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Article

Modelling Carbon Storage Dynamics of Wood Products with the HWP-RIAL Model—Projection of Particleboard End-of-Life Emissions under Different Climate Mitigation Measures

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Abstract: Harvested wood products (HWPs) store a significant amount of carbon, and their lifetime extension and appropriate waste management, recycling, and reuse can contribute remarkably to the achievement of climate goals. In this study, we examined the carbon storage and CO_2 and CH_4 emissions under different scenarios of 200,000 m^3 particleboard manufactured in 2020 by a hypothetical manufacturer. The scope of our investigation was to model the effects of a changing product lifetime, recycling rates and waste management practices on the duration of the carbon storage in wood panels and on their emission patterns. The aim of the investigation was to identify the most climate-friendly practices and find the combination of measures related to HWP production and waste management with the highest climate mitigation effect. We used the newly developed HWP-RIAL (recycling, incineration and landfill) model for the projections, which is a combination of two IPCC models parametrized for Hungarian circumstances and supplemented with a self-developed recycling and waste-route-selection submodule. The model runs covered the period 2020–2130. According to the results, the combined scenario with bundled mitigation activities had the largest mitigation potential in the modelled period, resulting in 32% emission reduction by 2050 as compared to the business-as-usual scenario. Amongst individual mitigation activities, increased recycling rates had the largest mitigation effect. The lifetime extension of particleboard can be a complementary measure to support climate mitigation efforts, along with the concept of cascade use and that of circular bioeconomy. Results showed that landfilled wood waste is a significant source of CH_4 emissions on the long term; thus, incineration of wood waste is preferable to landfilling.

Keywords: HWP; climate change mitigation; carbon storage; GHG emissions; climate goals; recycling; incineration; solid waste disposal; circular bioeconomy; Hungary

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

Academic Editor: Farooq Sher

Received: 7 March 2023
Revised: 4 April 2023
Accepted: 5 April 2023
Published: 6 April 2023

1. Introduction

Achieving the goals of the Paris Agreement requires significant reductions in anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) complemented with an increase in CO_2 removal [1,2]. The capacity of the forest industry to remove CO_2 from the atmosphere is key in climate mitigation pathways [2]. The European Green Deal relies on the forest sector and wood products for achieving climate neutrality in the European Union by 2050 [2].

Wood product models are used to estimate the carbon dynamics of harvested wood products (HWPs) and evaluate their effects on the mitigation of climate change; the increasing complexity of the models allows for the advanced analysis of industrial product conversion efficiency, product lifespan, and recycling rate [3]. Wood product models can be classified into two groups [4]. One group uses the production and trade data of wood commodities from statistical databases [5–12]. The other group of models uses estimations of the amount of harvested wood produced by dynamic forest-growth models or yield tables [13,14]. Several authors [15–20] have identified recycling as an important factor affecting the amount of carbon stored in wood products. To handle recycling in wood product models, a common methodology is to assign a recycling rate to each product category, and then allocate recycled products, or part of them, to the same product category [3]. CO2FIX [21], LANDCARB [22], and CAPSIS [14] models use this methodology. Brunet-Navarro et al. [3] analyse the effect of enhanced cascade chains in their model by replacing infinite recycling loops with one or two recycling loops, and by changing the use of recycled products. Most wood product models exclude emissions from landfilling, since carbon stock in HWPs disposed in landfills is only reported in the land use, land-use change and forestry (LULUCF) sector of greenhouse gas inventories (GHGIs) as an information item and it is not accounted for under LULUCF according to the IPCC methodology [7,8]. The European Landfill Directive [23,24] and the directive on waste and repealing certain directives [25,26] which will be fully implemented by 2025, do not allow the disposal of biodegradable waste at solid waste disposal sites (SWDSs) and in many EU countries landfilling organic waste is also banned [3,27]. To estimate the effect of wood waste landfilled in the past decades, the IPCC waste model [8,28] is a suitable tool.

Software applications for lifecycle assessment of GHG emissions can be also used to assess the GHG profiles of the forest industry, and the increasing popularity of carbon-accounting tools is not limited to the LULUCF sector [29]. However, most of the tools used show major limitations in the realistic representation of emission lifecycles and on the assessment of uncertainties associated with the data and assumptions related to the complex lifecycles under the LULUCF and the waste sector [29]. Gentil et al. [30] reviewed 15 tools in the waste sector; however, uncertainty assessment was not even selected as a primary criterion of software evaluation, since uncertainty assessment was applied in only 4% of the case studies [30,31]. In the case of the LULUCF carbon-accounting tools, similar observations were made by Whittaker et al. [32] and Brunet-Navarro et al. [4] stating that most tools do not implement any features for uncertainty assessment.

The EU is moving towards a circular bioeconomy with strong emphasis on waste reduction and resource efficiency [33]. The EU circular economy strategy [34] promotes actions that close the loop on product lifecycles through their reuse and recycling, considering sustainability and the use of by-products from one industry as the raw materials for another. The EU action plan for the circular economy [35] advocates maintaining the value of products, materials, and resources for as long as possible, whilst minimizing waste generation [36]. Bio-based materials can play a major role in climate change mitigation through temporary carbon storage [37] and cascading can increase this potential [36]. The circular economy goals include improvements in material and energy efficiency, and a significant increase in the use of residues and wastes as valuable raw materials [36,38]. The application of lifecycle analysis in industry can facilitate the prioritization of environmentally sustainable technologies [39]. Cherubini et al. [40] show that the temporal dynamics of carbon uptake in the forest, subsequent storage, and eventual release through wood combustion or decay strongly influence the global warming performance of wood products. Li and Toppinen [41] emphasize how little is known about corporate responsibility within small- and medium-sized enterprises and highlight that the application of corporate responsibility tools should be among future research priorities.

Wood-based panels are usually seen as potentially carbon neutral materials since they incorporate biogenic carbon [42]. However, GHG emissions related to their production, such as those associated with ancillary materials or manufacturing processes, can have a high contribution to their carbon footprint [42,43]. Wood-based panels have a relatively long service life; therefore, understanding the dynamics related to storage and delayed carbon emissions in both use and disposal phases is of key importance [42].

