Carbon accounting of material substitution with biomass: Case studies for Austria investigated with IPCC default and alternative approaches

Keywords: Biomass, Material substitution, Harvested wood products, Climate policy frameworks, Climate change mitigation, Carbon accounting

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Abstract:

There is evidence that the replacement of carbon-intensive products with bio-based substitutes (‘material substitution with biomass’) can be highly efficient in reducing greenhouse gas (GHG) emissions. Based on two case studies (CS1/2) for Austria, potential benefits of material substitution in comparison to fuel substitution are analysed. GHG savings are calculated according to default IPCC approaches (Tier 2 method assuming first-order decay) and with more realistic approaches based on distribution functions. In CS1, high savings are achieved by using wood residues for the production of insulating boards instead of energy. The superiority of material substitution is due to the establishment of a long-term carbon storage, the high emission factor of wood in comparison to natural gas and higher efficiencies of gas-fired facilities.

The biomass feedstock in CS2 is lignocellulosic ethanol being used for bio-ethylene production (material substitution) or replacing gasoline (fuel substitution). GHG savings are mainly due to lower production emissions of bio-ethylene in comparison to conventional ethylene and significantly lower than in CS1 (per unit of biomass consumed). While CS1 is highly robust to parameter variation, the long-term projections in CS2 are quite speculative.

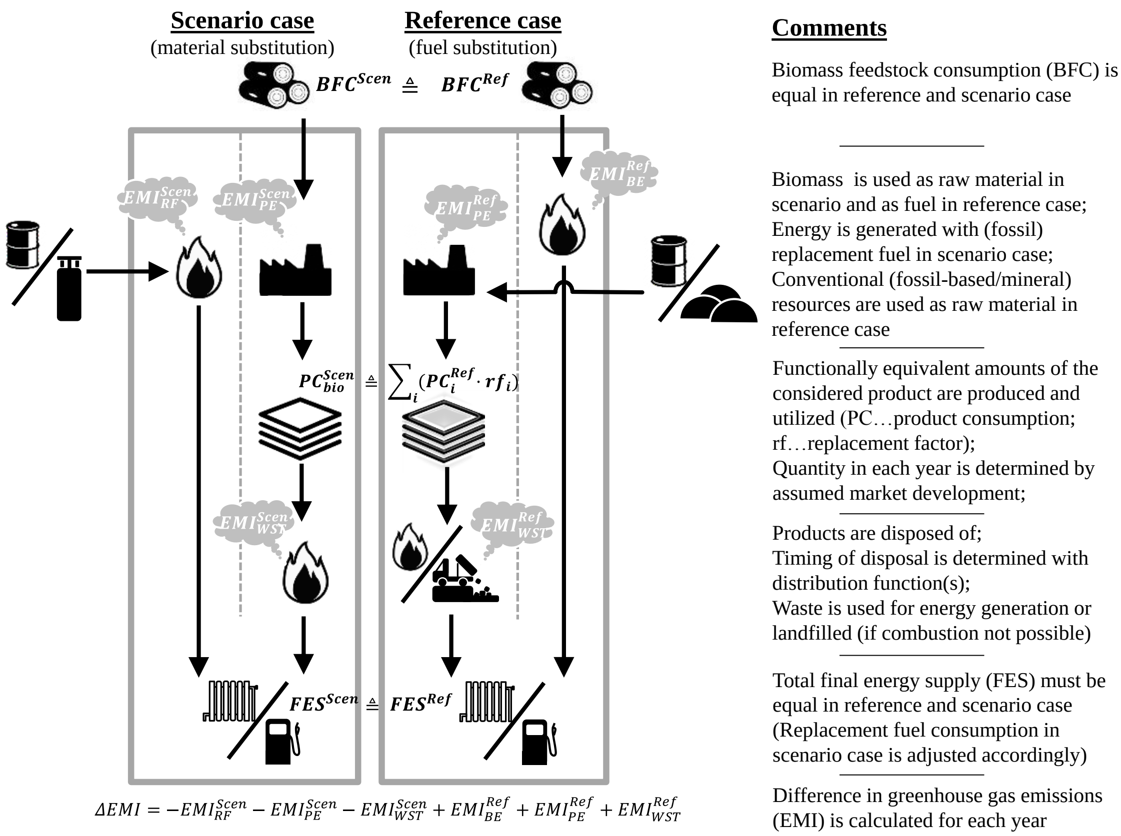
To create adequate incentives for including material substitution in national climate strategies, shortcomings of current default accounting methods must be addressed. Under current methods the GHG savings in both case studies would not (fully) materialize in the national GHG inventory. The main reason is that accounting of wood products is confined to the proportion derived from domestic harvest, whereas imported biomass used for energy is treated as carbon-neutral. Further inadequacies of IPCC default accounting methods include the assumption of exponential decay and the disregard of advanced bio-based products.

