th} nominal output. The system provides heat for the thermal oil required for the technology. Two more gas boilers, a NESS 6000 6.4 MW_{th} and a 5 MW_{th} IVAR5000 furnace, also contribute to thermal oil heating. The thermal oil system runs all the way across the ContiRoll press, high temperature heat treatment hall, CB particleboard production, Mirrorglass production facilities and impregnation plants, and, in some cases, also provides communal heat via a heat exchanger. Further heat generators on site include much lower capacity machines, e.g. Hoval furnaces for postforming, chemicals lab and central administration buildings. Furthermore, there are several Omega infra radiators (e.g. impregnation plant, storage building) as well as some smaller wall furnaces e.g. a 18 kW one in the storage building. The wide range of heat generators use various heat sources including natural gas, wood dust and bark[66, 67].
The following general formula was used for the determination of CO_2 emissions from heating:

$$CO_2 \text{ emission } [tCO_2] = \text{activity input}^{68} \cdot \text{emission factor} \cdot \text{oxidation factor}$$

The country-specific fuel oxidation factor was taken as 1 according to current regulations[69].
Activity input is usually interpreted as energy input, to be calculated by the following formula:

$$\text{Energy content [TJ]} = \text{fuel quantity [t or m}^3\text{]} \cdot \text{net calorific value of the fuel [TJ/t or TJ/m}^3\text{]}$$

[66] Description source: Get-Energy Magyarország Kft. 2019 január; Complex energy production audit of FALCO Zrt. 9700 Szombathely, Zanati út 26. 9700 Puskás Tivadar utca 12., 2641 Tárnok, Állomás utca 2. telephelyek komplex energiahatékonysági auditja
[67] FALCO Zrt.’s energy flow schematic: FS-2021-07-0801-FS_FALCO hőenergia termelő séma-MÓD.pdf
[68] activity input: the amount of fuel used for heat generation expressed as energy content (TJ), as well as the amount of raw materials, additives and products used (e.g. ton of wood/year)
[69] Government regulation nr. 410/2012 (XII. 28) concerning some application rules of the CCXVII. law of 2012 about the participation in the community greenhouse gas trade system an the exexution of the effort-sharing

10.4.1. Natural gas consumption

Natural gas usage is more straightforward, because, being a fossil fuel, it is not considered CO_2 neutral.

The determination of the emission factor is similar, but less ambiguous than in the case of electricity. Natural gas is not a secondary energy source, where the related energy data are more or less constant and independent of geographical regions.

The EU Commission Regulation Nr. 601/2012 allows using country-specific calorific values and emission factors. The table below is based on Appendix 5. of the national government regulation nr. 410/2012. (XII. 28.), as well as Table 1 in Appendix 1. of the EU Commission Regulation Nr. 601/2012.

Table 24 – Calorific values and emission factors for some fuels[69]

Fuel	Calorific value	Emission factor tCO₂/TJ
Firewood and wood waste	15.6 MJ/kg [a]	110-120 [b]
		0 [c]
Heating oil	42.0 MJ/kg	74.1
Petrol	44.3 MJ/kg [a]	69.3 [a]
Diesel	43.0 MJ/kg [a]	74.1 [a]
Natural gas at 15 °C, 1013,25 hPa	34.0 MJ/m³	56.1
Natural gas at 0 °C, 1013,25 hPa	35.87 MJ/m³	
LPG	47.3 MJ/kg [a]	63.1 [a]

[a]Based on EU Commission Regulation Nr. 601/2012[52]

[b] Based on literature data and stochiometric equations, if biomass is not considered carbon neutral

[c] Clean biomass fuels should be considered with an emission factor of zero (carbon-neutral)

<u>For FALCO Zrt., the weighted average of natural gas's emission factors (calculated based on the energetics parameters of the retailer): 56.27 tCO_2/TJ.</u>

10.4.2. Dendromass utilisation

Dendromass – which is a part of fitomass – is an energy source of biological origin. It encompasses all of the lignified organic material found in the forest, i.e. all of the stock including above- and belowground material. However, traditionally, when talking about the energetics utilisation of dendromass, obviously we mean aboveground stock, since the extraction and utilisation of belowground dendromass (stump and roots) is not practical.

A commonly held opinion is that the CO_2 generated during the preparation and energetics utilisation of wood does not impose extra CO_2 emission on the environment – especially when compared to fossil energy sources – since using wood for heat generation (through direct combustion or gasification) is "CO_2 neutral". This assumption is contested even among scientists. Even when used simply as firewood, we need to consider the carbon-dioxide balance for the whole life cycle.

Even the creation (or, in the case of bi-products, generation) of dendromass-based energy sources requires a certain amount of energy. The amount of energy required obviously depends on the type of extraction, preparation and transportation processes used.

Based on the above, all of these processes lead to CO_2 emissions locally. Thus, total CO_2 neutrality cannot be achieved, not even with dendromass-based energy sources. More accurately, wood may be considered nearly CO_2 neutral when used for energy creation. It is certainly more environment friendly than are fossil or fissile energy sources.

Renewable energy sources – including bio- and dendromass – undeniably contribute to decreasing greenhouse gas emissions. It is important to remember that CO_2 is not the only greenhouse gas in this case either, since methane (CH_4), nitrogen-oxides (NOx), and halogenated carbohydrates also play important roles. The latter (hydrofluorocarbons - HFC; perfluorocarbon - PFC; chlorofluorocarbon - CFC) constitute a group of greenhouse gases that do not occur naturally. Compared to the ubiquitous carbon dioxide, they are present in miniscule quantities, but their greenhouse potential may be thousands, or even tens of thousands times bigger.

Calculations of the carbon dioxide generated during wood combustion are usually based on carbon content. According to various studies, wood's carbon content falls between 46 and 55% (Ragland, Aerts 1991, Birdsey 1992; Francis 2000, Gifford 2000; Sampson 2002; Lamlom, Savidge 2003, Telmo et al. 2010). Gymnosperms have a somewhat higher carbon content above 50%, while angiosperms are usually below 50% (e.g. Barson 1989, Dias et al. 2005, Hassan et al 2005, IPCC 2014).. There are very small differences in the quantities of the main constituents among species, thus literature sources generally quote a composition of 50% carbon, 43% oxygen and 6% water. Thus, in broad terms, the carbon content of wood may be considered 50 % on average.

Wood generates and maintains a natural carbon-dioxide cycle in the atmosphere. Excluding externalities, wood can be said to release the same amount of CO_2 into the atmosphere during its degradation or combustion, as it had sequestered throughout its decades of growth.

Photosynthesis occurs according to the following formula. The energy for the transformation is provided by solar radiation.

$$6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

An approximate generalised model[70] for the whole tree is given, as follows[71]:

$$8.4\ CO_2 + 12\ H_2O + 3.8542\ MJ \rightarrow C_{8.4}H_{12}O_{5.4} + 8.7O_2 + 6\ H_2O$$

When describing the process in terms of mass balance, the creation of 1000 kg of wood is described, as follows:

$$1\,851\ kg\ CO_2 + 1\,082\ kg\ H_2O + 19\,271\ MJ\ solar\ energy \rightarrow$$
$$1\,000\ kg\ wood + 1\,392\ kg\ O_2 + 541\ kg\ H_2O$$

[70] The complete chemical equation of Photosynthesis with specific values for wood

[71] Zimmer, B., & Wegener, G. (1996). Stoff-und Energieflüsse vom Forst zum Sägewerk. *European Journal of Wood and Wood Products, 54*(4), 217–223. https://doi.org/10.1007/s001070050171

Table 25 – The material and energy balance of wood.