The objective of our study was to model the effects of the changing product lifetime, recycling rate, and waste management practices on the carbon storage of wood-based panels using the HWP-RIAL model (i.e., the harvested wood product recycling, incineration and landfill model), which is a newly developed combination of two IPCC models parametrized for Hungarian circumstances and supplemented with a self-developed recycling and waste-route-selection submodule. To quantify the magnitude of these effects on the corporate level, we examined the carbon storage and emissions of 200,000 m^3 particleboard manufactured by a hypothetical manufacturer in 2020 under different scenarios.

2. Materials and Methods

2.1. Input Data

In our study, we modelled the carbon storage and subsequent CO_2 and methane (CH_4) emissions of 200,000 m^3 particleboard manufactured in 2020 by a hypothetical manufacturer under different scenarios. We selected this amount of product as it is comparable to the average annual production of large wood panel manufacturers operating in Hungary.

2.2. Model Used: The HWP-RIAL Model

To estimate HWP carbon stock changes and emissions, the HWP-RIAL model was used, which is a combination of two IPCC models parametrized for Hungarian circumstances and supplemented with a self-developed recycling and waste-route-selection submodule. The model is able to project the amount of carbon stored in wood products as well as the CO_2 and CH_4 emissions from products going out of use and disposed of via incineration or solid waste disposal. The recycling submodule makes it possible to set the amount of wood waste recycled and define the product type which is subsequently produced from the recycled material. The model is Excel-based and is comprised of several Excel worksheets where the calculations are carried out, and an input worksheet where input data can be entered and model parameters can be set. In our study, we used a projection timeframe from 2020 to 2130, since a longer time period is needed to observe the magnitude of CH_4 emissions from landfilled wood.

2.2.1. First Order Decay HWP Model Supplemented with Recycling and Waste-Route-Selection Submodules

For estimating the amount of carbon stored in a particular HWP commodity category and the amount of HWP reaching the end of its lifetime and going out of use, a combination of the approaches recommended by the 2019 Refinement to the 2006 IPCC Guidelines [8] (herein after referred to as the Refinement) was used, as described by Király et al. [11]. In our estimate, we did not differentiate between HWP from domestic harvest and from imported raw material. We set the initial HWP stock to zero as we estimated the stock and emissions from the production of a single hypothetical manufacturer for a single year for a single product category (i.e., particleboard). The data in Table 1 show the default half-life value and conversion factors which were taken from the Refinement. Please note that half-life value can be set deliberately in the input sheet of the HWP-RIAL model and during the parametrization of the different scenarios, the half-life value was modified.

Table 1. Default half-life value and conversion factors recommended by the IPCC 2019 Refinement.

	Half-Life (Year)	Density (Oven Dry Mass over Air Dry Volume) (Mg/m^3)	Carbon Fraction	C Conversion Factor (per Air Dry Volume) ($Mg\ C/m^3$)
Particleboard	25	0.596	0.451	0.269

For the estimation of annual carbon stock change and the outflow in year 'i', equations from the Refinement were used as follows (Equations (1)–(3)).

$$\Delta C(i) = C(i+1) - C(i) \tag{1}$$

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

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

i: year; C(i): the carbon stock in the particular HWP commodity class i at the beginning of the year i, kt C; k: decay constant of first-order decay for each HWP commodity class i given in units yr-1 (k= ln(2)/HL, where HL is the half-life of the particular HWP commodity in the HWP pool in years); inflow(i): the carbon inflow to the particular HWP commodity class i during the year i, kt C yr-1; ΔC(i): carbon stock change in the HWP commodity class i during the year i, kt C yr-1; outflow(i): the carbon content of the particular HWP commodity class i that goes out of use during the year i, kt C yr-1.

HWP reaching its end of life can proceed in three different ways in the model: it can be recycled, incinerated, or landfilled. The share of waste wood recycled and disposed of via incineration or solid waste disposal can be set as appropriate. In model runs used in this study, wood waste from particleboard going out of use was set as raw material for production of the same product category (i.e., particleboard produced from recycled material). This assumption was made according to Deilmann et al. [44] who asserted that recycled wood is currently used as wood resource mainly to produce particleboard. The share of wood waste recycled and disposed of was calculated with the following Equations (4)–(7).

$$\text{recycled WW}\ (i) = \text{outflow}\ (i) \cdot F_{\text{recycled WW}} \tag{4}$$

$$\text{landfilled WW}\ (i) = \text{outflow}\ (i) \cdot F_{\text{landfilled WW}} \tag{5}$$

$$\text{incinerated WW}\ (i) = \text{outflow}\ (i) \cdot \left(1 - F_{\text{recycled WW}} - F_{\text{landfilled WW}}\right) \tag{6}$$

$$CO_2\ \text{Emissions from incineration}\ (i) = \text{incinerated WW}\ (i) \cdot 44/12 \tag{7}$$

recycled WW (i): the wood waste generated in year i from the particular HWP commodity class i and recycled thereafter, kt C yr^{-1}; $F_{recycled\ WW}$: the fraction of wood waste recycled (fraction); landfilled WW (i): the wood waste generated in year i from the particular HWP commodity class i and landfilled thereafter, kt C yr^{-1}; $F_{recycled\ WW}$: the fraction of wood waste landfilled, fraction; incinerated WW (i): the wood waste generated in year i from the particular HWP commodity class i and incinerated thereafter, kt C yr^{-1}; 44/12: CO_2/C molecular weight ratio.

2.2.2. Solid Waste Disposal Model

For estimating CH_4 and CO_2 emissions from waste wood disposed at SWDSs, the modified version of the waste model of the 2006 IPCC Guidelines [28] was used and parametrized for Hungary, consistent with the Hungarian Greenhouse Gas Inventory [45]. The CH_4 generation potential of the waste that is disposed in a certain year decreases gradually throughout the following decades; thus, the CH_4 released from this specific amount of waste decreases as well. These decreasing CH_4 emissions are modelled with a first order decay (FOD) pattern. The FOD model is built on an exponential factor that describes the fraction of degradable organic material which each year is broken down into CH_4 and CO_2. CH_4 is generated under anaerobic conditions. One part of the CH_4

generated is oxidized in the cover of the SWDS. Other part can be recovered for energy or flaring. The percentage of CH_4 recovery can be set in the input sheet of the HWP-RIAL model. The basis for the calculation of the CH_4 generated is the amount of decomposable degradable organic carbon (DDOCm) which is the part of the organic carbon that will decompose under anaerobic conditions in SWDS. The amount of DDOCm available and the accumulated and the decomposed amounts of organic carbon were calculated using the following Equations (8)–(10).

