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Climate mitigation by energy and material substitution of wood products has an expiry date

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ABSTRACT

The expected increased share of renewables due to the ongoing energy transition may reduce the estimated potential mitigation effect of wood. Here, we estimated the climate change mitigation effect for five scenarios of wood products use in Europe applying dynamic substitution factors embracing a future energy mix with an increasing share of renewables in accordance with the emission reductions necessary to achieve the Paris Agreement targets. Our innovative modelling approach also included the elimination of eternal recycling loops, the inclusion of more realistic wood use cascading scenarios, and adoption of a more realistic marginal (ceteris paribus) substitution approach. Results show that the mitigation effect derived from material substitution is 33% lower in 2030 than previously predicted, and even 96% lower in 2100, showing its expiry date by the end of the century. Nevertheless, the mitigation effect of wood product use, in addition to mitigation by forests, may represent 3.3% of the European emission reduction targets by 2030.

1. Introduction

Strong policies for rapid decarbonization of the atmosphere are needed to limit the global temperature increase to 1.5 °C, as committed in the Paris Agreement (Rockström et al., 2017; Roe et al., 2019). The building sector is identified as a sector with a large potential for climate change mitigation (Churkina et al., 2020; Hurmekoski, 2017), now that engineered massive wood products like Cross Laminated Timber (CLT) become more suitable to substitute energy intensive materials such as steel or concrete. New policies could promote wood use for new and refurbished buildings that will be required to accommodate the expected population increase (United Nations, Department of Economic and Social Affairs, 2017).

Sustainable wood harvesting followed by wood product use significantly contributes to climate change mitigation (Nabuurs et al., 2017). Although big uncertainties exists (Roe et al., 2019), the global greenhouse gas (GHG) balance of wood products was estimated at 0.54 Gt CO_2e year^{-1} (Miner and Perez-Garcia, 2007). At European level, it was estimated at 0.04 Gt CO_2e year^{-1} (Pilli et al., 2017). But these sink effects only accounts for carbon stock increments.

Besides carbon stock changes, the climate change mitigation potential of wood use should consider substitution effects (Fortin et al., 2012; Lemprière et al., 2013; Pukkala, 2014). Substitution represents the potential reduction of GHG emissions coming from the marginal replacement of a non-wood based functional equivalent product. For example, the reduction of GHG emissions when employing wood for construction instead of concrete (Gustavsson et al., 2006). The substitution effect of a product is estimated

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using life cycle assessments (LCA) and comparing the life cycle emissions of a wood product with the ones of a functionally equivalent product made from different materials. To account for substitution effect, studies use substitution factors, also called displacement factors. The substitution factor is a measure of the avoided GHG emissions due to the replacement with wood of other materials or energy carriers (Sathre and O'Connor, 2010). Sathre and O'Connor (2010) compared the substitution factors used in 21 studies and concluded that most of them ranged between 1.0 and 3.0 t C/t C (where positive values represent a decrease of emissions when using wood). Meanwhile it has been widely accepted that the substitution effect is largely determined by the system boundaries and local characteristics (e.g., Geng et al., 2017).

Substitution factors may differ as a function of product, geographical region and time (Brunet-Navarro et al., 2016). Lack of specific data and difficulties to identify product substitutes force to group specific products into larger categories. Local data is preferred (Bais-Moleman et al., 2018; Faraca et al., 2019) but often difficult to get. Despite this uncertainty, studies including substitution effect analyse its impacts at long term (e.g., McKechnie et al. (2011); Chen et al. (2014); Soimakallio et al. (2016)). Several studies consider the time effect of future energy mixes on the substitution factors (e.g. Mathiesen et al. (2009) or Smyth et al. (2017)). Assuming an increase of renewable energies in the energy mix (e.g., EU Directive, 2018/2001), we expect that emissions from fossil energy-intensive materials will reduce. Therefore, the long-term substitution effect of wood products and its expected impact on climate policies may be lower than previously predicted.

The objectives of this study were (i) to estimate the GHG balance of wood product use at continental scale for Europe (EU-28) comparing realistic and gradually implemented future scenarios; (ii) to quantify the substitution effects of these scenarios adopting a realistic marginal (ceteris paribus) substitution approach and displacement factors for material and energy substitution that consider a decreasing share of fossil fuels in national energy mixes, and (iii) to compare the overall climate change mitigation potential of the wood product sector (carbon stock change and substitution effect all together) with that of the forest and with the official EU emission reduction targets.

The followed approach was to simulate carbon stocks and flows in wood products until 2100 for a business as usual scenario and four alternative scenarios of wood product use that followed the same trend in wood supply to keep them comparable and independent from forest carbon dynamics. The alternative scenarios explore possible futures of wood product use, considering EU policy decisions in preparation or implementation, and touching upon new technologies changing the use/re-use/recycling patterns of harvested wood. Carbon stock changes were estimated with simulations from year to year. Substitution effects for each alternative scenario were estimated by comparing the inflow changes to each product category with the business as usual scenario, with both conventional and dynamic substitution factors. Substitution factors were made dynamic simulating an expected increase of renewable energies in line with the Paris Agreement commitment. We expect that these dynamics should point to an expiry date of substitution effects.