	Input	Output
Energy (MJ)	19 271	-
CO_2 (kg)	1 851	-
H_2O (kg)	1 082	541
O_2 (kg)	-	1 392
Wood (kg)	-	1 000

During combustion, wood emits CO_2, the same way as fossil fuels do, but in the case of trees, the carbon cycle is much shorter (50-100 years or shorter), while fossil fuels take millions of years to regenerate. However, the carbon uptake of trees can still not keep up with the rate of carbon dioxide emissions caused by biomass energy production. All in all, energy production by wood combustion is not completely CO_2 neutral, but most of the carbon emissions are counteracted by the CO_2 sequestration capabilities of trees, if the forest stock increment is equal or greater than the wood used for energy generation and industrial purposes.

Based on EU guidelines[52], the emission factor of biomass is zero[72]. The above discussion shows that in reality, the situation is more complex. Net CO_2 emission – different from the traditional approach in that CO_2 sequestered during photosynthesis is subtracted from the carbon dioxide emitted during combustion and other related processes – is a more realistic parameter to use.

Many international studies have been published concerning wood combustion and (net) CO_2 emission, with very different results. Reliable data is mostly available for electric energy generation. Because of the similarities in the applied machinery, these results may be adapted for heat generation as well, taking the differences in efficiency into account. Based on our own research and earlier studies[73], generating electricity requires 2.4 times more energy, and thus, that much more fuel, compared to producing heat. Accordingly, the emissions below can be analysed and converted to apply to heat generation:

1. The Environmental Protection Agency[74] found that biomass power plant carbon dioxide emissions are generally – but not always – lower than those of CCGT (combined-cycle gas turbine) plants, which are considered the lowest-emission fossil fuel power plants. E.g., the estimated carbon footprint of electricity generation from short-rotation energy plantation wood chips is 60–270 gCO_2eq / kWh[75], which is definitely lower than CCGTs' value of 365 gCO_2eq / kWh.

[72] when using wood from sustainably managed forests with the appropriate certification (FSC, PEFC)

[73] assuming an average efficiency factor of 35% and 85% for electric energy and heat generation, respectively.

[74] Mortimer ND. 2010. Comparison of Greenhouse Gas Benefits Resulting from Use of Vegetable Oils for Electricity. Heat. Transport and Industrial Purposes.

[75] **Bates, J., Edberg, O., & Nuttal, C. (2009).** Minimising greenhouse gas emissions from biomass energy generation. *Science Report EA/BR/E/SCI/V1*. Environment Agency, Bristol, UK.

2. In an earlier study [76] two alternatives of direct combustion for electric power generation – gasification and pyrolysis – were shown to have lower carbon footprint. In case of electric energy production from the gasification of wood coming from forest residues or short-rotation plantations, the carbon footprint amounted to 25 gCO_2eq / kWh. [77]
3. 2013 Canadian data [78] is available for heat generation directly. In this source, 110 $kgCO_2eq$/ton of biomass, i.e. 0.03 $kgCO_2eq$/kWh net emissions are quoted when generating heat from biomass.
4. The British government uses data in the following table when calculating emissions for electric energy generation:

Table 26 – CO_2 emissions for biomass-based electric energy production in the UK (DEFRA[79] data)[80]

Fuel	Unit	kg CO_2eq
Wood logs	tonnes	61.523
	kWh	0.015
Wood chips	tonnes	56.881
	kWh	0.015
Wood pellets	tonnes	70.473
	kWh	0.015

By converting the above data, using a conversion factor of 2.4 (as FALCO Co. provided) for heat generation, as discussed above, the values typically range from 1.7 to 8 tCO_2eq/TJ, apart from one outlier. There is apparently much variation in the literature values.

Based on our earlier research concerning the EROEI (Energy Returned On Energy Invested) values of wood-based energy materials in Hungary[81], the realistic value for the net emissions is approx. 2 to 4 tCO_2eq/TJ (in case of cleft or chopped firewood from forests or plantations). Since both the literature data and our own research seems to support this vale, **a net emission value of 4 tCO_2eq/TJ is proposed for wood-based energy production** to be used in Hungary.

In our calculations, the composition of the different materials, and their calorific parameters are important, since all of these combined affect the amount of energy produced.

[76] Elsayed, M. A., Matthews, R., & Mortimer, N. D. (2003). *Carbon and energy balances for a range of biofuels options.* Report, Project No. BB6/00784/REP. Resources Research Unit, Sheffield Hallam University.
[77] Houses of Parliament; Parliamentary Office of Science&Technology: Carbon Footprint of Electricity Generation; Number 383 June 2011
[78] https://www.winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/Appendix%207.pdf
[79] Department for Environment Food & Rural Affairs: UK Government GHG Conversion Factors for Company Reporting (2018) (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting#conversion-factors-2018)
[80] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018
[81] Németh, G. (2014) Decentralizált dendromassza alapú kiserőművek, falufűtőművek elterjedését támogató kutatások (Study to support the propagation of decentralised dendromass-based auxillary and village power plants.) Project report

Table 27. Example: Calorific parameters of various fuel materials (2016/17)[82]

	Unit	Dust extracted from the board lamination lines and MG	Wood dust from chipboard manufacturing	Raw chipboard sanding dust	Sanding / manufacturing dust mixture
Upper Calorific Value	MJ/kg	15.1	17.9	17.6	15.0
Lower Calorific Value	MJ/kg	13.6	16	16	13.4
Density	kg/m^3	340	260	320	320
Moisture content	m/m%	2.83	15.16	4.93	5.46
Ash content	m/m%	4.97	2.05	2.13	4.75
Biomass content	%	96.49	94.36	96.52	93.86

Direct CO_2 emissions related to heat generation were calculated using three different methods. In one (Scenario I.), according to EU directives and Hungarian regulations, an emission factor of 0 was used for the emissions of biomass heat generation. In the second case (Scenario II.), the net CO_2 (4 tCO_2/TJ) emission factor calculated above was used, In the 2016/17 study, for third case, we considered 109.63 [tCO_2/TJ] as base value according to the contemporary principles laid out in the OKTF-KP/12243-1/2016. document.

In the 2023/24 financial year, we used the new energy flow scheme and the accredited measurement data available for FALCO Zrt.

[82] **Wessling Hungary Ltd. (2018).** Measurements conducted by the accredited testing laboratory. *Reports No. 503145/1 and 497350/1* (October and November 2018).

Table 28. Heating values and CO_2 emission factors for various fuels (2020/21; 2021/22; 2022/23; 2023/24)[83]

		Unit	Dust extraction from PB production and sanding	FS-AH-2 recycling cleaning system's wastes	Biomass (bark, waste wood) firing	Weighted average
2020/21	Heating value (weighted average)	MJ/kg	17.27	14.97	15.60	16.54
	Specific CO_2-emission factor of SRF2	tCO_2/TJ	92.94	92.44	109.63	**98.93**
2021/22	Heating value (weighted average)	MJ/kg	18.03	12.70	15.60	17.07
	Specific CO_2-emission factor of SRF2	tCO_2/TJ	90.28	91.63	109.63	**97.10**
2022/23	Heating value (weighted average)	MJ/kg	17.09	10.88	15.60	16.50
	Specific CO_2-emission factor of SRF2	tCO_2/TJ	96.24	75.3	109.63	**101.40**
2023/24	Heating value (weighted average)	MJ/kg	16.89	--	15.60	16.40
	Specific CO_2-emission factor of SRF2	tCO_2/TJ	95.33	--	109.63	**100.77**

[83] Based on data provided by FALCO Zrt: MO01 & FS01-CO2 summary report-2020_21/2021_22/2022_23/203_24-Final.xlsx;

Table 29 – Annual heat generation and related CO_2 emissions in total and broken down to products (2020/21; 2021/22; 2022/23; 2023/24)