$$\mathrm{DDOC_m} = \mathrm{C} \cdot \mathrm{DOC_f} \cdot \mathrm{MCF} \quad (8)$$

$$\mathrm{DDOCm\ accum_T} = \mathrm{DDOCmd_T} + \left(\mathrm{DDOCmd_{T-1}} \cdot e^{-k}\right) \quad (9)$$

$$\mathrm{DDOCm\ decomp_T} = \mathrm{DDOCm\ accum_{T-1}} \cdot \left(1 - e^{-k}\right) \quad (10)$$

DDOCm: mass of decomposable degradable organic carbon deposited, kt C; C: degradable organic carbon deposited, kt C; DOCf: fraction of degradable organic carbon that can decompose (fraction); MCF: CH_4 correction factor for aerobic decomposition in the year of deposition (fraction); DDOCm $accum_T$: DDOCm accumulated in the SWDS at the end of year T, kt C; DDOCm $accum_{T-1}$: DDOCm accumulated in the SWDS at the end of year (T-1), kt C; $DDOCmd_T$: DDOCm deposited into the SWDS in year T, kt C; DDOCm $decomp_T$: DDOCm decomposed in the SWDS in year T, kt C; k: reaction constant, given in units yr^{-1} (k = ln(2)/HL, where HL is the half-life of the particular waste category).

Only part of the degradable organic carbon in waste wood disposed in SWDS will decay into both CH_4 and CO_2; the part that will not decompose will be stored long-term in the SWDS [28]. Long-term stored carbon was calculated as follows (Equation (11)).

$$\mathrm{C_{Long-term\ T}} = \mathrm{C} \cdot (1 - \mathrm{DOC_f}) \cdot \mathrm{MCF} \quad (11)$$

MCF: CH_4 correction factor for aerobic decomposition in the year of deposition (fraction); DOCf: fraction of degradable organic carbon that can decompose (fraction); $C_{Long\text{-}term\ T}$: Long-term stored carbon in the SWDS in year T, kt C.

CH_4 generated and emitted was calculated as follows (Equations (12)–(13)).

$$\mathrm{CH_4\ generated_T} = \mathrm{DDOCm\ decomp_T} \cdot \mathrm{F} \cdot 16/12 \quad (12)$$

$$\mathrm{CH_4\ Emissions} = [\mathrm{CH_4\ generated_T} - \mathrm{R_T}] \cdot (1 - \mathrm{OX_T}) \quad (13)$$

CH_4 $generated_T$: amount of CH_4 generated from decomposable material in year T, kt; DDOCm $decomp_T$: DDOCm decomposed in year T, kt C; F: fraction of CH_4 by volume in generated landfill gas (fraction); 16/12: CH_4/C molecular weight ratio; CH_4 emissions: CH_4 emitted in year T, kt; R_T: recovered CH_4 in year T, kt; OX_T: oxidation factor in year T (fraction).

The amount of CH_4 recovered was calculated from the amount of CH_4 generated and the percentage of methane recovery set on the input sheet. There was no differentiation between CH_4 recovered for energy and CH_4 flared, as in both cases CH_4 is oxidized and released to the atmosphere in the form of CO_2. Carbon dioxide emissions from SWDS were calculated as the sum of CO_2 directly emitted from the landfill and CO_2 generated and emitted during the energetic utilization or flaring of the CH_4 component of the landfill gas (Equations (14)–(15)).

$$\mathrm{R_T} = \mathrm{CH_4\ generated_T} \cdot \mathrm{CH_4\ recovery\%} \quad (14)$$

$$\mathrm{CO_2\ Emissions\ from\ landfills} = \left(\mathrm{CH_4\ emissions} \cdot \frac{44}{16}\right) + \left(\mathrm{R_T} \cdot \frac{44}{16}\right) \quad (15)$$

CH_4 recovery%: fraction of CH_4 recovered from landfill (fraction); 16/12: CO_2/CH_4 molecular weight ratio.

The solid waste disposal model was parametrized taking into account the Hungarian circumstances, climate zone (dry temperate) and consistently with the Hungarian GHGI (Table 2). All wood waste was regarded as being disposed in managed SWDS.

Table 2. Parametrization of the solid waste disposal module of the HWP-RIAL model.

Waste Model Parameters	
DOCf (fraction of DOC dissimilated)	0.5
k (methane generation rate constant, years^{-1})	0.02
Half-life of wood waste (years)	35
OX (oxidation factor, fraction)	0.1
MCF (methane correction factor for aerobic decomposition in the year of deposition, fraction)	1
F (fraction of methane in developed gas)	0.5

2.3. Scenario Parametrization

In this study, eight different scenarios were developed (Table 3) to examine the impact of possible wood-industry-related measures and different waste management practices. This made it possible to quantify the climate mitigation potential of the different measures. In the scenarios, four parameters were modified following different concepts. These parameters were the proportion of wood waste recycled, the proportion of wood waste landfilled, the proportion of methane recovered, and the half-life value of the produced particleboard.

Table 3. Parametrization of the scenarios used in this study. [The X scenario series were developed to showcase the effects of an increase in the amount of the landfilled wood waste, with methane recovery unchanged (X.1) and increased (X.2)].