2. Material and methods

2.1. CASTLE_WPM forest product model

Carbon stock and fluxes were estimated using the CASTLE_WPM model (Brunet-Navarro et al, 2017, 2018). For this study, the model was improved to allow for substitution effects and for time dependent allocation parameters and substitution factors. We used tons of carbon as the working unit in the model and 1 year as time step unit. The amount of carbon was transformed to CO_2 eq. using the atomic weight (1 t C equals to 44/12 tons of CO_2) to show the results. We defined four categories, corresponding to the three IPCC categories to estimate carbon stock (*sawn wood*, *wood based panels*, and *paper and paperboard*) with their respective default half-life values of 35, 25 and 2 years, as described in the Tier 2 of IPCC (IPCC, 2014), and an additional category *fuel wood* with an estimated half-life of zero years, for which it is obviously not needed to estimate the amount of carbon stock in wood products. However, the *fuel wood* category was included to estimate the inflow, as well as the substitution effect.

The rate at which products are removed from use was calculated following a normal distribution around the maximum removal rate at the products' half-life. The standard deviation needed to define this normal distribution for each product category was assumed to be one third of the half-life as done by Brunet-Navarro et al. (2017) and Brunet-Navarro et al. (2018).

Products were allocated to a new product category once they were removed from use. This allocation differed according to each scenario (see sub-section Scenarios). We assumed it unfeasible to recollect 100% of wood fibres, and therefore the recycling parameters achieved 73% or less in this study. Carbon content of non-recovered products was assumed to be emitted to the atmosphere at the end of use. Carbon content in wood fibres that were recycled and reused until energy use (*fuel wood*), were assumed to be emitted to the atmosphere once burned.

2.2. Input data

We used the stock-change approach defined in the IPCC guidelines to define the system boundaries (IPCC, 2006). It means that production, imports and exports were included in the estimation of carbon stock changes in wood products physically located in a studied region. Production, imports and exports were selected from the statistical database of the Food and Agriculture Organization of the United Nations (FAOSTAT). Categories of *sawn wood* and *wood-based panels* in FAOSTAT are aggregates of different items (Table 1). In FAOSTAT, the item "*Fibrewood, compressed*" was split up into "*Hardboard*" and "*Medium Density Fibreboard*" ("*MDF*") from 1995. FAOSTAT provides country specific production values in m^3 or Mg depending on the product category. We used the conversion factors described in IPCC (IPCC, 2014) to transform values downloaded from the FAOSTAT website to t C (Table 1). Once transformed to t C, the production data was merged into the four product categories used (*Sawn wood*, *Panels*, *Paper* and *Fuel wood*).

The oldest values provided in FAOSTAT are from 1961 and the newest from 2019. According to Brunet-Navarro et al. (2017), a spin-up simulation of 57 years (from 1961 to 2019) is not enough for products with 35 years of half-lives (the longest half-life used in this study) and 31% of recycling rate (see sub-section Scenarios). Therefore, we run the model from 1800 to 2019 to avoid underestimations of carbon stock in 2019. Production data from 1800 to 1960 were assumed to increase linearly from zero in 1800 to the first value reported in FAOSTAT for each item. Production data in some years between 1961 and 2019 in the FAOSTAT database is missing. In these cases, we applied a linear interpolation between neighbouring years.

FAOSTAT data include products produced from virgin wood and from recycled wood, but without making this distinction. Introducing these data in CASTLE_WPM, the model would overestimate total production understanding that it is only produced from virgin wood and generating additional products produced from recycled wood. Aiming to reduce this overestimation, we estimated what should be the share of products made from virgin wood in FAOSTAT

Table 1
Description of the FAOSTAT data used to estimate production from harvested wood (IPCC, 2014).

Product category	Item name	Time series available	Original unit	Conversion factor to t C
Sawn wood	*Sawn wood (coniferous)*	1961–2019	m^3	0.225
	Sawn wood (non-coniferous)	1961–2019	m^3	0.280
Wood-based panels	*Veneer Sheets*	1961–2019	m^3	0.253
	Plywood	1961–2019	m^3	0.267
	Particle Board	1961–2019	m^3	0.269
	Hardboard	1995–2019	m^3	0.335
	MDF	1995–2019	m^3	0.295
	Fibreboard, Compressed	1961–1994	m^3	0.315
	Insulating Board	1961–2019	m^3	0.075
Paper and paperboard	*Paper & paperboard*	1961–2019	tonnes	0.386
Fuel wood	*Wood fuel (coniferous)*	1961–2019	m^3	0.225
	Wood fuel (non-coniferous)	1961–2019	m^3	0.280

data to correctly simulate the total production from virgin and recycled wood in 2019, as reported by FAOSTAT. Through an iterative process applied to the *Business as Usual* scenario (see subsection Scenarios), we identified that production from virgin wood of *sawn wood*, *panels*, *paper* and *fuel wood* should be 83%, 81%, 60% and 70%, respectively of the one reported by FAOSTAT. Employing this methodology, the total production for each product category between 1984 and 2019 simulated is the same (<1% difference) as the production reported by FAOSTAT.