	Energy source	Consumption [m³/a]	Consumption [t/a]	Heating value [MJ/Nm³] (Based on FALCO of data)	Heating value [MJ/kg] (Based on FALCO of data; calculated and weighted)	Energy produced [MJ/a]	Emission factors [tCO_2/TJ]	CO_2 emissions [t/a] TOTAL	CO_2 emissions [t/a] PB	CO_2 emissions [t/a] CBPB	CO_2 emissions [t/a] MF-PB (for laminating only)	CO_2 emissions [t/a] MG (for laminating only)	CO_2 emissions [t/a] IMP (for impregnation only)
2020/21	Natural gas	**3 191 468**	-	**34.84**	-	111 191 760	55.62	6 185	2 570	1 119	609	885	1 002
	Biomass Scenario I.	-	**51 047**	-		844 143 425	0.0	0	0	0	0	0	0
	Biomass Scenario II	-	**51 047**	-	**weighted average: 16.54**	844 143 425	4.0	3 377	1 138	676	400	574	589
	Biomass Scenario III.	-	**51 047**	-		**844 143 425**	**weighted average: 98.93**	83 747	28 218	16 762	9 915	14 231	14 621
2021/22	Natural gas	**2 997 386**	**-**	**34.92**	-	104 672 376	55.77	5 837	2 209	1 029	623	848	1 128
	Biomass Scenario I.	**-**	**53 664**	**-**		915 989 190	0.0	0	0	0	0	0	0
	Biomass Scenario II	**-**	**53 664**	**-**	**weighted average: 17.07**	915 989 190	4.0	3 664	1 152	691	431	597	792
	Biomass Scenario III.	**-**	**53 664**	**-**		**915 989 190**	**weighted average: 97.103**	88 945	27 978	16 775	10 469	14 495	19 229
2022/23	Natural gas	**2 931 765**	**-**	**35.50**	-	104 672 376	55.77	5 837	2 209	1 029	623	848	1 128
	Biomass Scenario I.	-	**48 827**	-		805 645 335	0.0	0	0	0	0	0	0
	Biomass Scenario II	**-**	**48 827**	**-**	**weighted average: 16.50**	805 645 335	4.0	3 223	946	629	410	554	684
	Biomass Scenario III.	-	**48 827**	-		805 645 335	**weighted average: 101.4**	81 683	23 973	15 9400	10 382	14 054	17 333
2023/24	Natural gas	**2 885 097**	-	**35.50**	-	101 935 181	56.27	5 736	2 311	974	572	819	1 060
	Biomass Scenario I.	-	**47 947**	-		786 325 716	0.0	0	0	0	0	0	0
	Biomass Scenario II	-	**47 947**	-	**weighted average: 16.40**	786 325 716	4.0	3 145	933	638	369	528	677
	Biomass Scenario III.	-	**47 947**	-		786 325 716	**weighted average: 100.77**	79 238	23 516	16 063	9 306	13 298	17 055

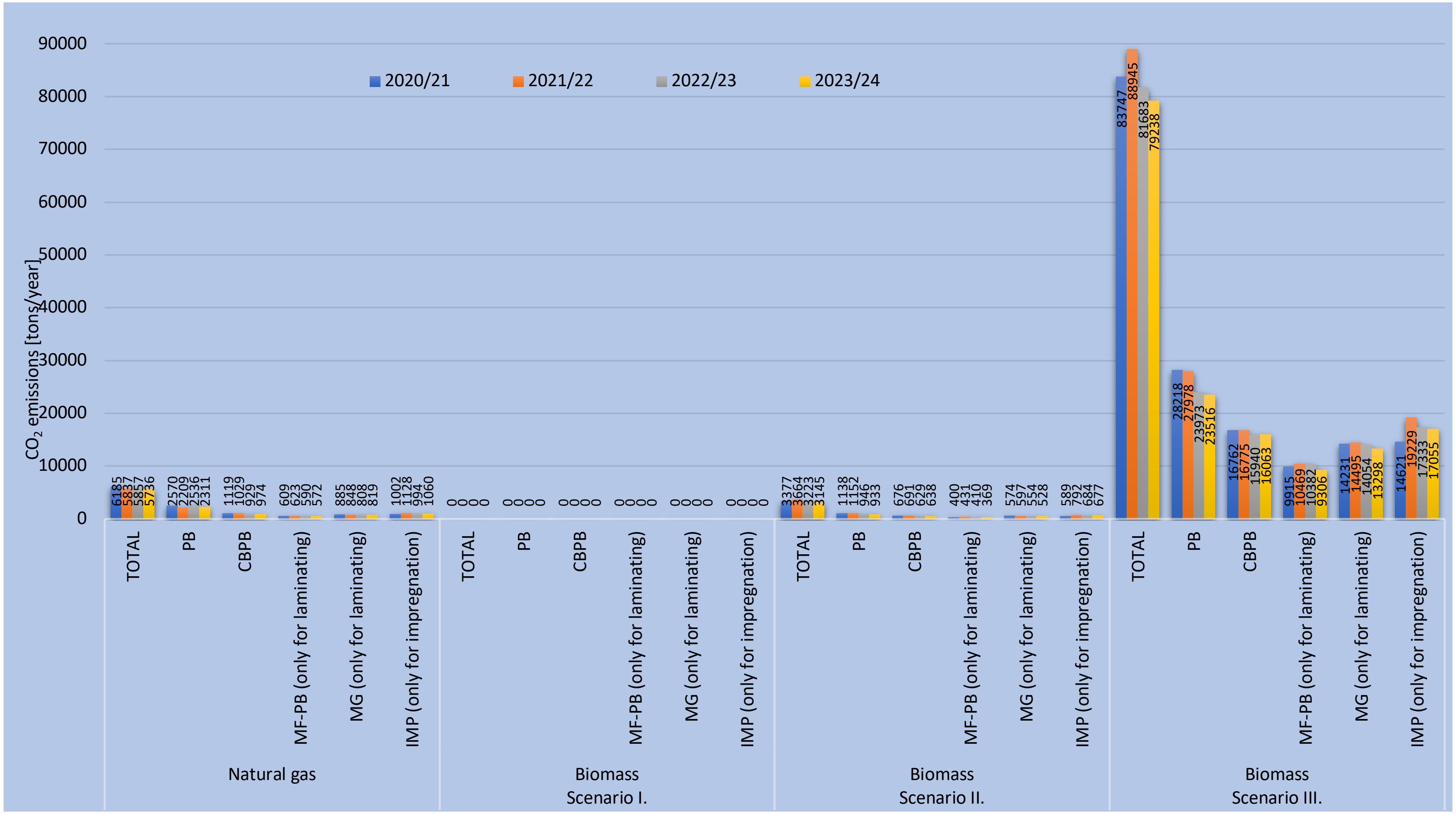

Figure 20. Annual heat generation and related CO_2 emissions in total and broken down to products (2020/21; 2021/22; 2022/23; 2023/24)[84]

[84] Scenario I.: emission factor of 0, according to EU directives and Hungarian regulations. Scenario II: net CO_2 emission factor of 4 tCO_2eq/TJ, Scenario III.: emission factor of 109.63 tCO_2/TJ (2016/17); 98,93 tCO_2/TJ (2020/21);

Table 30 – Unit heat-related CO_2 emissions overall and broken down to product (2020/21; 2021/22; 2022/23; 2023/24)