Highlights:

- Carbon accounting of material substitution with biomass compared to fuel substitution
- GHG benefits of material substitution are analysed under different accounting methods
- High benefits in comparison to fuel substitution with biomass are possible

- Benefits do not (fully) materialize under default methods, creating wrong incentives
- Default IPCC accounting methods need to be revised to provide adequate incentives

Graphical abstract:



1 Introduction

The substitution of fossil fuels with biomass is a core element of the EU's climate and energy strategy (see European Commission, 2011; Beurskens and Hekkenberg, 2011; Kalt, Kranzl, Matzenberger, 2012). Much less promoted is material substitution with biomass, despite evidence that the replacement of energy-intensive materials with bio-based counterparts can be highly efficient in reducing greenhouse gas (GHG) emissions (Sathre and O'Connor, 2010; Gustavsson et al., 2007; Burschel et al., 1993; Perez-Garcia et al., 2007; Kalt et al., 2015; Sikkema and Nabuurs, 1995; Sathre and Gustavsson, 2006). In optimal applications of long-lived bio-based products the benefits of material substitution are threefold: (1) Energy consumption and GHG emissions from production processes can be reduced, (2) biogenic carbon is stored over a considerable period of time instead of being released into the atmosphere and (3) bio-based products can be used as renewable fuel or secondary raw material at the end of their lifespan ('cascading biomass use').

The 1996 IPCC Guidelines assumed that all carbon removed from forests is oxidized in the year of harvest (Grêt-Regamey et al., 2008). Hence, a main advantage of material substitution over fuel substitution was disregarded in GHG accounting, creating a considerable 'incentive gap' (cf. Ellison, Lundblad, Petersson, 2011), as this methodology favoured bioenergy over material use (Ellison, Lundblad, Petersson, 2014).

Recognizing that the dynamics of artificial carbon pools in the form of long-lived wood products are actually quite relevant, accounting of 'harvested wood products' (HWP) was made obligatory for the second commitment period of the Kyoto protocol from 2013 to 2020 (cf. Frieden et al., 2012). Several accounting methods have been under discussion, and the implications, incentives and shortcomings of different approaches have been compared and discussed thoroughly (e.g. Lim, Brown, Schlamadinger, 1999; Grêt-Regamey et al., 2008; Kohlmaier et al., 2007). The current IPCC Guidelines (IPCC, 2014) define some general rules and good practice guidance for HWP accounting, but also leave methodological options open; most notably the treatment of international trade with HWP and the selection of decay functions, which determine the temporal distribution of outflows from the carbon pool (based on typical product lifespans).

The most common approach, which is also applied in Austria's GHG inventory report (Umweltbundesamt, 2015), is the default 'Tier 2 method' with system boundaries according to the ‘production approach’ (PA) (cf. Pilli, Fiorese, Grassi, 2015; Brunet-Navarro et al., 2016; Butler et al., 2014; Sikkema et al., 2013; Yang and Zhang, 2016). Under Tier 2 it is assumed that HWP carbon stocks decline according to a first-order (exponential) decay function. All HWP produced from domestic harvest are considered as inflow to the pool under the PA, regardless of whether they are exported or consumed domestically (cf. Pingoud et al., 2003; Pingoud et al., 2006). It has further been argued that exponential decay is actually unrealistic for many (especially long-lived) wood products, because it assumes high outflows from the HWP pool in the first years (cf. Cherubini, Guest, Stroman, 2012; Marland, Stellar, Marland, 2009). Hence, it is questionable whether results of the default Tier 2 method appropriately reflect carbon stock changes (cf. supplementary material for a more detailed description of the default Tier 2 approach).