The wood supply trend from 2020 to 2100 was estimated extrapolating projections by Mantau et al. (2010) for each country, as follows. We used the values of total potential wood resources provided for 2010 and 2030 to estimate the production increment from 2010 to 2030 (Table 2). Then, the future production of each product in 2030 was estimated applying the averaged percentage of each product category over 10 years of data available (from 2006 to 2015). The production of the years in between (from 2020 to 2029) was estimated applying a linear interpolation between neighbouring years. The increment estimated was extrapolated to the period from 2031 to 2100 despite the uncertainty of such long-term projection.

Table 2
Future periodical increment (in %) of wood production per country based on Mantau et al. (2010).

Country	Country abbreviation	Increment from 2010 to 2030 (%)
Austria	AT	8.30
Belgium	BE	16.51
Bulgaria	BG	18.63
Cyprus	CY	50.00
Czech Republic	CZ	11.95
Germany	DE	18.03
Denmark	DK	13.73
Estonia	EE	10.00
Spain	ES	15.31
Finland	FI	11.88
France	FR	6.87
Greece	GR	31.43
Croatia	HR	0.00
Hungary	HU	11.86
Ireland	IE	39.66
Italy	IT	−9.92
Lithuania	LT	11.11
Luxembourg	LU	0.00
Latvia	LV	31.65
Malta	MT	0.00
The Netherlands	NL	17.31
Poland	PL	12.85
Portugal	PT	27.74
Romania	RO	15.80
Sweden	SE	11.90
Slovenia	SI	2.38
Slovakia	SK	18.24
United Kingdom	UK	13.56

2.3. Scenarios

The amount of input as described above was assumed to be the amount of harvested wood allocated to the product categories of *Sawn wood I*, *Panels I*, *Paper I* and *Fuel wood*. The *Business as Usual* scenario (BaU) was used to simulate past allocation of recycled wood to wood product categories of *Panels II*, *Paper II*, *Paper III* and *Fuel wood* as close as possible to current reality (Fig. 1a). The recycling rate of *Sawn wood* and *Panels* categories were approximated from a study by the Joint Research Centre (Joint Research Centre, 2009). We assumed a linear increase from 0% in 1950 to 31% in 2020 for material uses, and to 34% for energy recovery. The recycling parameters of the *Paper* category were derived from the European Recovered Paper Council (European Recovered Paper Council, 2015). We assumed a linear stepwise increase from 0% at 1950 to 40% at 1991, to 47% at 1995, to 52% at 2000, to 62% at 2005, to 69% at 2010, to 71.9% at 2015 and up to 72.5% at 2016. We assumed paper fibres would not be suitable for production of new recycled paper products after three uses (European Recovered Paper Council, 2015) and allocated those streams to energy recovery. From 2017 to 2100 we assumed constant recycling parameters.

Four alternative scenarios were created to represent future trends (from 2021 to 2100) of wood use without altering domestic forest carbon balance. We assumed that these scenarios were implemented gradually between 2021 and 2040. Thus, the allocation parameters were assumed to change smoothly (following a Bézier curve (Bézier, 1974) with four control points: one at the start and at the end of the curve and the other two following the adjacent lines until the year in between) from the *BaU* scenario to the new one within a period of 20 years. From 2041 to 2100 the allocation parameters were assumed to stay constant.

The *Long cascade* scenario aims at representing an improved cascade use of wood (Fig. 1b). In this scenario harvested wood is allocated the same way as in the *BaU* scenario, recycled wood was used for the same purpose as the original product category with one additional recycling loop for *sawn wood* and *panels*; two in this scenario for all product categories. The percentage of *paper* being recycled and allocated to the new *paper* category was also 72.5% as in the *BaU* scenario, but the recycling rate of *Sawn wood* and *Panels* was increased to 50% being allocated to a new category with the same characteristics of half-life and recycling rate. In addition, 40% of *Sawn wood* and *Panels* was recovered and used as *Fuel wood*.

The *Short cascade* scenario aims at representing an energy-oriented use of wood (Fig. 1c). Again, the allocation of harvested wood was done as described in the input data sub-section. The distinctive characteristic of this scenario is that at the end of use 73% of wood was allocated to the *Fuel wood* category.

The *Engineered wood* scenario aims at representing a situation where engineered wood products are actively promoted (Fig. 1d). In