			Total raw material production PB+CBPB	**Production of particle board PB**	**Production of CBPB CBPB**	**Particleboard lamination MF-PB**	**Particleboard lamination MG**	**Paper impregnation for MF IMP**	**Paper impregnation for MG IMP**
			A	B	C	D	E	F	G
2020/21	Produced, processed material [m³]		450 810	**421 065**	**29 745**	**189 970**	**22 371**	**26 203 764 [m²] production**	**6 647 392 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [kgCO$_2$/m³]	13.72	6.10	37.60	3.20	39.58	4.21	9.06
	Scenario II.		21.21	8.81	60.32	5.31	65.23	6.68	14.39
	Scenario III.		199.49	73.12	601.13	55.40	675.74	65.60	141.31
2021/22	Produced, processed material [m³]		**478 619**	**450 121**	**28 498**	**246 380**	**16 401**	**29 067 504 [m²] production**	**6 115 587 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [kgCO$_2$/m³]	12.20	4.91	36.12	2.53	51.72	3.78	11.95
	Scenario II.		19.85	7.47	60.36	4.28	88.13	6.44	20.35
	Scenario III.		198.03	67.06	624.76	45.02	935.49	68.26	215.75
2022/23	Produced, processed material [m³]		**434 905**	**408 239**	**26 666**	**223 209**	**16 549**	**23 102 991 [m²] production**	**6 829 341 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [kgCO$_2$/m³]	13.47	6.21	34.83	2.64	48.81	3.44	13.70
	Scenario II.		20.88	8.53	58.41	4.48	82.32	5.80	23.13
	Scenario III.		201.28	64.94	632.60	49.16	898.04	63.37	252.67
2023/24	Produced, processed material [m³]		**415 401**	**387 119**	**28 282**	**221 962**	**14 637**	**28 625 250 [m²] production**	**3 574 591 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [kgCO$_2$/m³]	13.81	5.97	34.45	2.58	55.98	4.25	8.04
	Scenario II.		21.38	8.38	57.00	4.24	92.04	6.96	13.17
	Scenario III.		204.56	66.72	602.39	44.50	964.49	72.55	137.39

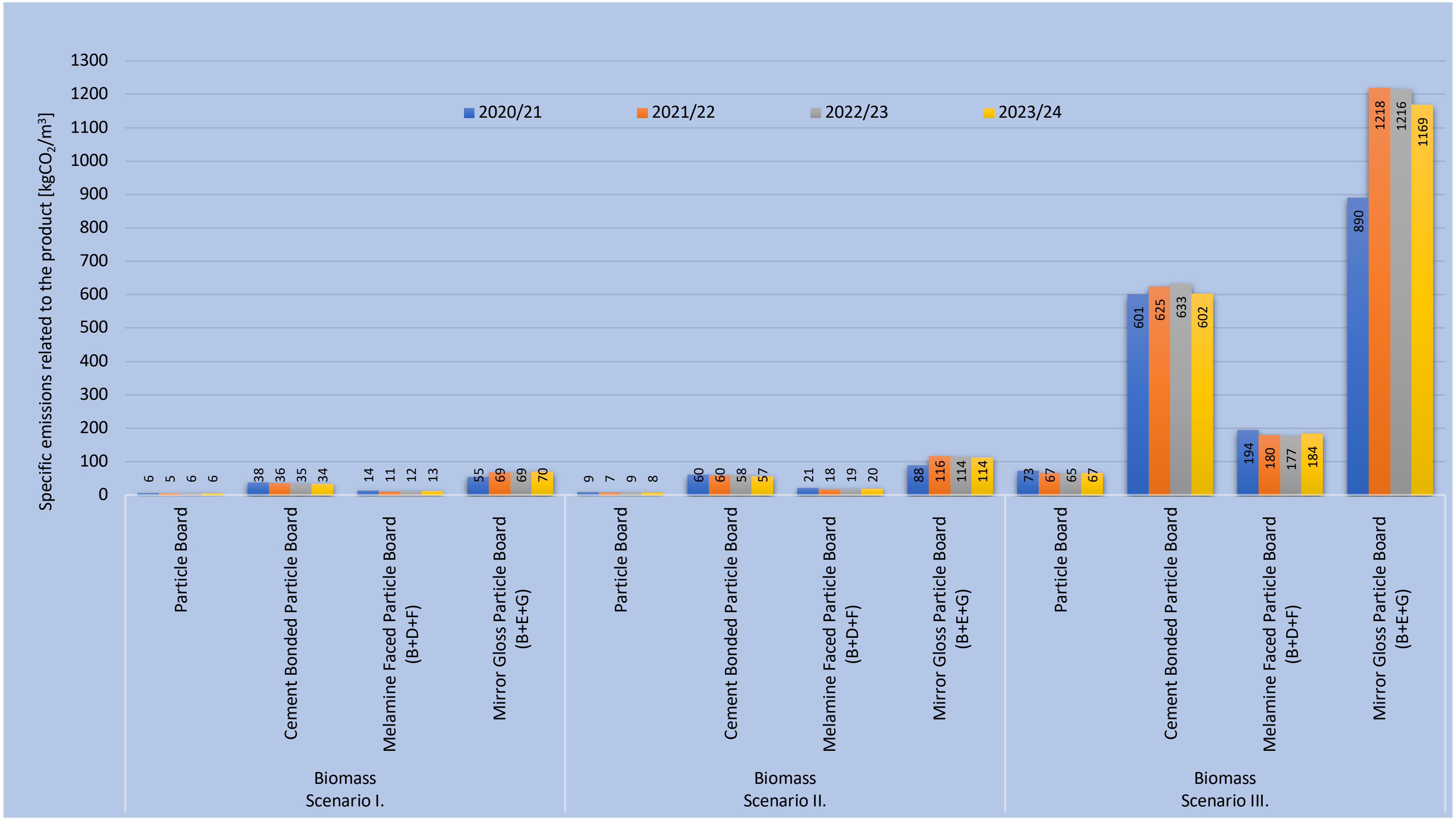

Figure 21. Unit heat-related CO_2 emissions overall and broken down to product (2020/21; 2021/22; 2022/23; 2023/24)[85]

[85] For MF-PB, the values in columns B, D and F were added up, since its manufacturing involves particleboard production, face layer impregnation and lamination. MG-PB manufacturing's emissions are calculated similarly, by adding up columns B, E and G.

According to the tables, depending on how we account for the biomass-related CO_2 emissions, there could be a fivefold difference between the calculated emission values. In our opinion, the most realistic method is using net carbon-dioxide emission factor based on our calculations. Thus, we recommend using scenario II.

10.5. CO_2 emissions originating from internal logistics and transportation

Compared to heat generation, electric energy consumption related to internal logistics is negligible. It is not possible to break this down to products. Thus, unit costs were calculated as an overall average for the whole plant, as shown in the table below:

Table 31 – The amount of energy used for internal logistics and transportation, and the related total and unit CO_2 emissions (2020/21; 2021/22; 2022/23; 2023/24)

		Consumption [l/a]	Consumption [kg/a]	Density [kg/m³]	Energy content (Heating value) [MJ/kg]	Consumption [MJ/a]	Emission factors [tCO₂/TJ]	CO₂ emissions [tons/a] TOTAL	Average unit emissions [kgCO₂/ product m³]
2020/21	Diesel	382 239	321 081	840	43	13 806 473	74.1	1 023	2.27
	PB GaS 11 kg	9 465	23	2.43	47.30	1 088	63.1	0	0.0002
	Total trans-portation					13 807 561		1 023	2.30
2021/22	Diesel	504 969	424 174	840	43	18 239 480	74.1	1 352	2.82
	PB GaS 11 kg	0	0	2.43	47.30	0	63.1	0	0
	Total trans-portation					18 239 480		1 252	2.80
2022/23	Diesel	388 230	326 113	840	43	14 022 868	74.1	1 039	2.39
	PB GaS 11 kg	0	0	2.43	47.30	0	63.1	0	0
	Total trans-portation					14 022 868		1 039	2.39
2023/24	Diesel	380 747	319 827	840	43	13 752 582	74.1	1 019	2.45
	PB GaS 11 kg	0	0	2.43	47.30	0	63.1	0	0
	Total trans-portation					13 752 582		1 019	2.45

10.6. Total on site CO_2 emissions from using primary and secondary energy sources

Based on the analyses and calculations in chapter 10, overall energy-related unit CO_2 emissions may be determined for each of the products manufactured by FALCO. Of the three scenarios presented in the following table, nr. 2 is most realistic. Thus, in the final calculation (**Table 32**, **Figure 22**), these results are used. These energy values are on the positive side of the carbon balance calculations.