So far there is hardly any literature focusing on the GHG mitigation resulting from material substitution under different accounting approaches; only one case study for Canada by Sikkema et al. (2013) is known, where only first-order decay is considered. Considering the EU’s long-term commitment to establish a bioeconomy until 2050 (European Commission, 2012), material substitution will likely become increasingly important in Europe; and so will carbon accounting of bio-based products. The benefits of material substitution compared to fuel substitution are of special interest, as enhanced cascading biomass use is considered essential for a sustainable and efficient biomass sector (Keegan et al., 2013; Van Lancker et al., 2016). Therefore, appropriate methods for analysing specific utilization paths need to be developed.

2 Research question

This work seeks to quantify the climate benefits of material substitution as compared to fuel substitution under different accounting approaches. A specific methodology for comparing GHG mitigation from material substitution and fuel substitution is presented. A special focus is put on the implications of different decay functions used for modelling outflows from HPW stocks.

Two case studies (CS) are investigated: Wood insulating boards produced from wood residues (CS1) and bio-ethylene produced from lignocellulosic ethanol (CS2). A core objective is to identify implications of different accounting methods and general shortcomings of the default approach.

Due to the long-term nature of the assumed market developments and according carbon pool changes, the considered timeframe is 2015 to 2075. The robustness of results against uncertain parameters is investigated in sensitivity analyses. The case studies are based on conditions in Austria, but most findings – especially about methodological issues –are universally valid.

3 Methodology

3.1 Decay functions

Distribution functions with the highest probability near the typical product lifespan are considered more appropriate than exponential decay for modelling carbon stocks of long-lived products (Cherubini, Guest, Stroman, 2012; Marland, Stellar, Marland, 2009). Cherubini et al. (2012) have applied the dirac function (delta function) and chi-square distribution to model the temporal distribution of carbon outflow from wood product pools over time. They found that the chi-square distribution 'appears the most reliable and appropriate option under a methodological perspective'. Following Cherubini et al. (2012), a chi-square distribution with k degrees of freedom and the time dimension t is applied:

$$\chi^2(t;k) = \frac{1}{2^{k/2}\Gamma(k/2)} t^{((k/2)-1)} e^{(-t/2)} \tag{1}$$

Γ(k/2) is the gamma function, defined as:

$$\Gamma(k/2) = \int_0^{\infty} x^{((k/2)-1)} e^{-x}\, dx \tag{2}$$

In deviation from Cherubini et al. (2012), k is assumed equal to the mean product lifetime τ (rather than τ + 2).

The delta function is a suitable representation if it is assumed that 100 % of a wood product is combusted after a fixed lifespan. A key benefit of this approach is its simplicity, which makes it attractive for comprehensive simulation and optimization models (e.g. Kalt et al., 2015). The delta function has the following analytical form:

$$\delta(t;\tau) = \begin{cases} 0, & t \neq \tau \\ \infty, & t = \tau \end{cases} \tag{3}$$

It is zero for all values of t except for a single point (the product lifetime τ) where all the carbon is oxidized. Fig. 1 shows an illustration of these decay functions for a product with a mean lifetime of 30 years. The left graph shows the distribution functions, i.e. the temporal distribution of carbon outflow from the HWP pool. The right graph shows the according carbon stock developments under the assumption that the stock is established at t = 0 and no inflows occur thereafter. If the delta function is assumed, all carbon stored in the HWP pool is oxidized/removed from the pool at the end of the product lifespan, so the carbon stock drops to zero at t = τ. Chi-square decay exhibits almost constant carbon stock until about 50 % of the typical product lifespan and a rapid decrease around the typical product lifespan. Exponential decay, as assumed under Tier 2 method, exhibits high outflows from the carbon pool in the first years; even for a product with a typical lifespan of 30 years.