Parametrization of the Scenarios				
		2020	**2050**	**2130**
BAU	**Half-life (years)**	25	25	25
	Landfilled wood waste %	15	15	15
	Recycled wood waste %	20	20	20
	CH_4 recovery %	12	12	12
HL	**Half-life (years)**	35	35	35
	Landfilled wood waste %	15	15	15
	Recycled wood waste %	20	20	20
	CH_4 recovery %	12	12	12
RECYCL	**Half-life (years)**	25	25	25
	Landfilled wood waste %	15	15	15
	Recycled wood waste %	20	50	80
	CH_4 recovery %	12	12	12
LF	**Half-life (years)**	25	25	25
	Landfilled wood waste %	15	5	3
	Recycled wood waste %	20	20	20
	CH_4 recovery %	12	12	12
CH_4-rec	**Half-life (years)**	25	25	25
	Landfilled wood waste %	15	15	15
	Recycled wood waste %	20	20	20
	CH_4 recovery %	12	25	50
Combined	**Half-life (years)**	35	35	35
	Landfilled wood waste %	15	5	3
	Recycled wood waste %	20	50	80
	CH_4 recovery %	12	25	50
X.1	**Half-life (years)**	25	25	25
	Landfilled wood waste %	65	65	65
	Recycled wood waste %	20	20	20
	CH_4 recovery %	12	12	12
X.2	**Half-life (years)**	25	25	25
	Landfilled wood waste %	65	65	65
	Recycled wood waste %	20	20	20
	CH_4 recovery %	12	25	50

A business-as-usual (BAU) scenario was developed as a reference scenario. For the parametrization of the BAU scenario, data were collected from the National Waste

Management Plan 2021–2027 [46], the National Environmental Information System [47] and from the Hungarian GHGI [45]. The half-life value in the BAU scenario was set to the default value as defined by the Refinement. A HL (half-life) scenario was developed to reflect on the impacts of technological improvements in the wood industry extending the lifetime of wood products. The RECYCL (recycling) scenario was set to examine increased recycling rates. The LF (landfill) scenario modelled the decreasing share of landfilled wood waste as targeted by the National Waste Management Plan 2021–2027 [46]. The CH_4-rec (CH_4 recovery) scenario modelled the effects of increased methane recovery. The combined scenario was set to model the combined effects of the HL, RECYCL, LF, and CH_4-rec scenarios. The X scenario series were developed to showcase the effects of an increase in the amount of the landfilled wood waste, with methane recovery unchanged (X.1) and increased (X.2).

3. Results

In the BAU scenario, total projected cumulative emissions were 88 kt CO_2 equivalent (eq) and 197 kt CO_2 eq until 2050 and 2130, respectively. The projected amount of carbon stored in wood products was −100 kt CO_2 eq for 2050 and −17 kt CO_2 eq for 2130. The total amount of carbon stored long-term at landfills was predicted to be −9 kt CO_2 eq in 2050 and −17 kt CO_2 eq in 2130. Figure 1 shows the carbon storage and cumulative CO_2 and CH_4 emissions of the different scenarios until the year 2050.

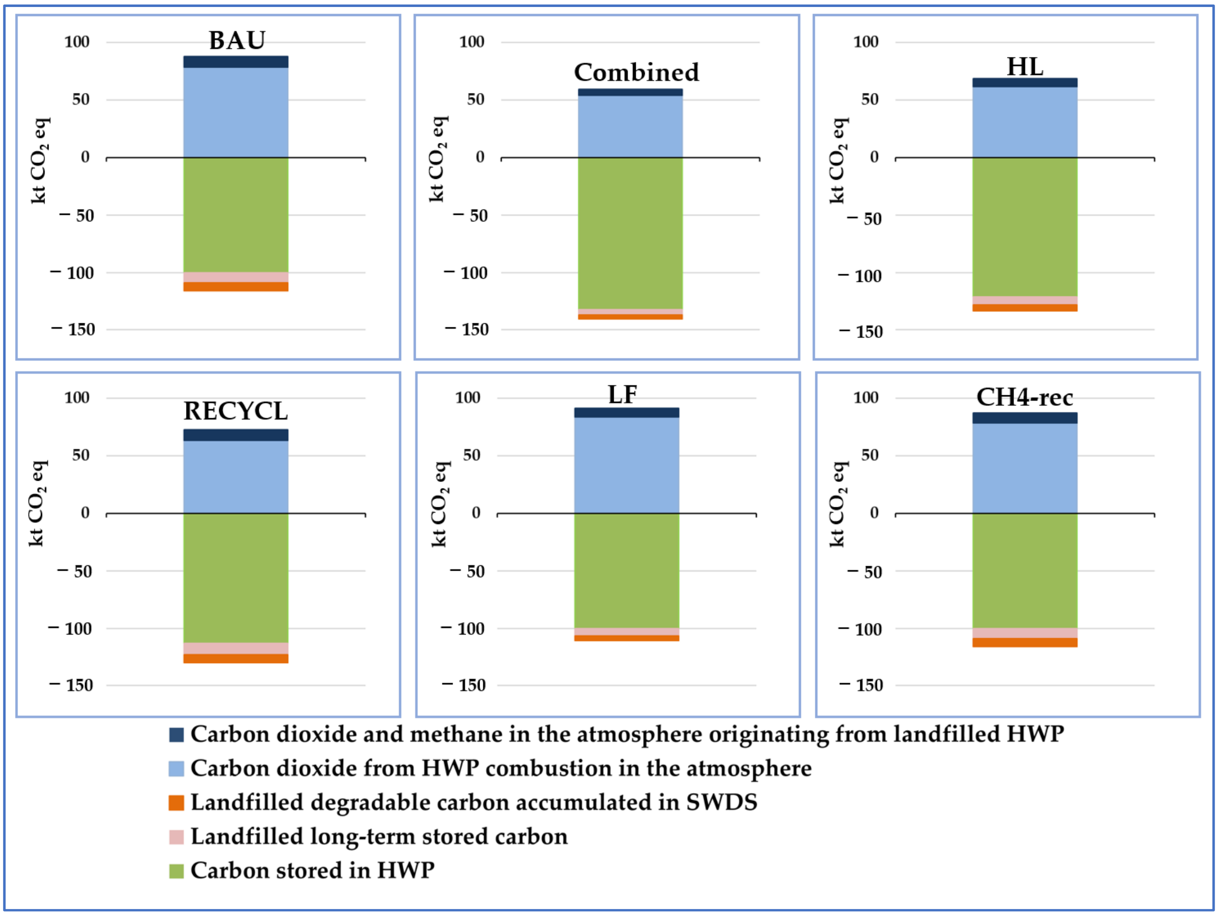

Figure 1. Carbon storage and cumulative emissions from 2020 until 2050 in kt CO_2 equivalent (negative values indicate carbon stored whereas positive values indicate carbon emitted and accumulated in the atmosphere).