Table 32 – Overall unit CO_2 emissions originating from using various energy sources (2020/21; 2021/22; 2022/23; 2023/24)

			Total raw material production PB+CBPB	**Production of particle board PB**	**Production of CBPB**	**Particleboard lamination MF-PB**	**Particleboard lamination MG**	**Paper impregnation for MF IMP**	**Paper impregnation for MG IMP**
			A	**B**	**C**	**D**	**E**	**F**	**G**
2020/21	Produced, processed material [m³]		450 810	**421 065**	**29 745**	**189 970**	**22 371**	**26 203 764 [m²] production**	**6 647 392 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	83.51	64.50	107.32	19.67	77.27	7.69	16.56
	Scenario II.		88.73	67.20	130.04	21.78	102.92	10.16	21.89
	Scenario III.		267.01	131.52	670.84	71.87	713.43	69.08	148.81
2021/22	Produced, processed material [m³]		478 619	**450 121**	**28 498**	**246 380**	**16 401**	**29 067 504 [m²] production**	**6 115 587 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	75.43	57.47	102.38	15.31	89.27	6.96	22.01
	Scenario II.		80.26	60.04	126.63	17.06	125.68	9.62	30.40
	Scenario III.		258.44	119.63	691.03	57.80	973.03	71.44	225.80
2022/23	Produced, processed material [m³]		434 905	**408 239**	**26 666**	**223 209**	**16 549**	**23 102 991 [m²] production**	**6 829 341 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	70,06	53,12	90,01	14,51	79,30	6,34	25,27
	Scenario II.		75,09	55,44	113,60	16,34	112,80	8,70	34,70
	Scenario III.		255,49	111,85	687,79	61,02	928,53	66,27	264,23
2023/24	Produced, processed material [m³]		415 401	**387 119**	**28 282**	**221 962**	**14 637**	**28 625 250 [m²] production**	**3 574 591 [m²] production**
	Scenario I.	Specific emissions related to produced or processed materials [$kgCO_2/m^3$]	71.87	54.42	87.20	14.18	90.98	7.38	13.97
	Scenario II.		76.99	56.83	109.74	15.84	127.04	10.09	19.11
	Scenario III.		260.16	115.16	655.14	56.11	999.50	75.69	143.33

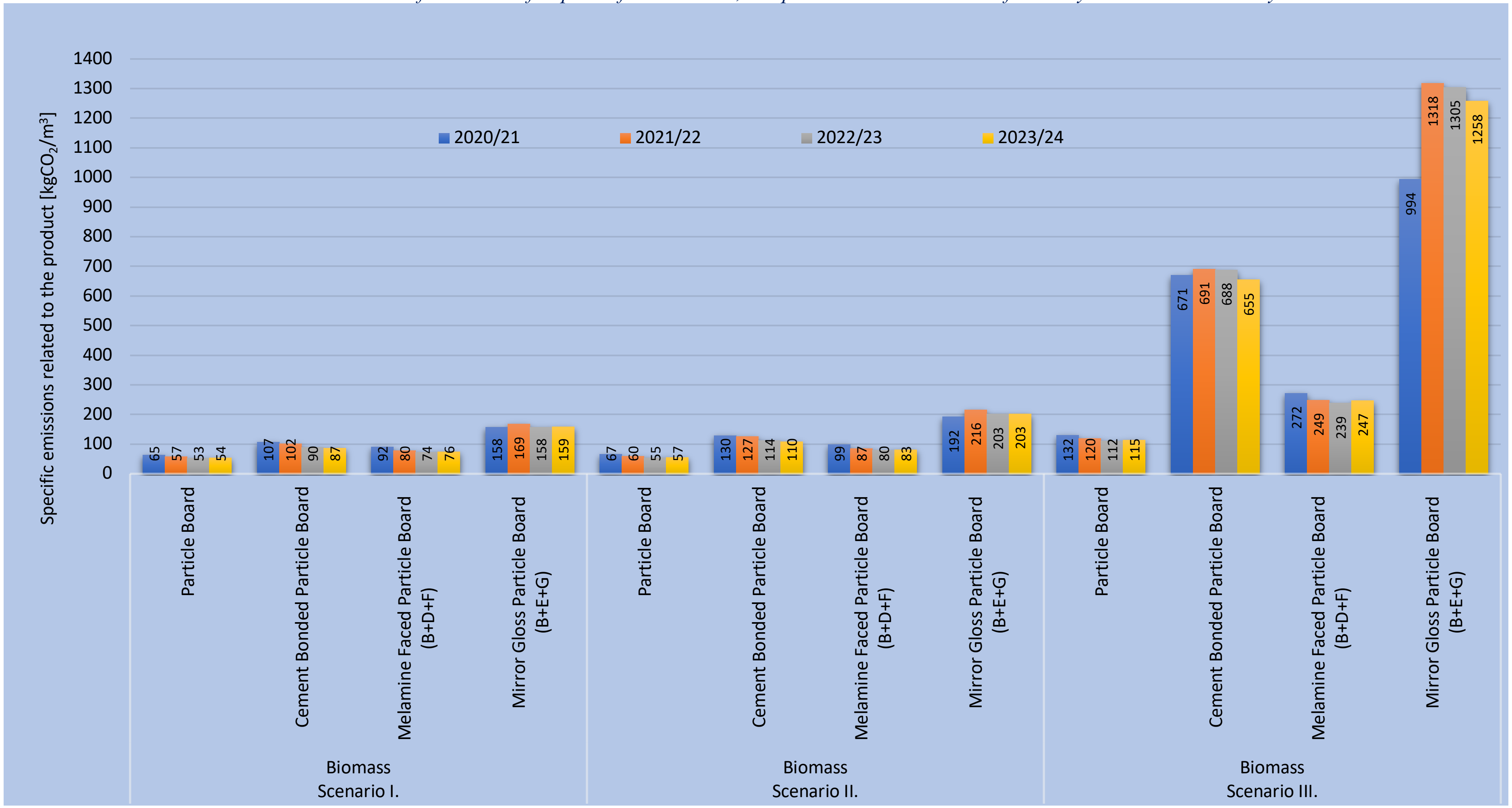

Figure 22. Overall unit CO_2 emissions originating from using various energy sources (2020/21; 2021/22; 2022/23; 2023/24)[86]

[86] For information about the three scenarios and calculating the unit CO_2 emissions of MF-PB and MG-PB, see footnotes nr. [84] and [85], respectively.

Compared to the financial years 2020/21–2022/23, which serve as the basis for comparison, there are minor changes in the year 2023/2024.

- Regarding the energy system, the following modernizations have been implemented:
    - Transformation of the technological cooling system to a modern cooling system equipped with free cooling functionality (Tochio and VITS impregnation machines).
    - Installation of a heat transfer fluid (thermal oil) regeneration station to reduce natural gas consumption in the thermal oil network.
- Emission values showed a 2-5% increase or decrease across individual product types (PB; CB; MF-PB).