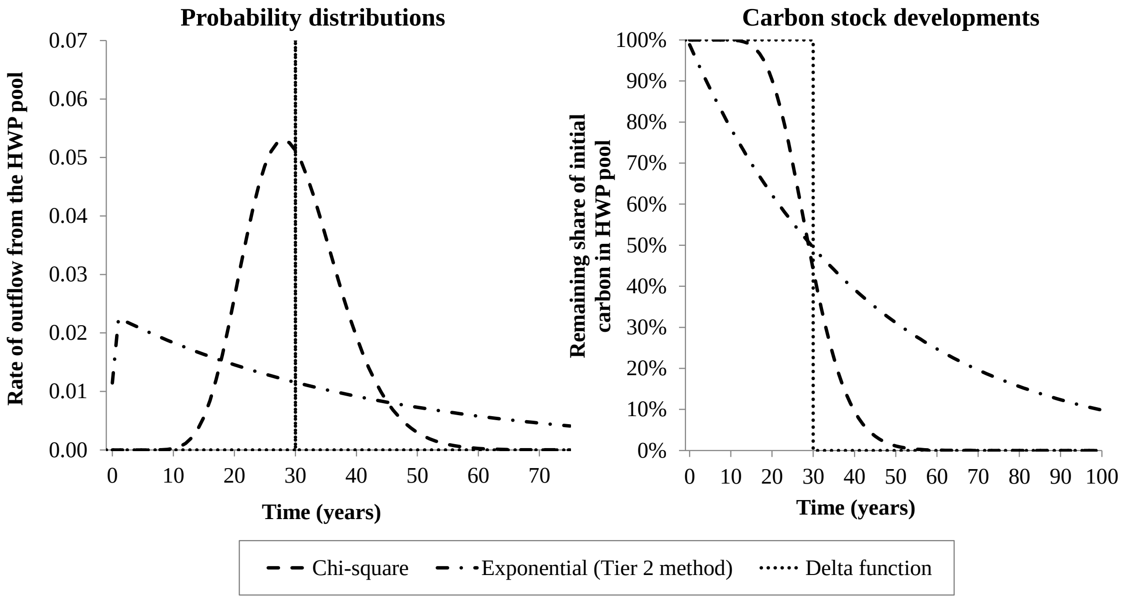


Figure 1. Probability distributions used to model carbon stock changes of wood products (left) and according carbon stock developments assuming a single inflow at t = 0 (right)

Source: Authors' illustrations based on Cherubini et al. (2012) and IPCC (2014)

3.2 Scenario analysis

A calculation model has been developed to quantify potential benefits of material substitution in terms of GHG mitigation. It is applicable for biomass feedstocks which are currently widely used for energy generation, but may be diverted to material uses (such as wood processing residues and bioethanol). Fig. 2 shows an illustration of the concept. The basic idea is to compare a scenario with increasing material substitution (superscript 'Scen') with a reference case (superscript 'Ref'), where the same amount of biogenic feedstock is directly used for energy in each year. The amount of energy supplied (in the scenario case by using a 'replacement fuel'; the most likely alternative fuel) is also identical in the two cases.