The scenario resulting in the least emissions until 2130 was the combined scenario (Table 4). However, if examined just until 2050, the combined scenario was only at third place in emission reduction. The X scenarios, characterized by increased solid waste disposal, resulted in the least emissions until 2050. Nevertheless, by 2130 the performance of X scenarios changed, and additional emissions were projected as compared to the BAU scenario. The X.1 scenario resulted in 28% more emissions than the BAU scenario.

Table 4. Reduction in the total cumulative emissions of the developed scenarios in the percentage of the BAU emissions (positive values mean emission reduction, negative values mean additional emissions).

Emission Reduction in the Percentage of BAU Emissions (%)		
Scenario	**2050**	**2130**
HL	22	11
RECYCL	17	18
LF	−4	3
CH_4-rec	1	5
Combined	32	37
X.1	34	−28
X.2	37	−7

In Figure 2, we demonstrate the results of a sensitivity analysis carried out to assess the impact of modifying each parameter between its lowest and highest possible values, while keeping the other three parameters constant at the BAU scenario value. As shown in Figure 2, an increased half-life, recycling rate, and methane recovery reduced emissions over the entire projection period. On the other hand, an increase in the amount of landfilled wood waste reduced emissions until 2050 but increased them significantly between 2050 and 2130. Changing methane recovery had the smallest emission reduction effect, as in the BAU scenario the amount landfilled was only 15% and CH_4 emissions did not have a great share in total BAU emissions. Increasing the recycling rate had the biggest emission reduction effect, followed by increasing half-life values.

The mitigation potential of each scenario was calculated as the difference between the cumulative emissions of the BAU scenario and the examined scenario. Considering the entire projection period, the mitigation potential of the combined scenario was the largest, followed by that of the RECYCL scenario (Figure 3). This means that these scenarios allowed for the largest emission reductions in the modelled period. Considering the period up to 2130, scenarios of the X series had negative mitigation potential values, i.e., these scenarios resulted in additional emissions as compared to the BAU scenario.

Figures 4 and 5 show the emission patterns of the BAU and the combined scenarios. The overall decay of the carbon stored in wood products was slower in the combined scenario than in the BAU scenario. According to the model results for the year 2050, the carbon stored in wood products was, with 32 kt CO_2 eq, higher in the combined scenario than in the BAU. For year 2130, it was, with 59 kt CO_2 eq, higher in the combined scenario than in the BAU scenario. Emissions from landfilled wood waste were, with 4 kt and 31 kt CO_2 eq, lower in the combined scenario than in the BAU scenario for the years 2050 and 2130, respectively.

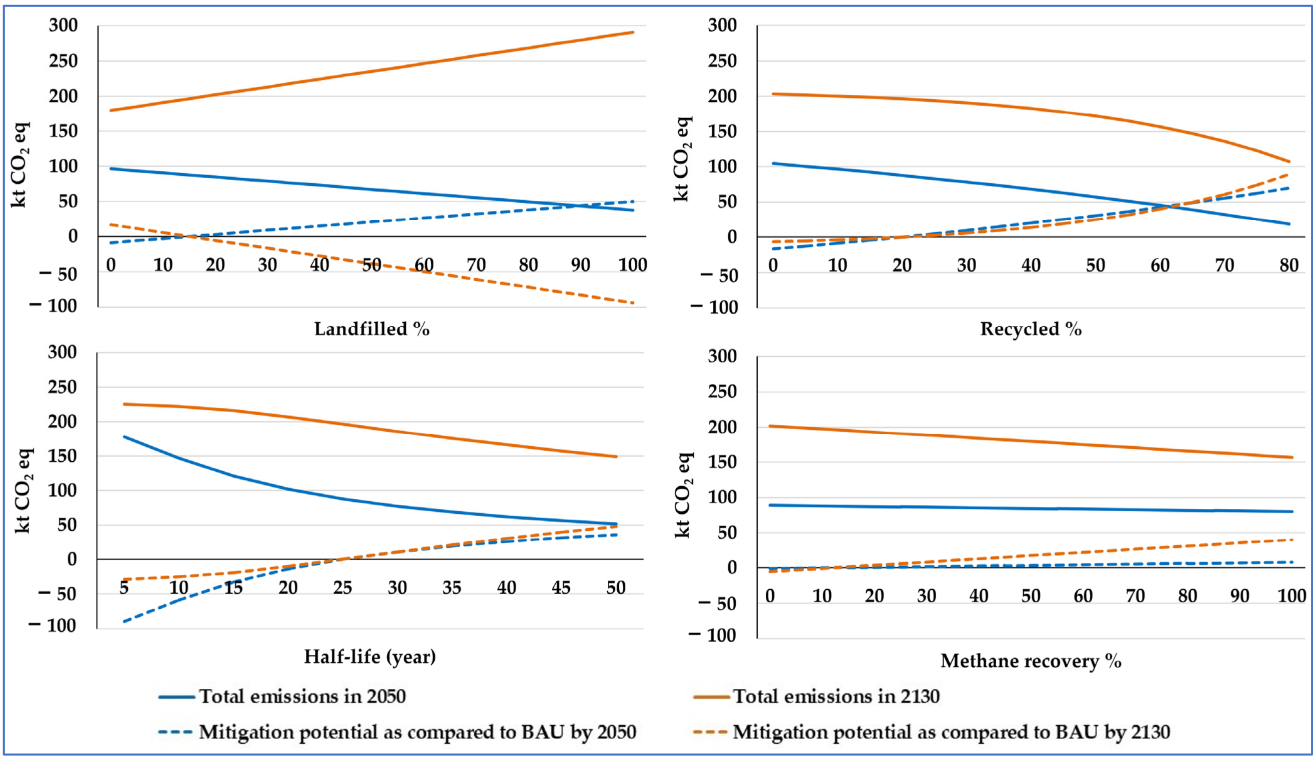

Figure 2. Total cumulative emissions and mitigation potential as a function of the parameters, in kt CO_2 equivalent. In each figure, three parameters are kept constant on the values of the BAU scenario and one parameter is modified between its lowest and highest possible values. (Emissions are positive values. In the case of the mitigation potential, positive values indicate emission reduction as compared to the BAU scenario, whereas negative values indicate emission increase as compared to the BAU scenario).