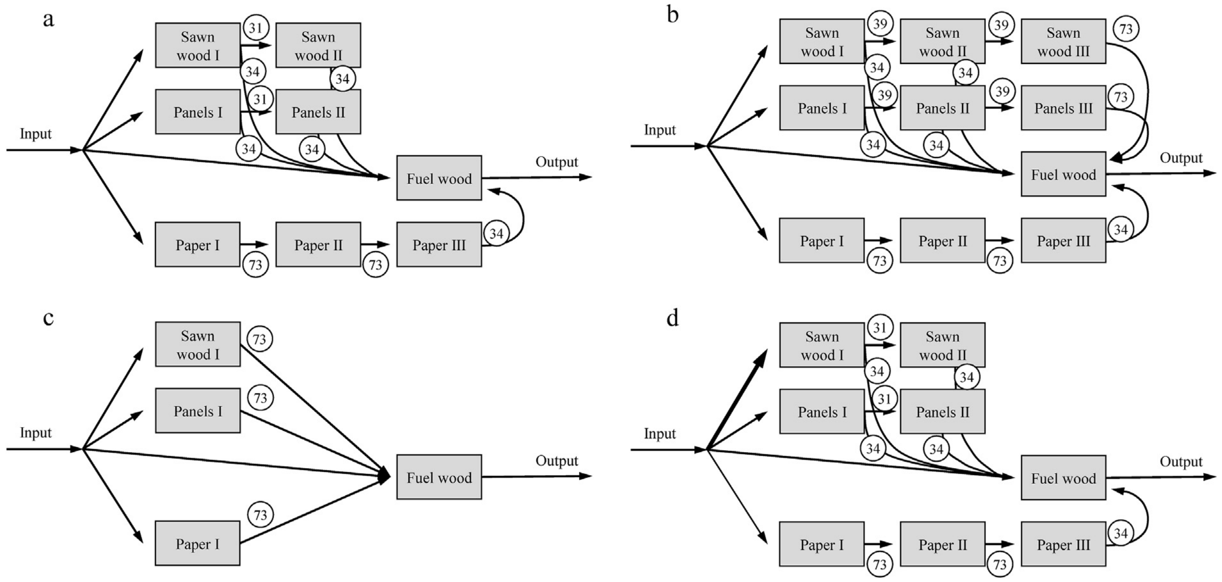

Fig. 1. Wood allocation patterns in the different scenarios (in %). a) *Business as usual* scenario & *Energy target* scenario. b) *Long cascade* scenario. c) *Short cascade* scenario. d) *Engineered wood* scenario. Notice that in scenario d) the arrow going to Sawn wood is thicker and the arrow to Paper I thinner than in scenario a), illustrating a different allocation.

this scenario we assumed that some low-quality logs currently employed to produce paper are getting used to produce engineered wood products instead. We assumed that engineered wood products are included in the category of *Sawn wood*. According to the review from Hetemäki and Hurmekoski (2016), paper production in West Europe will decrease in 2020 and 2030 by approximately 5 and 10%, respectively, compared to paper production in 2010. To define this scenario, we adapted these decreases to 10 and 20%, respectively. This expected percentage decrease of paper production in the indicated period was estimated from the average paper production between 2009 and 2018 and allocated to the production of *Sawn wood*.

The *Energy target* scenario aims at simulating the increment of *fuel wood* consumption in Europe needed to achieve the EU objectives on renewable energy production using wood fuel. Since specific European objectives on renewable energy production with wood fuel do not exist, we used projections of the PRIMES model (E3MLab/ICCS, 2014), which is one of the model results analysed by the European Commission (European Commission, 2016) to promote the use of energy from renewable sources. According to PRIMES, the increase of bioenergy use is estimated for the periods for 2020–2025 at 4%, for 2025–2030 at 0%, and for 2030–2050 at 46%. We extrapolated the increase of bioenergy use from 2030 to 2050 up to 2100. Recycling parameters used in this scenario were the same as the *BaU* scenario. The use increment of fuel wood estimated by PRIMES model includes harvested and recycled wood. The carbon stock and the carbon stock changes in domestic forests in this scenario is kept the same as in all scenarios. For this reason, we used an iterative approach increasing linearly the imports of fuel wood between the above-mentioned years to achieve the bioenergy use from virgin and recycled wood estimated by PRIMES model.

In short, alternative scenarios differ from the *BaU* scenario in the use of harvested wood but harvesting intensities and thus wood supply was kept the same among scenarios, but not constant. Therefore, emissions due to forest management and carbon stored in domestic forests are equivalent in all scenarios. The imports only increased in the *energy target* scenario. In the *BaU*, *long cascade* and *short cascade* scenarios the allocation of harvested wood to products is exactly the same. Only the use of recycled wood differs between these scenarios. The harvesting intensity in the *engineered wood* scenario is the same as in the *BaU* scenario, but here part of the wood previously consumed in paper industries is used to produce engineered wood products.

2.4. Substitution effect

As defined by Rüter et al. (2016), a substitution factor is a means to quantify the extent to which a wood product or fuel generates less or more greenhouse gas emissions over its whole life cycle than a functionally equivalent material or fuel. We used substitution factors for each product to estimate the substitution effect at country and continental scale of future production of alternative scenarios compared to *BaU* scenario. In this study, a positive value for the substitution factor indicates that the use of wood products emits fewer greenhouse gases than its alternatives. The substitution effect of year 2020 was estimated using European weighted average substitution factors taken from the FORMIT project (Cardellini et al., 2018). These substitution factors are calculated using LCA and based on the average European conditions in terms of type of energy and material used for the construction of the products. They ranged between 0.1 and 0.7 t C/t C, much lower than the value of 2.1 t C/t C found by Sathre and O'Connor (2010). For further years, we made these substitution factors dynamic by reducing them proportionally to the reduction of emissions consistent with the Paris Agreement as estimated by Rockström et al. (2017) (see Dynamic substitution factors section).