  Overall, no significant changes can be observed.(PB; CB; MF-PB):
    - The minimal increase in electricity consumption was offset by the decrease in CO_2eq values.
    - The slight decline in heat usage had only a minimal impact on the specific emission values, as production volumes in particleboard manufacturing simultaneously dropped by approximately 7%.
- For impregnated papers used in MG and MF particle boards, we adjusted the 2024 data and ratios based on new data and information (production distribution, residues, purchases, sales). As a result, in Scenario III, a significant ~4% decrease was observed for MG boards, while a 2-3% increase was noted for MF boards.

11. The overall carbon footprint of panel board production

In chapters 5 through 10, the carbon footprint of the raw materials and the on-site energy consumption in the production of various particleboard products was calculated, respectively, to a high level of accuracy. These results are combined in this chapter, to calculate the overall carbon footprint of the products manufactured at FALCO Zrt in 2023/2024. **Table 33** below is based on the overall raw material carbon footprint results presented in **Table 18**, and the overall emission values related to energy consumption in **Figure 22** (Scenario II).

Table 33 – Total net annual and unit carbon footprint of FALCO Zrt's production (2023/24)

	Unit emissions (tCO_2eq / m^3)			Production m^3/a	Net annual emissions (tCO_2eq / a)		
	Raw material production[a]	On-site energy consumption[b]	Total		Raw material production[a]	On-site energy consumption[b]	Total
Raw PB	-1.149	0.057	**-1.092**	150 520	-172 920	8 579	**-164 341**
CB PB	0.155	0.109	**0.264**	28 282	4 711	3 082	**7 793**
MF	-1.115	0.016	**-1.099**	221 962	-247 320	3 551	**-243 769**
MG	-1.114	0.127	**-0.987**	14 637	-16 305	1 858	**-14 447**
Production, total					-432 191	17 070	-415 120

[a]Based on **Table 18**; [b]Based on **Figure 22**, Scenario II.

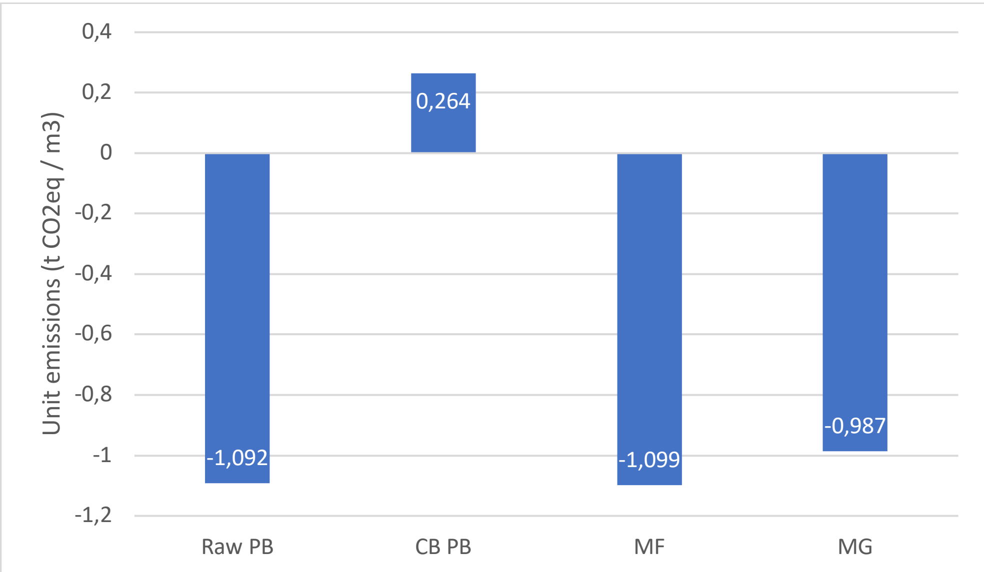

Figure 23 – Total net Unit carbon footprint of FALCO Zrt.'s products in 2023/24

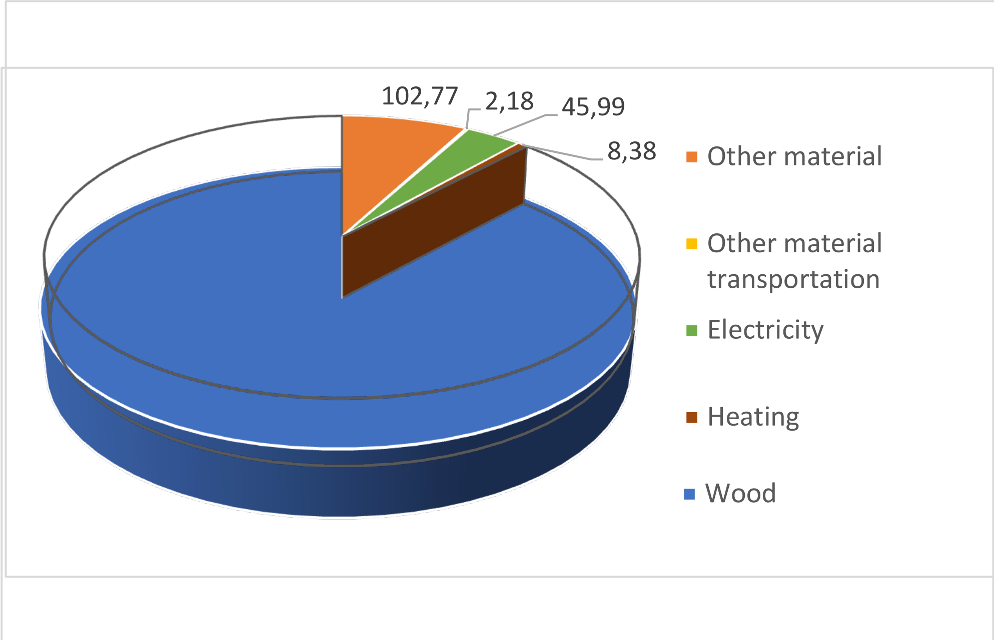

Figure 24 – The different components of the net emission calculations of raw particleboard (kgCO_2eq / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the top chart corresponds to the negative carbon footprint of raw PB.

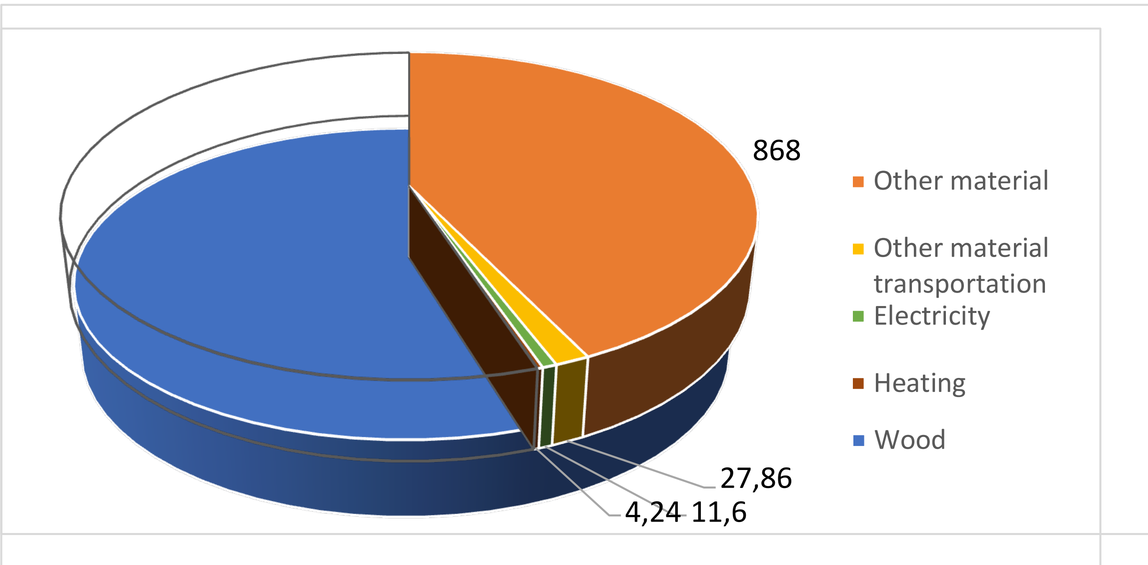

Figure 25 – The different components of the net emission calculations of melamine faced particleboard (kgCO_2eq / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the top chart corresponds to the negative carbon footprint of MF PB.