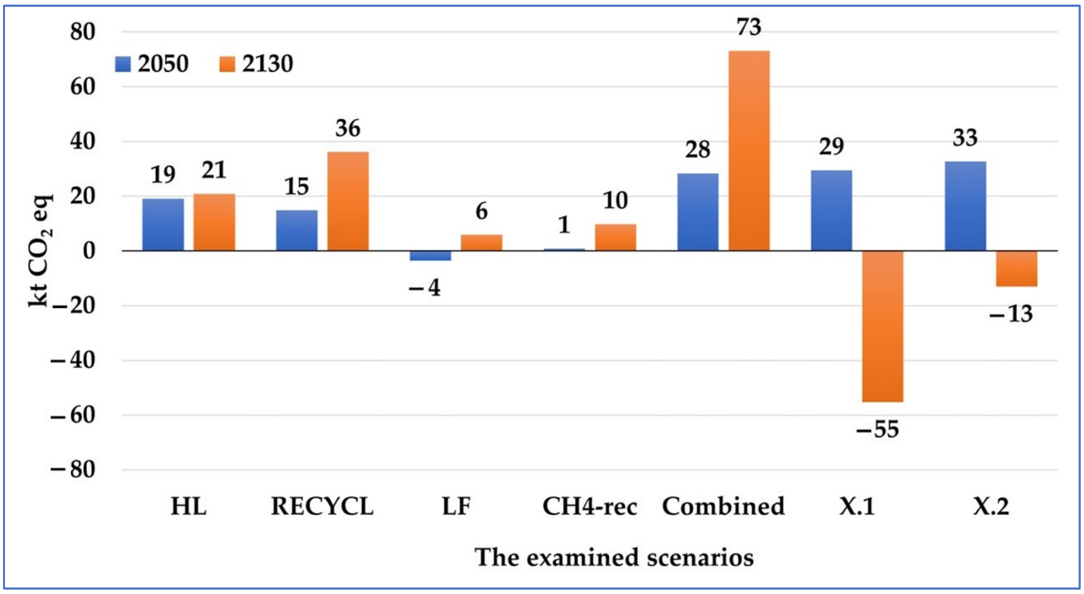

Figure 3. Mitigation potential until 2050 and until 2130 as compared to the BAU scenario in kt CO_2 equivalent (positive values mean emission reduction; negative values mean additional emissions).

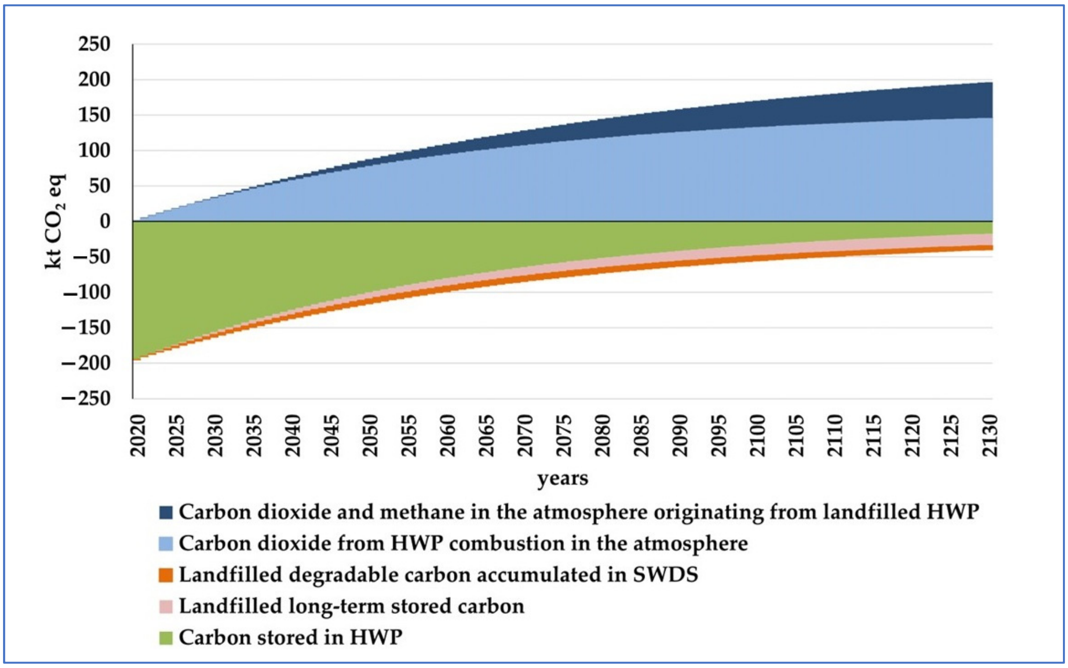

Figure 4. Carbon storage and cumulative emissions under the BAU scenario from 2020 until 2130 in kt CO_2 equivalent (negative values indicate carbon stored whereas positive values indicate carbon emitted and accumulated in the atmosphere).