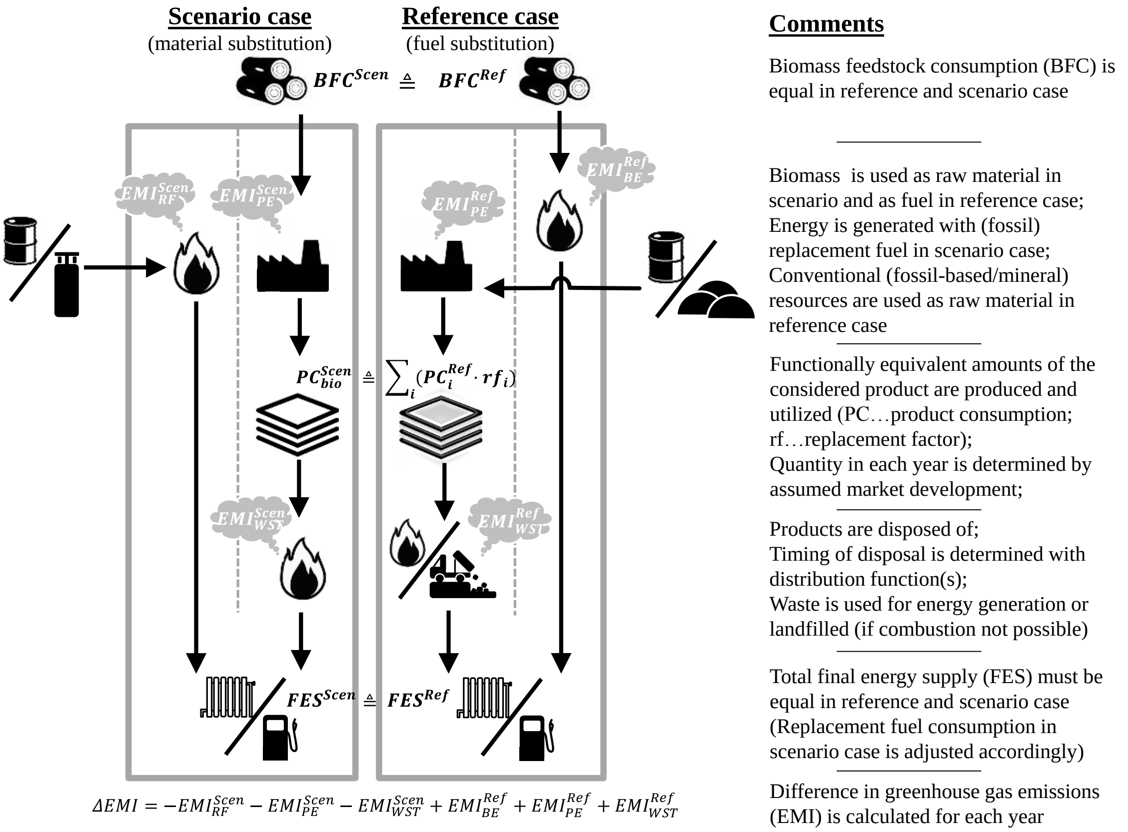


Figure 2. Schematic illustration of the model concept

Biomass feedstock consumption ('BFC') in the scenario case is determined by an assumed market diffusion of the respective wood product (wood insulating boards in Case Study 1 (CS1) and wood-based bio-ethylene in CS2). Considering cradle-to-gate GHG emissions of these products ('production emissions'; index 'PE') and the conventional counterparts, direct and upstream GHG emissions of biomass and replacement fuels used for energy ('BE'; 'RF') and waste combustion ('WST') the GHG savings achieved in the scenario case are determined. These savings correspond to the sum of emissions in the reference case minus emissions in the scenario case:

$$\Delta EMI(t) = EMI^{Ref}(t) - EMI^{Scen}(t) = EMI_{BE}^{Ref}(t) + EMI_{PE}^{Ref}(t) - EMI_{PE}^{Scen}(t) + EMI_{WST}^{Ref}(t) - EMI_{WST}^{Scen}(t) - EMI_{RF}^{Scen}(t) \quad (4)$$

Since the BFC as well as energy supplied in the scenario and the reference case are by definition equal in each year, it is methodically correct to directly compare the two

cases. Moreover, the GHG balance of biomass production (e.g. changes in natural carbon stocks) may be disregarded because it is identical in the two cases.
The delta and chi-squared function are used to determine the temporal distribution and amount of HWP leaving the pool and being used for energy generation in waste incineration plants. Assuming the chi-squared distribution, the amount of waste from discarded bio-based products is

$$WST_{bio}^{Scen}(t) = \sum_{t'=t_0}^{t-1} \chi^2(t-t';\tau) \cdot BFC(t') \quad (5)$$

for all years t > t_0, where t_0 is the first year of the scenario analysis (2015). Assuming the delta function, the amount of waste in the year t corresponds to the BFC in (t-τ):

$$WST_{bio}^{Scen}(t) = BFC(t-\tau) \quad (6)$$

A complete mathematical description of the model is provided in the supplementary material.

3.3 Scenario evaluation: 'Actual' vs. 'Tier 2 method savings'

Methods based on the distribution functions chi-square and delta are considered to reflect real-world conditions better than the default approach based on exponential decay. Still it is interesting to know how the assumed trends towards material substitution would materialize in national GHG balances under the current accounting approach. Therefore, the GHG savings calculated in accordance with Tier 2 method (ΔEMI_{Tier2}) are compared against the savings according to the 'flux data approach' applied in the model (ΔEMI). The latter are hereafter called 'actual savings'.

It is, however, important to note that the temporal distribution of waste generation and combustion is always determined by the respective probability function, not the exponential decay function assumed for Tier 2 method. This discrepancy between 'actual' stock developments and such assumed in the Tier 2 method is deliberately assumed, as it is considered to reflect real-world conditions. Also, the half-lives assumed under Tier 2 method are always the default values according to IPCC (2014), regardless of the specific product lifetimes assumed in the model. The GHG savings according to Tier 2 method are calculated as follows:

$$\Delta EMI_{Tier2}(t) = \Delta C(t) + EMI_{PE}^{Ref}(t) - EMI_{PE}^{Scen}(t) + EMI_{WST}^{Ref}(t) - EMI_{RF}^{Scen}(t) \quad (7)$$

ΔC(t) is the carbon stock change of the HWP pool during year t according to Equ. 2.8.5 in IPCC (2014).