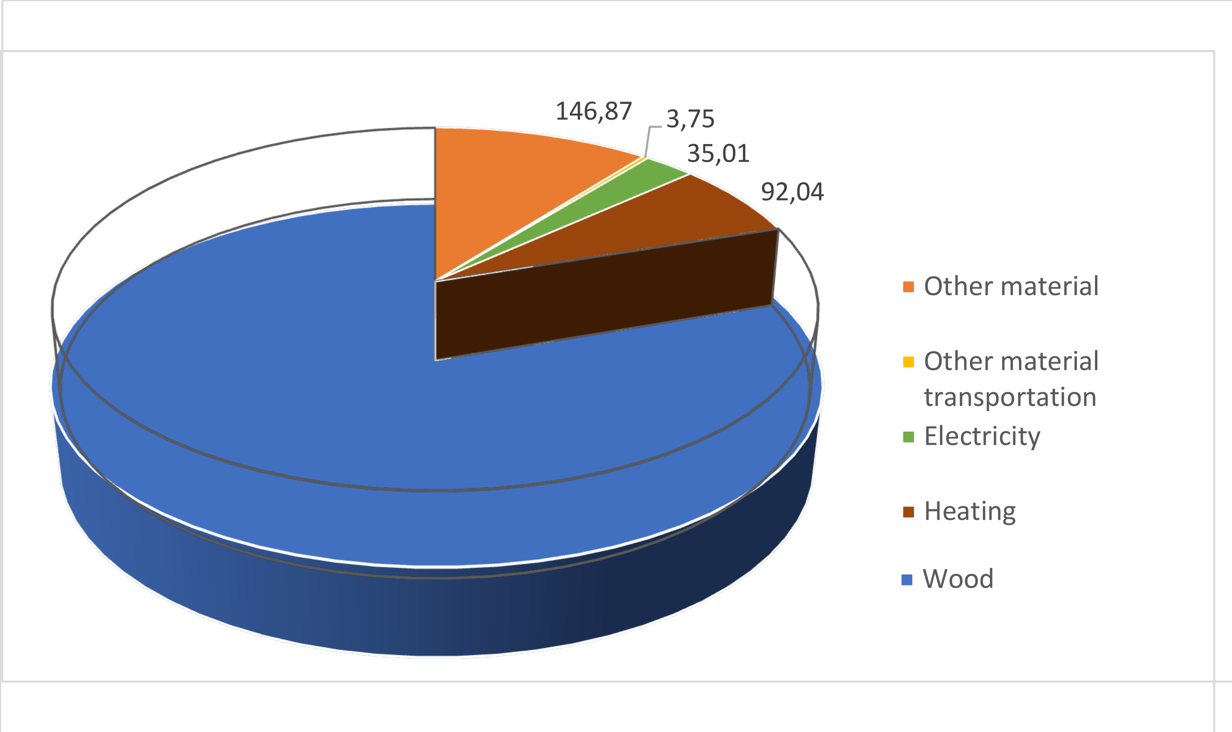

Figure 26 – The different components of the net emission calculations of mirror gloss particleboard ($kgCO_2eq$ / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the top chart corresponds to the negative carbon footprint of MG PB.

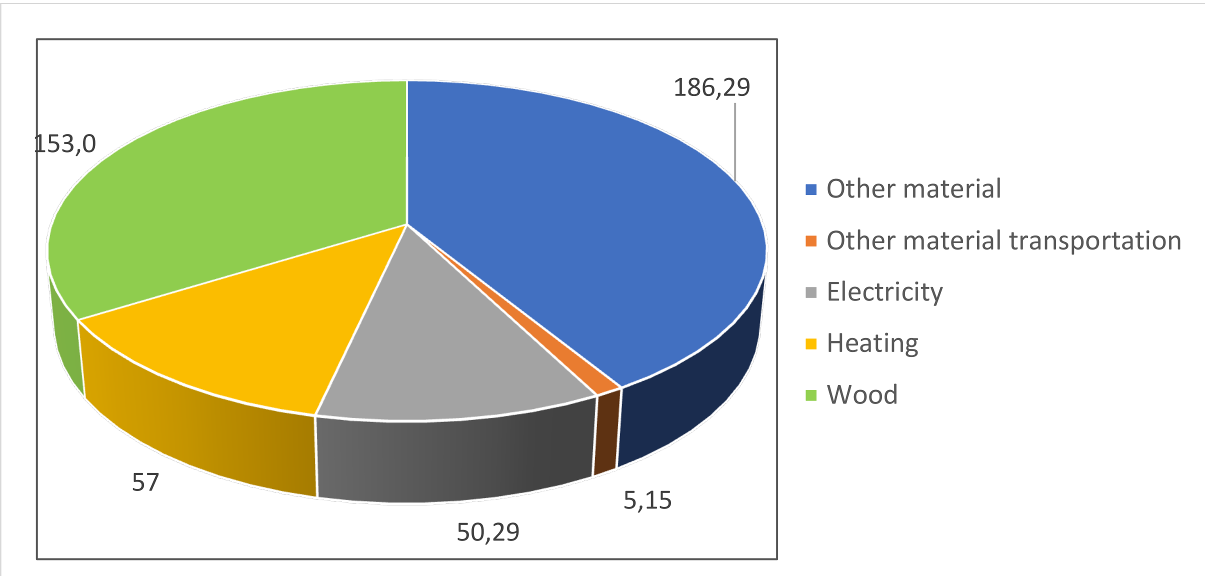

Figure 27 – The different components of the net emission calculations of cement bonded particleboard ($kgCO_2eq$ / m^3). The bottom green chart represents the carbon stored in the wood chips incorporated in the panels, while the values in the top chart are the positive footprint coming from other sources. The empty part of the bottom chart corresponds to the carbon footprint of CB PB.

Figures 18 through 21 present a more detailed breakdown of the various sources of unit carbon footprint of the four types of panels produced at FALCO Zrt. The following conclusions can be drawn based on these diagrams:

1. For all organic bonded panels, **the most significant environmental impact is the carbon sink effect** of the wood incorporated. On average, there is over 1000 kg of CO_2 sequestrated in a m^3 of panel, which is considered as negative carbon footprint
2. **Other materials** used for the production **have positive carbon footprint** values. In organic bonded panels, this carbon footprint rages from ranges from 100 to 200 kg of CO_2eq per m^3, which is not nearly enough to counter the negative carbon footprint of wood. The situation is different in cement bonded particleboard, where the energy-intensive production process (and transportation) of cement counterbalances the already decreased negative footprint of wood.
3. **The carbon footprint of** material **transportation is very small** compared to the impact of the materials. The production of the materials is much more energy intensive than their transportation.
4. Of the **Energy-related emissions,** electric energy is the most significant source of greenhouse gas emissions. Heat generation has a relatively low impact, due to the intensive use of low-impact biomass energy produced on site. On the total impact of energy usage is in the range of 5 to 15 percent of the CO_2 stored in organic bonded products.
5. As a result of the very significant negative carbon footprint of wood as a raw material, **the overall unit carbon footprint of raw and overlaid particleboard is** also **negative**, in the range of -1000 to near -1100 kgCO_2eq/m^3. These products can be considered very environmentally friendly, based on a realistic, net neutral carbon footprint accounting of wood. **Cement bonded particleboard has** a **positive carbon footprint** of 264 kgCO_2eq/m^3, due to the energy intensive production and transportation processes of cement.
6. Since the majority of FALCO's production is organic bonded particleboard (more than 90% on a volume basis), **the company's total net carbon footprint was** also **overwhelmingly negative** in 2023/24.