The methodology to calculate the revised substitution factors in the FORMIT study was based on Rüter et al. (2016) and is summarised as follows. Substitution factors were calculated separately for the production and end-of-life phases (a cradle-to-gate LCA and an end-of-life LCA) for both the wood based and the non-wood based alternative products. System expansion is used for the end-of-life phase. When wood products are incinerated to recover energy or if alternative products are recycled, the benefits associated with these end-of-life processes are accounted for by expanding the system boundaries. Consequently, a higher recovery rate for the wood product increases the value of the substitution factor. On the contrary, a higher recovery rate for the non-wood product decreases it. The material and energy substitution are differentiated considering the main function of the wood used. If saw dust is used as pellets, it is considered as energy substitution. On the other hand, when sawn wood is burnt at the end of life and energy is recovered, the substitution associated with this energy production is accounted for in the material substitution factor. This is because in the former case the wood leaves the boundary of the main product (i.e., the one which produced the saw dust) and enter the one of the new one (i.e., the pellet) for which the sole function is the production of energy. As such this is considered to be energy substitution. In the latter case the energy produced is functionally linked to the main product and thus the produced benefits in terms of energy saving are credited to it.

The substitution factors used for 2020 simulations are a weighted average of the substitution factors calculated for several final products in the FORMIT project (Valada et al., 2016). Specifically, the substitution factors used for sawn wood products were calculated as a weighted average of the substitution factor of the products reported in Table 3, while the ones used for panels were calculated as the weighted average of the substitution factor of the products reported in Table 4. As it is not possible to weigh the substitution factors based on the consumption of each single secondary wood products due to the well-known lack of such type of consumption data (Mantau, 2015), the individual product substitution factors were weighted based on the consumption data reported in EPF (2017) and EOS (2014). Information on the consumption of semi-finished products into the added-value market (i.e., primary and secondary construction products, furniture, packaging and others) by group (hardwood vs softwood) were extracted from these sources and used to weigh the displacement factors.

When panels or sawn timber were recycled into panels, the substitution factors (see Table 4) were recalculated by subtracting the impact of forest management since the recycling prevents the use of virgin wood with its associated impact. The reduction in energy use due to the use of already dried wood was not considered. When sawn wood was reused as sawn wood, the substitution factors and subsequent average considered in Table 3 were recalculated by subtracting the impact of producing sawn timber. Only the second transformation from the sawmill to the forest-based functional unit was considered in the wood product life cycle.

2.5. Decarbonization through dynamic substitution factors

As described in the Substitution effect section we calculated a substitution factor for each product category used in this study and its source including current non-wood-based material and energy alternatives (Table 5). However, according to the roadmap for rapid decarbonization described by Rockström et al. (2017), anthropogenic CO_2 emissions by fossil fuel and industry will decrease and use of renewable energies will increase. Consequently, substitution factors calculated for current use of products and energies will be affected. In order to represent these changes, we estimated dynamic substitution factors from our first calculations proportionally to gross anthropogenic CO_2 emissions estimated by Rockström et al. (2017) from 2010 to 2100 (Fig. 2).

3. Results and discussion

3.1. Continental scale GHG balance of wood product use

The GHG balance of wood product use in Europe will increase from 19.42 to 25.10 Mt CO_2 eq. year^{-1} between 2020 and 2030 if harvested wood is used as currently done (*BaU* scenario) (Fig. 3), where positive values means a sink effect. The slowing-down compared to previous years is explained by a lower increase in harvested volumes. This result represents 6.9% of the GHG balance of European forest land (364.96 Mt CO_2 eq. year^{-1} in 2018 according to the UNFCCC (2020)). The GHG balance could be larger in 2030 by increasing the consumption of wood for long-lived products, like in the *Long cascade* and *Engineered wood* scenarios (33.66 and 50.98 Mt CO_2 eq. year^{-1}, respectively) or by increasing the wood product consumption through import, like in the *Energy target* scenario (25.82 Mt CO_2 eq. year^{-1}). Instead, the GHG balance in 2030 will be reduced if all recycled wood is burnt, even when increasing the recovery rate to 73%, as simulated in the *Short cascade* scenario (0.85 Mt CO_2 eq. year^{-1}). These differences could be bigger if policies promote a faster transition towards the new scenarios than the simulated ones. In line with earlier studies (Brunet-Navarro et al., 2017; Smyth et al., 2018), the climate change mitigation effect of wood products becomes bigger in scenarios where the use of long-lived products is increased or more wood products are consumed. Rüter et al. (2016) identified an increment of cascade chains and use of harvested wood for long-lived products as the best strategies to increase the GHG balance of the forestry sector. We observed that longer cascade chains (*Long cascade* scenario) have a positive but limited impact on the GHG balance in comparison to employing low-quality wood for long-lived products (*Engineered wood* scenario), where the GHG balance is higher.

Table 3
Substitution factors for sawn wood used in building and construction (in t C/t C contained in semi-finished products). FBFU: Forest-based functional unit. CSW: Coniferous sawn wood. NCSW: Non-coniferous sawn wood. W. Avg. SF: Average substitution factor, weighted based on the consumption of the wood products.