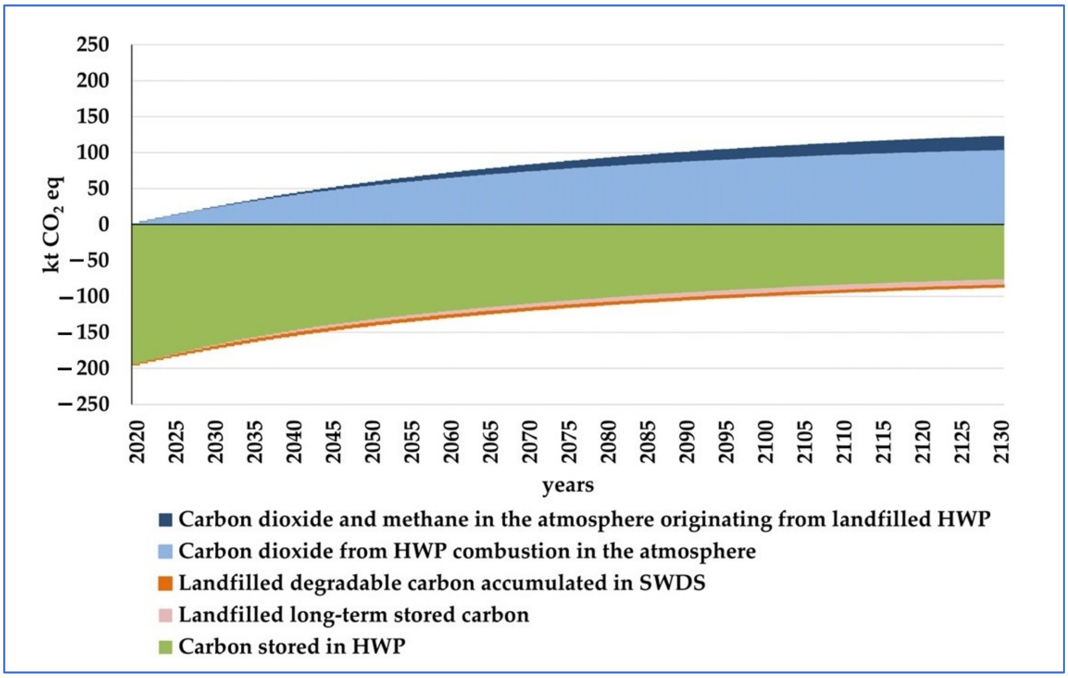

Figure 5. Carbon storage and cumulative emissions under the combined scenario from 2020 until 2130 in kt CO_2 equivalent (negative values indicate carbon stored whereas positive values indicate carbon emitted and accumulated in the atmosphere).

4. Discussion

The objective of our study was to model the effects of the changing product lifetime, recycling rate, and waste management practices on the carbon storage of particleboards using the newly developed HWP-RIAL model. In this demonstration we used the example of 200,000 m^3 particleboard manufactured in 2020 to provide insight into the operation of the model by following the lifecycle and emissions of this amount of product. The model used is a combination of two IPCC models, parametrized for Hungary, supplemented with a self-developed recycling and waste-route-selection submodule. Besides the possibility of the waste route selection, the novelty of the HWP-RIAL model is that it is a country-specific model, as the ratios of landfilled and recycled wood waste and the ratio of methane recovery at SWDSs (i.e., the amount of CH_4 collected and flared or energetically utilized as compared to the total amount of CH_4 generated) is derived from the processing and analysis of country-specific databases. These country-specific values are based on the data of the National Environmental Information System [47], the Hungarian Greenhouse Gas Inventory [45], and the National Waste Management Plan [46]. The Hungarian National Environmental Information System [47] is a very detailed database which contains more than 322,000 data records related to waste management. Data are available in the database from 2004 onward, and the database stores the waste management data of every industrial company as well as all the waste management service providers. These data are processed and analysed during the preparation of the waste sector of the national GHGI, and aggregated information from this database was used in this study for the parametrization of the BAU scenario. This is why the HWP-RIAL model, and especially its BAU scenario, is regarded as country-specific. The waste routes specified in the BAU scenario are typical for Hungarian circumstances, and are regarded to be new results, as thus far, according to the best knowledge of the authors, there has not been a similar modelling approach generated or parametrized for Hungary.

Our results showed that the combined scenario with bundled mitigation activities had the maximum mitigation potential in the modelled period. As regards individual mitigation activities, increasing the rate of wood waste recycled had the largest mitigation effect, followed by increasing the lifetime of the produced particleboard. Decreasing the landfilled amount and increasing methane recovery had less significant mitigation effects. Budzinski et al. [15] also found that the increase in the cascade use of wood products provides a higher reduction potential in climate change impacts compared to lifetime extension.

According to the report of the European Forest Institute [2], forests and wood products can provide a significant contribution to achieving climate neutrality by 2050 and the types of wood use that give the largest net emission reductions should be prioritized. Increasing recycling rates and the cascade utilization of wood and changing the allocation of harvested wood to long-lived wood products increases carbon stored and contributes to climate change mitigation [1,3,48–51]. Priority should be placed on long-term carbon storage in wood used for construction [52]. The increased use of HWPs in the building sector results in a lower climate impact in all scenarios examined by Peñaloza et al. [53] concerning the climate impact of newly constructed Swedish dwellings. The national energy and climate plans (NECPs) of the EU member states are a first indication that they are moving towards a ‘zero-carbon economy’ by 2050 [52,54]. Sixteen member states out of 27 included HWPs in their NECPs, and 10 member states have specifically mentioned the use of HWPs for construction [52]. According to Sikemma et al. [52], these tendencies indicate that at the international level, a new HWP category should be included in the IPCC guidance for international reporting and modelling purposes for construction wood with a longer lifespan than the current HWP categories.

One of the most important differences between wood-based panels is the type of wooden resource used as raw material to manufacture each product; fibreboard and particleboard are reconstituted panels manufactured from wood chips that can come from a variety of sources [55]. Even if the industrial use of wood as a raw material for particleboard is well established [56], the development bottleneck of the wood-based-panel industry is wood resource consumption [57]. The need to reduce resource consumption leads people to seek alternative sources of raw materials [55]. The production of wood products from recycled material and the use of more recycled or recovered fibre in board manufacturing contributes to reducing environmental impacts [58]. Given the importance of recycling and the cascade utilization of products in climate change mitigation, it is important to assess the possible extent of increasing recycling rates. Wilson [59] examined the industrial manufacturing process of particleboard using 100% recycled wood materials and concluded that particleboard can be made completely by recycled wood material without compromising the quality of the product. According to Saravia-Cortez et al. [55], the environmental footprint of particleboard production is fundamentally affected by the type of raw material used, and the incorporation of recycled wood in particleboard production is an important measure to improve the environmental performance of the production process.

Despite the practical possibilities of the recovery and management of a significant amount of post-consumer wood waste, there is a large data and methodological gap concerning the definition of the market and the resources of wood waste [60]. The situation is also complicated by the fact that in most European countries knowledge of the market in post-consumer waste cannot be gained from official reporting [60–62]. Wood comes for recycling from different sources, such as households, recycling centres, and industries; the parts of treated and of coated wood products differ with regard to the source of origin [63]. Impurities, such as coatings, wood preservatives, binding agents, and flameproofing agents, determine the applicability of recycling technologies and the fate of wood products in recycling [63,64]. Untreated solid wood products, wood products and composites treated with materials free of organic halogen-compounds, and other harmful substances are suitable to be converted into wood chips for wood composite production [63]. Furniture coated and painted with halogenated organic compounds can also be used in material recycling but only after the removal of coatings and varnishes [63]. Wood products with preservatives and with a high pollutant content can only be used in energetic recycling, while hazardous PCB-containing wood waste is to be specially treated and disposed of [63]. In the case of particleboard, the justifiable potential for extending its lifetime is limited due to the type and use of the product and consumers' attitudes, according to Budzinski et al. [15]. The most probable wood-product lifetime extension varies between 20% and 30% in Germany [15]. Lifetime extension can be regarded as a complementary option to support recycling and cascade use [15]. It is also important to consider that in the design of cascading routes, the efficiency of the recycling of raw materials should be considered [18]. There might be limitations in reasonable cascading cycles due to logistical challenges, as cascading use might require a lot of energy and other auxiliary inputs [18].