   It is apparent from the data that FALCO's carbon footprint for raw and overlaid PB is somewhat more favourable to that found in other studies. The difference may be due to technological differences, or different transportation distances. **Compared to other industrial branches, FALCO's raw and overlaid particleboard production has a much lower carbon footprint**, due to the carbon sink effect. Cement bonded particleboard production has a much higher carbon footprint, but still lower than competitor materials (e.g. gypsum plasterboard), in addition to the favourable technical characteristics.

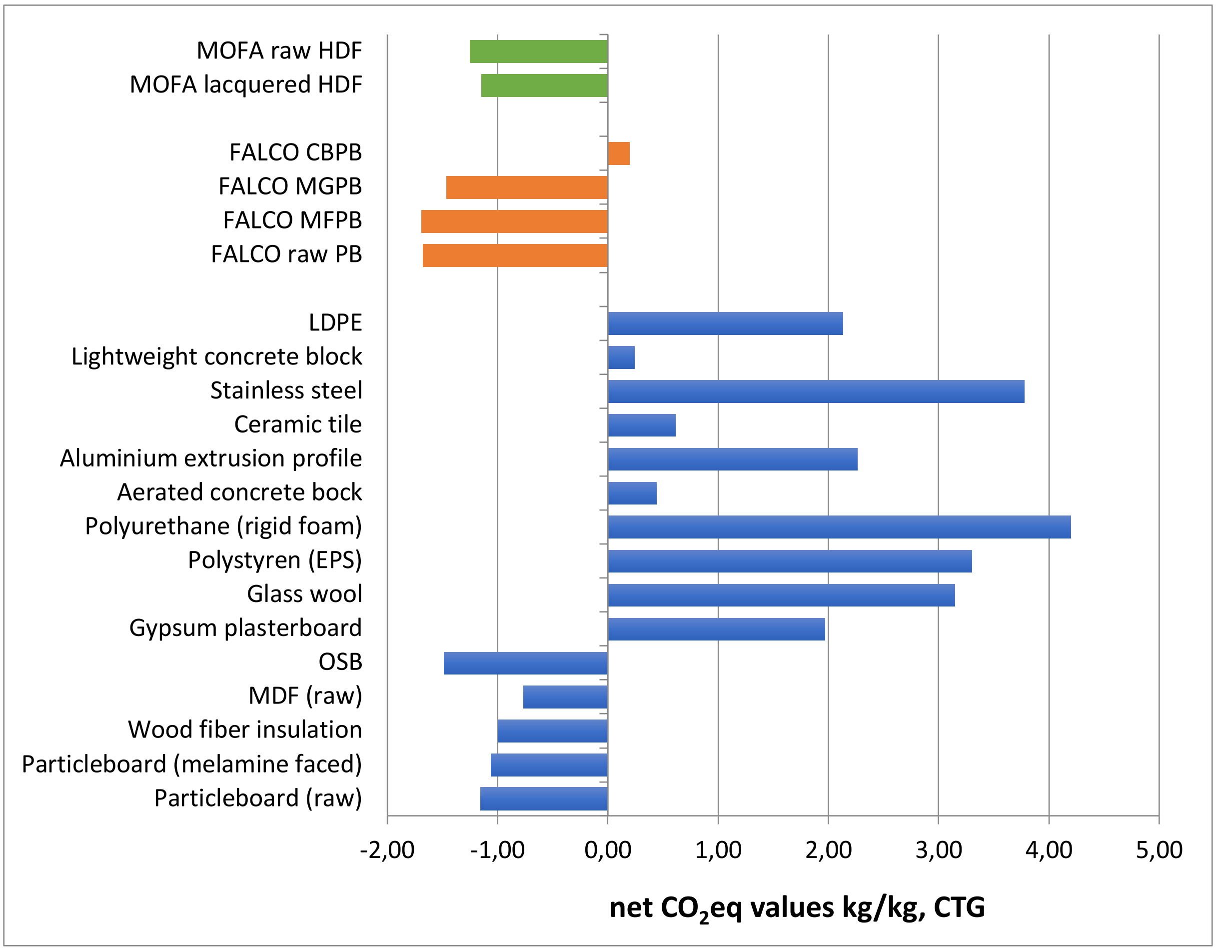

Figure 28 – FALCO's net unit carbon footprint values compared to other industrial branches (Cradle to Gate)

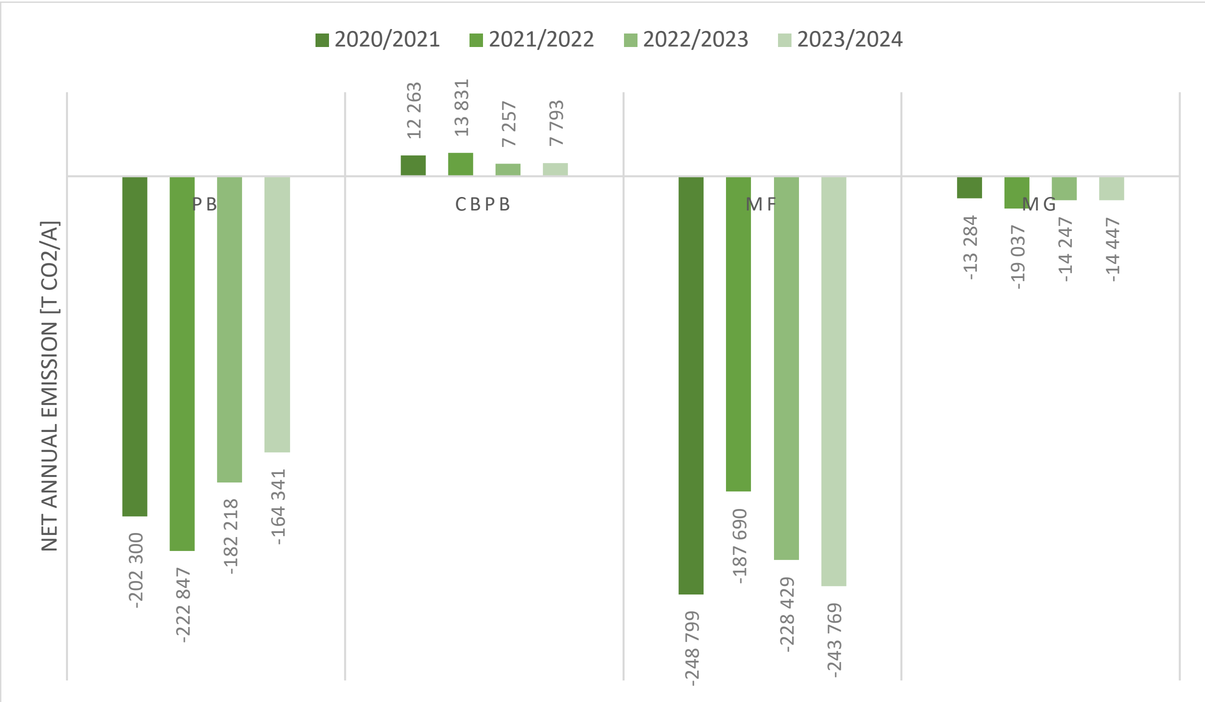

Figure 29 – Net annual emissions from 2020/21 to 2023/24