4 Case studies

Two case studies are considered. The following descriptions include a rationale for the design and parameter settings of each case study, an analysis of results and sensitivity analyses. Fig. 3 shows the assumed market developments of wood insulating boards (CS1) and bio-ethylene (CS2). The supplementary material provides an analytical description of the assumed market diffusion curves as well as all relevant material and fuel parameters.

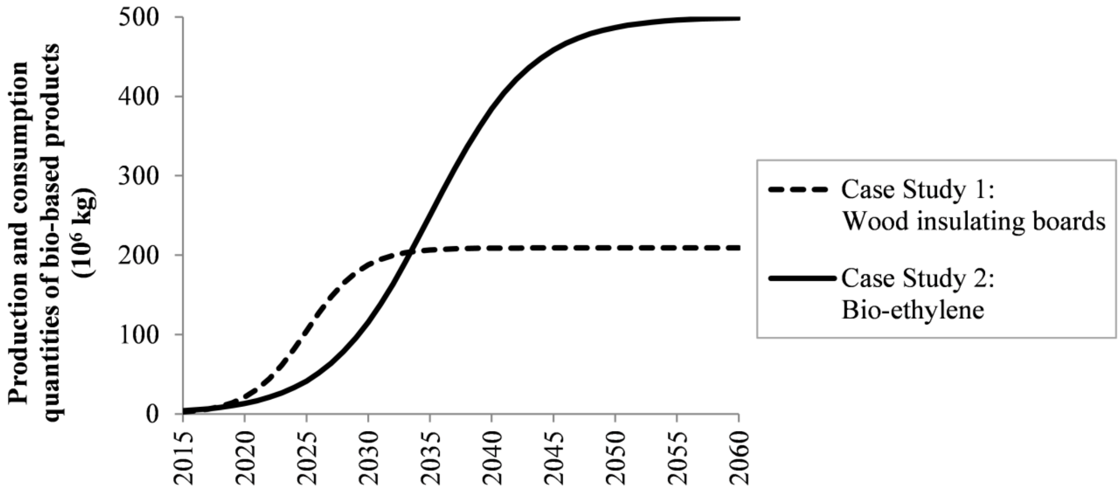


Figure 3. Assumed market developments in the scenario cases

4.1 CS1: Wood insulating boards

4.1.1 Design and assumptions

The market for insulation material in Austria is dominated by mineral (rock and glass wool) and synthetic products (polyurethane, extruded polystyrene etc.). Wood insulating boards (WIB), which currently hold an insignificant share of the market, usually have slightly higher thermal conductivities than these products. Hence, more material is needed to achieve a certain insulating quality. Apart from that, WIB can be considered functionally equivalent and to have a high market potential. This makes them an interesting case study to investigate.

Based on current market data (KFP, 2016) and under the assumption of an ambitious energy efficiency scenario developed with a simulation tool for the Austrian building sector (Müller, 2015), a market potential for WIB of 1.2 million m^3 is assumed.

This is functionally equivalent to approximately 20 % of today's consumption of insulation material.

The raw material for WIB is usually wood processing residues in the form of chips and particles. Large quantities of this commodity are available from Austrian sawmills. Currently, they are partly used for paper and panelboard production, and partly for energy generation in bioenergy plants. Therefore it is justified to assume direct utilization for energy as reference case to a scenario with increasing material substitution. The replacement fuel, assumed to be used for energy generation instead of biomass in the scenario case, is natural gas. Energy supply is measured in terms of final energy to account for differences in plant efficiencies. Based on typical efficiencies of large-scale heat supply systems, they are assumed 80 % for biomass, 75 % for wastes and 90 % for natural gas. Cradle-to-gate emissions of all types of insulating boards, which are mainly caused by energy use in production, are assumed to decrease to 20 % of their original values until 2050 and 5 % until 2075 as a consequence of progressing decarbonisation of energy supply. By default the mean lifetime of insulating boards is assumed 30 years.

4.1.2 Results

The following figures show the model results under default assumptions. Fig. 4 shows the development of emissions in the scenario and the reference case, assuming chi-square distribution. As in Equ. 4, emissions in the scenario case are represented as negative, and emissions in the reference case as positive values. ΔEMI describes the annual GHG savings in the scenario compared to the reference case.