FBFU	Roofing - household		Roofing - industrial hall	External wall	Cladding		Window		Parquet		W. Avg. SF
Semi-finished product	CSW	NCSW	CSW	CSW	CSW	NCSW	CSW	NCSW	CSW	NCSW	
Production	0.517	0.486	0.494	0.710	0.807	0.714	0.898	0.908	0.645	0.879	**0.388**
End of life	0.434	0.516	0.390	0.802	0.127	0.265	−0.278	−0.278	0.490	0.539	**0.364**

Table 4
Substitution factors for panels used in furniture (in t C/t C contained in semi-finished product). Weighting of substitution factors based on the consumption of the wood products.

FBFU	Shelve				Weighted Average substitution factor
Semi-finished product	Plywood	Particle board	MDF	Hardboard	
Production	−0.072	0.259	0.036	0.154	**0.179**
End of life	0.485	0.449	0.484	0.449	**0.458**

Table 5
Substitution factors estimated for each product and wood source under current conditions of product and energy uses.

	Sawnwood I	Sawnwood II	Sawnwood III	Panels I	Panels II	Panels III	Fuelwood	Paper I	Paper II	Paper III
Input	0.562910	0	0	0.178765	0	0	0.490098	0	0	0
Sawnwood I	0	0.636751	0	0	0.188011	0	0.383950	0	0	0
Sawnwood II	0	0	0.636750	0	0	0	0.383950	0	0	0
Sawnwood III	0	0	0	0	0	0	0.383950	0	0	0
Panels I	0	0	0	0	0.188011	0	0.457962	0	0	0
Panels II	0	0	0	0	0	0.188011	0.457962	0	0	0
Panels III	0	0	0	0	0	0	0.457962	0	0	0
Fuelwood	0	0	0	0	0	0	0	0	0	0
Paper I	0	0	0	0	0	0	0	0	0	0
Paper II	0	0	0	0	0	0	0	0	0	0
Paper III	0	0	0	0	0	0	0	0	0	0

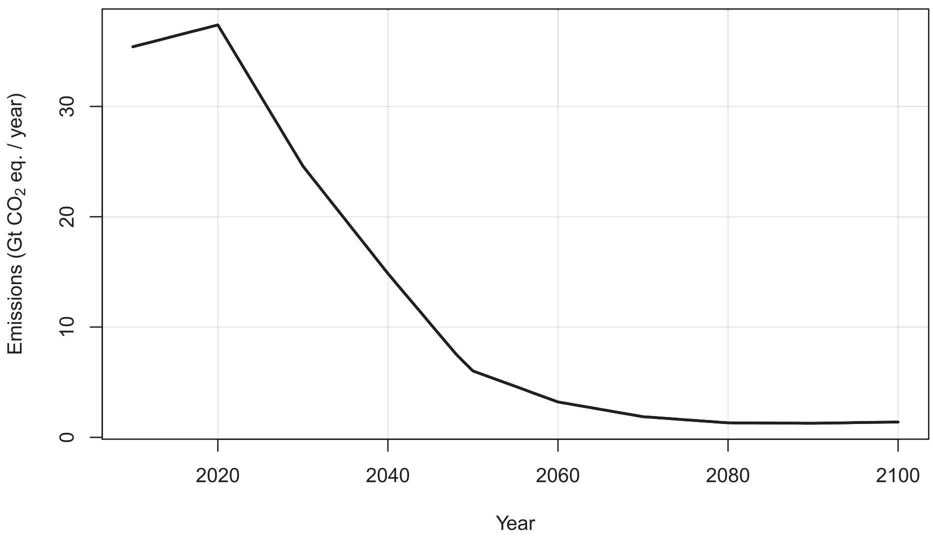

Fig. 2. Evolution of global anthropogenic CO_2 emissions (Gt CO_2 per year) by fossil fuel and industry according to estimations by Rockström et al. (2017).

3.2. *Mitigation effect of scenarios along time*

The mitigation effect of a scenario in comparison to the baseline results from both substitution and additional carbon stock change (Fig. 4). In general, the additional carbon stock change has a bigger impact than the substitution effect. This is in contrast to Werner et al. (2010) who claimed that in the long-term the substitution effect may be more important than the carbon stock change. The only exception is the *Energy target* scenario where the production of fuel wood (lifespan = 0 years) is the only production affected and therefore the carbon stock change is the same as in the *BaU* scenario. We also observed that the additional carbon stock change effect decreases over time once the scenarios are fully implemented in 2040. This reduction stabilizes about 35 years later (the average lifespan of the new products) moving closer to the *BaU* scenario. This effect is not observed in the *Engineered wood* scenario because its consequences appear later than 2100. Notice that if the alternative scenarios were applied suddenly since 2021, the mitigation effect during the next years would be much bigger due to an abrupt increase in production. Inversely, a slower implementation of scenarios would weaken the mitigation effect but extend it in time.