Regarding the impacts of solid waste disposal, the results of scenario series X are the most representative. We extended the modelling period until 2130 in order to examine the delayed impact of the decay of degradable organic material in landfills. Wood waste with its half-life of 35 years degrades relatively slowly and results in significant methane emissions many years after being deposited. Our results show that in the long term, increasing the rate of the wood waste being landfilled results in disproportionately high methane emissions. As the global warming potential (GWP) of CH_4 is 25 times higher than that of CO_2, emissions expressed in CO_2 equivalent units are even higher. Considering climate mitigation objectives, it is essential that every possible CH_4 emission is avoided; therefore, landfilling organic waste is the worst alternative [23,27]. Speak et al. [65] also found in their study that the fate of end-of-life wood has significant implications for carbon budget calculations, and there are remarkable differences between end-of-life wood management technologies. According to their investigation, energy recovery for electricity was the most efficient with a carbon-emissions-per-input ratio of 0.5 [65]. They found that landfilling wood waste was the least efficient measure, with a ratio of 121.9 [65].

Methane recovery for energy or flaring is a useful measure to mitigate the negative environmental impacts of solid waste disposal and gain energy from landfill gas. According to Oonk [66] for landfills with state-of-the-art liners, landfill gas-collection efficiencies can be 90–100%; for closed landfills, efficiencies range from 10–90% and for landfills in operation, efficiencies vary between 10% to 80%. In case of a very high CH_4 recovery, the deposited wood waste can act as a carbon sink without significant additional environmental burden, but this requires an extremely high rate of CH_4 recovery which is not currently the case of Hungarian managed waste disposal sites.

Our results showed that particleboard manufactured by one single manufacturer in a single year can store significant amounts of carbon over the period 2020–2050. The total projected amount of carbon stored in the combined scenario in 2050 was −140 kt CO_2 eq, which is the 22% of the annual carbon removal of the Hungarian HWP pool in 2020 [11] and which is equal to 12% of the annual CO_2 removal of forests planted in the last 20 years and 3% of the total average (2010–2020) LULUCF removals as reported by the Hungarian GHGI [39]. According to our calculations the mitigation potential of the combined scenario was 28 kt CO_2 eq until 2050, which is 5% of the annual carbon removal of the Hungarian HWP pool in 2020 [11] and which is equal to the 2% of the annual CO_2 removal of forests planted in the last 20 years [45]. These comparisons indicate that mitigation measures and climate protection efforts implemented at the corporate level can have a significant impact on shaping the total national emissions by 2050. Climate awareness and action at the company level is of high impact and importance, and significant results can be achieved by technological development and by increasing the lifespan of products, collecting them for recycling, and promoting the cascade reuse and recycling of HWPs.

The limitation of our study is the fact that no country-specific half-life or carbon fraction values are available for particleboard. Another deficiency of the presented approach is that the emissions associated with the production and transport of HWPs have not been considered. In the future, the model should be tested in a real situation with the production data of a selected company. Data on production- and logistics-related emissions should also be incorporated in the modelling framework. Conducting an uncertainty analysis is also a future step to be carried out.

Based on our study, we can state that the HWP-RIAL model proved to be suitable for predicting CO_2 and CH_4 emissions associated with the end-of-use and waste management of wood products, and therefore it is appropriate for supporting the planning of wood-industry-related climate mitigation measures as well as company-level decision making. In the framework of our ForestLab project (TKP2021-NKTA-43), we are planning to parametrize the HWP-RIAL model for national scale calculations to evaluate the mitigation potential and the impact of individual and bundled climate mitigation measures related to the Hungarian wood industry.

5. Conclusions

In our study, we examined the carbon storage and CO_2 and CH_4 emissions of 200,000 m^3 particleboard under different scenarios. The purpose of this investigation was to identify the most climate-friendly practices and find the combination of measures related to HWP production and waste management with the highest climate mitigation effect. The main conclusion of our study is that the combined scenario with bundled mitigation activities had the largest mitigation potential in the modelled period. Amongst individual mitigation activities, increased recycling rates had the largest mitigation effect. Lifetime extension can be regarded as a complementary measure to support the cascade use of the particleboard. Our results showed that landfilled wood waste is a significant source of methane emissions in the long term. Therefore, it is advisable to reduce the amount of wood waste deposited to zero. The incineration of wood waste should be preferred over landfilling. CH_4 recovery is a good option to reduce emissions from already-disposed wood waste. To facilitate the recycling and cascade use of wood panels, it is recommended to develop and use non-harmful and environmentally friendly coatings, wood preservatives, binding agents, and flameproofing agents.

The projected mitigation potential associated with the measures of the combined scenario indicated that differences in the production, usage, and waste management of 200,000 m^3 particleboard can have a share in achieving the 2050 climate goals, and thus climate awareness and action at the corporate level is essential. Technological development in the production of wood products as well as their collection for reuse and recycling and the promotion of a circular bioeconomy are of high importance.

Author Contributions: Conceptualization, É.K. and A.B.; methodology, É.K. and G.K.-K.; validation, G.K.-K.; Z.B., Z.K., G.N., A.P. and A.B.; formal analysis, É.K.; investigation, É.K., G.K.-K.; Z.B., Z.K., G.N., A.P. and A.B.; data curation, É.K.; writing—original draft preparation, É.K.; writing—review and editing, G.K.-K.; Z.B., Z.K., G.N., A.P. and A.B.; visualization, É.K.; supervision, A.B.; project administration, Z.B. and A.B.; funding acquisition, A.B. All authors have read and agreed to the published version of the manuscript.

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

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data that are necessary for the reconstruction of this study can be found in this paper and in the referenced sources.

Conflicts of Interest: The authors declare no conflict of interest.

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