3.3. *Effects of dynamic substitution factors*

When dynamic substitution factors are applied, the substitution effect also decreased along time after reaching its maximum. This shrinking reflects a more prominent and increasing use of renewable, thus carbon neutral energy sources. This result is in contrast with model results using constant substitution factors, where the substitution effect increases over time for all scenarios (Fig. 5). Applying constant substitution factors, the substitution effect would be bigger than the carbon stock change effect as identified in literature previously (Werner et al., 2010). The difference between using dynamic or constant substitution factors in the scenarios analysed ranged from 0.25 to 4.84 Mt CO_2 eq. year^{-1} in 2030, and from −7.56 to 197.40 Mt CO_2 eq. year^{-1} in 2100 (Fig. 5). When employing constant substitution factors instead of dynamic factors, the total climate change mitigation effect for the most climate friendly scenario of *Engineered wood* increased from 50.98 to 55.82 Mt CO_2 eq. year^{-1} in 2030, and from 189.10 to 386.50 Mt CO_2 eq. year^{-1} in 2100. The substitution effect in the dynamic scenario will be reduced 96.2% in 2100. Hence, defining the expiry date as when the share of renewables is bigger than 95% in the energy mix, it will arrive at the end of the century. Notice results could differ if emissions are heterogeneously reduced among sectors as it happens in the real world.

Other reasons for the lower substitution effect in our study is the assumption of marginal substitution in comparison to the baseline scenario rather than full substitution and the non-cumulative effect (Geng et al., 2017).

3.4. *Policy recommendations on wood use*

Future policies aiming to reduce GHG emissions should promote the use of harvested and recovered wood instead of fossil-energy intensive materials. Although substitution may not be as big as

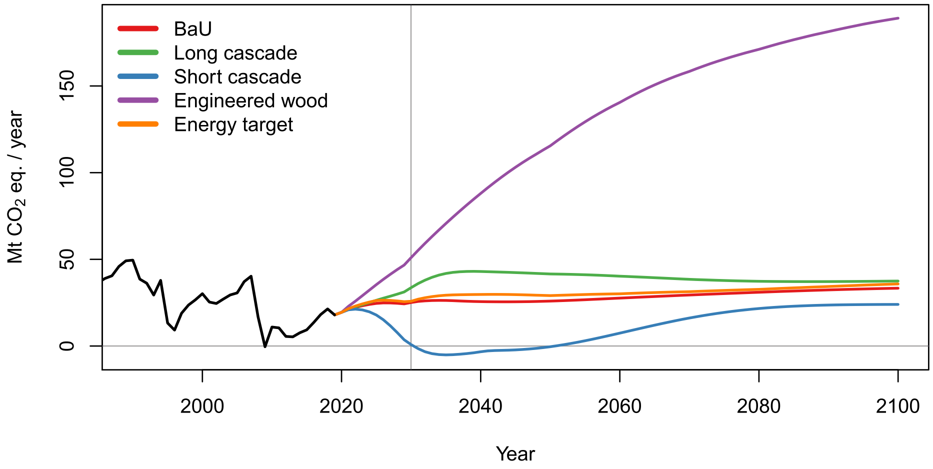

Fig. 3. Overall GHG balance of wood product use scenarios for the EU-28 (where positive values means a sink effect). The BaU scenario only includes carbon stock change effects, as it is considered to have no substitution effect. The four alternative scenarios include stock changes and marginal substitution effects in comparison to the BaU, using dynamic substitution factors.

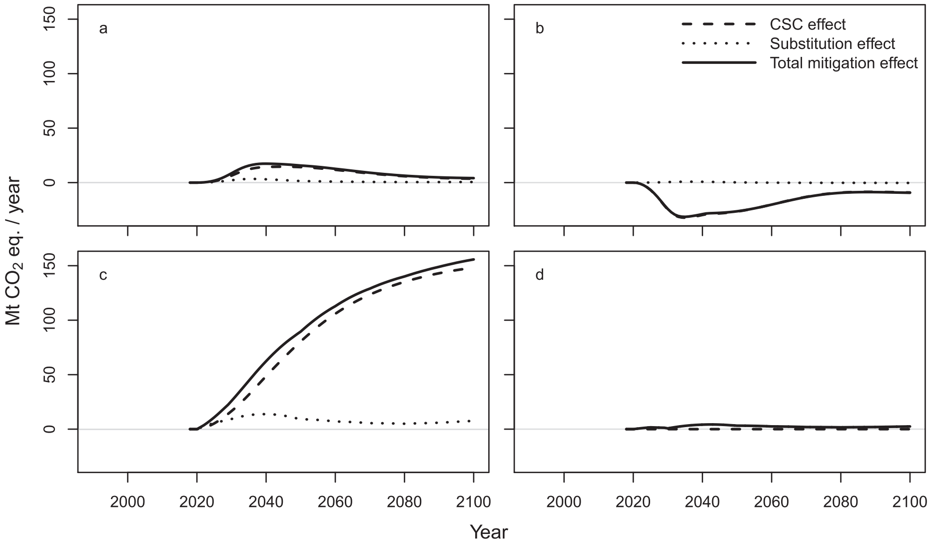

Fig. 4. Mitigation effect of four alternative scenarios in comparison to the *Business as Usual* scenario. a) *Long cascade* scenario. b) *Short cascade* scenario. c) *Engineered wood* scenario. d) *Energy target* scenario. Dashed lines represent the additional carbon stock change (CSC) in each scenario compared to the carbon stock change of the *Business as Usual* scenario. Dotted lines represent the substitution effect of each alternative scenario compared to the *Business as Usual* scenario. Continuous lines represent the total mitigation effect of each alternative scenario.

previously expected, measures aiming to enhance cascade chains and to employ low-quality wood for long-lived engineered wood products may increase the mitigation effect from 25.10 to 50.98 Mt CO_2 eq. year^{-1} by 2030. This represents 3.3% of the EU GHG emission reduction target of 1524.2 Mt CO_2 eq. year^{-1} (from the 3953.0 Mt CO_2 eq. year^{-1} in 2018 to the 55% reduction target of 2428.8 Mt CO_2 eq. year^{-1} in 2030). By this, wood products could increase their contribution to reduce GHG emissions in 2030 at EU level from 1.0 to 2.1%. At longer term, the mitigation effect of wood products will be smaller, but the increased use of renewable energies will already contribute to reduce GHG emissions.

4. Conclusions

We used a novel but more realistic approach to calculate the mitigation of alternative wood use scenarios by applying marginal substitution with dynamic substitution factors on the energy substitution, which inherently effects the material substitution. The results show that effective policies aiming at the decarbonization of the atmosphere should not promote the use of low-quality logs for energy, but rather for long-lived wood products first, and then, to promote cascade chains. Although lower than expected at long term, climate change mitigation effects of wood product use will play a role in the order of several percent, and therefore are policy relevant. This role becomes smaller the closer we get to the substitution expiry date, i.e. the date when a high percentage of renewable sources in the energy mix will be reached, estimated to occur around 2100. Policies to promote the use of wood in construction should be implemented with urgency to take advantage of the window of opportunity with strong substitution effect now that the share of renewable energy sources is still low.

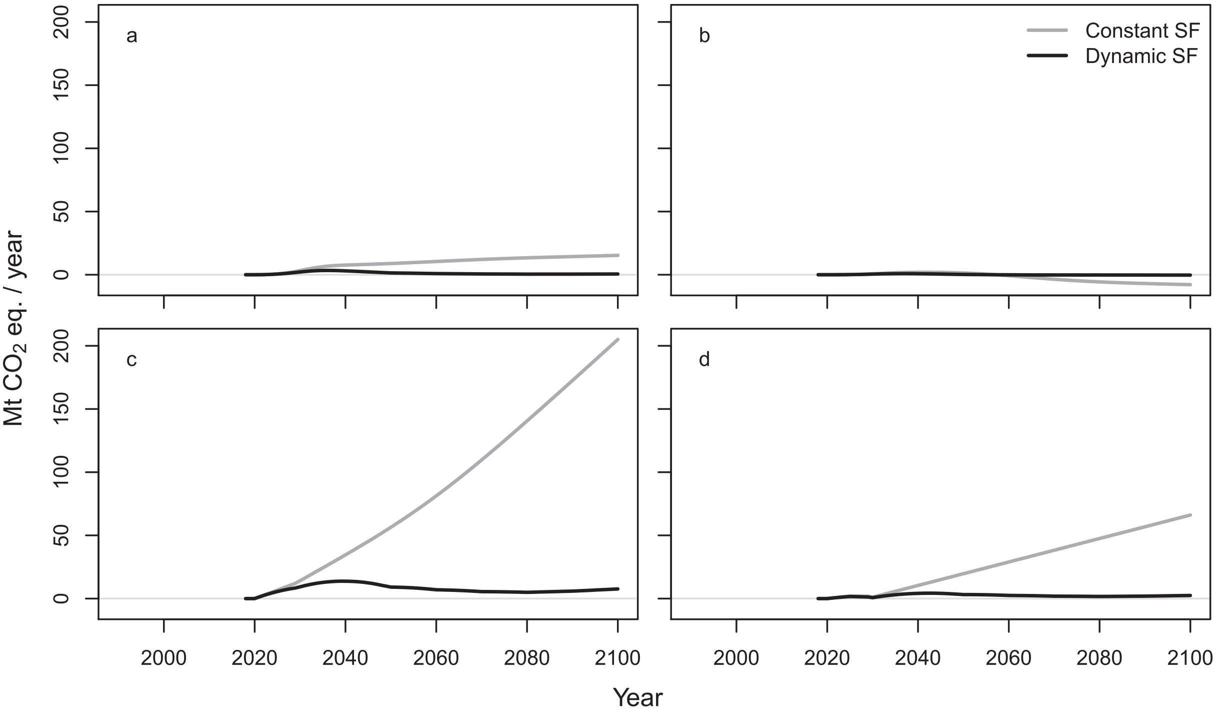

Fig. 5. Effect of dynamic vs. constant substitution factors (SF) on the substitution effect. *Business as Usual* scenario is used as baseline scenario. a) *Long cascade* scenario. b) *Short cascade* scenario. c) *Engineered wood* scenario. d) *Energy target* scenario.

CRediT authorship contribution statement

Pau Brunet-Navarro: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Hubert Jochheim:** Conceptualization, Funding acquisition, Writing – review & editing. **Giuseppe Cardellini:** Project administration, Writing – review & editing. **Klaus Richter:** Methodology, Writing – review & editing. **Bart Muys:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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