Material substitution apparently results in significant GHG savings during market diffusion, as carbon stored in wood residues, which is oxidized in the reference case, is diverted to a long-term carbon pool. Until about 2050, the annual carbon savings account for close to 40 % of the carbon stored in wood consumed and almost 70 % of the carbon contained in the replacement fuel.

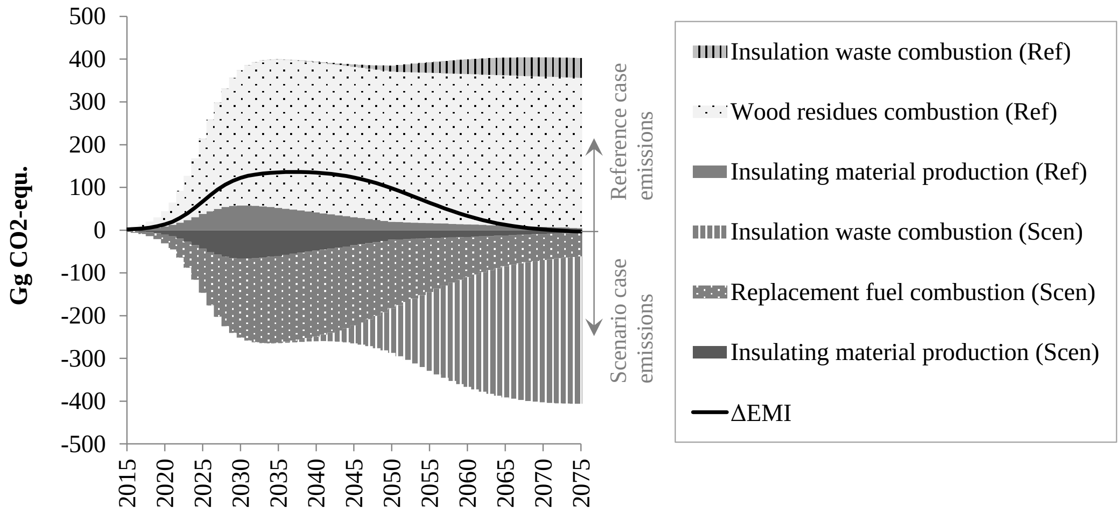


Figure 4. Annual GHG emissions in the reference ('Ref') and the scenario ('Scen') case of CS1 under default parameter settings

Fig. 5 shows the GHG savings assuming chi-square and delta distribution, as well as results from Tier 2 method. The deviations resulting from the (methodically simpler) delta function in comparison to the chi-square distribution are moderate. Regarding cumulated savings, they are more or less limited to the period 2045 to 2060. The time series for annual savings ΔEMI has a smoother characteristic if chi-square distribution is assumed. On the long term, cumulated GHG savings of about 4 Tg CO_2-equ. are achieved in the scenario case ('actual savings'). The average annual savings in the timeframe 2015 to 2050 are close to 100 Gg CO_2-equ. and equivalent to 0.12 % of Austria's base year emissions under the Kyoto Protocol (79 Tg; UNFCCC, 2014).

For evaluations based on Tier 2 method, three different cases are assumed. First, HWP accounting is entirely disregarded ('No HWP accounting'; ΔC(t) in Equ. 7 is equal zero throughout the whole period). In this case material substitution has a strong negative effect on the GHG balance because of additional consumption of natural gas. With HWP accounting, the share of domestic raw material is of crucial importance (Equ. 2.8.1 in IPCC, 2014): Assuming a typical share of 60 % domestic roundwood (which is consistent with the Austrian average during the last 20 years), annual GHG savings in the scenario case are negative until after 2055. Hence, under current framework conditions and if Tier 2 method is applied, material substitution with WIB does not appear as an efficient climate strategy, although it would actually result in CO_2 mitigation. The reason for this discrepancy is a methodological inconsistency regarding wood imports: If used for energy, imported biomass (and residues derived from imported roundwood) is a carbon neutral fuel, whereas HWP accounting is restricted to the proportion of domestic supply. Under the (quite unrealistic) assumption of 100 % domestic raw material, cumulated GHG savings according to Tier 2 method are positive but significantly lower than actual savings, due to the shape of exponential decay functions.

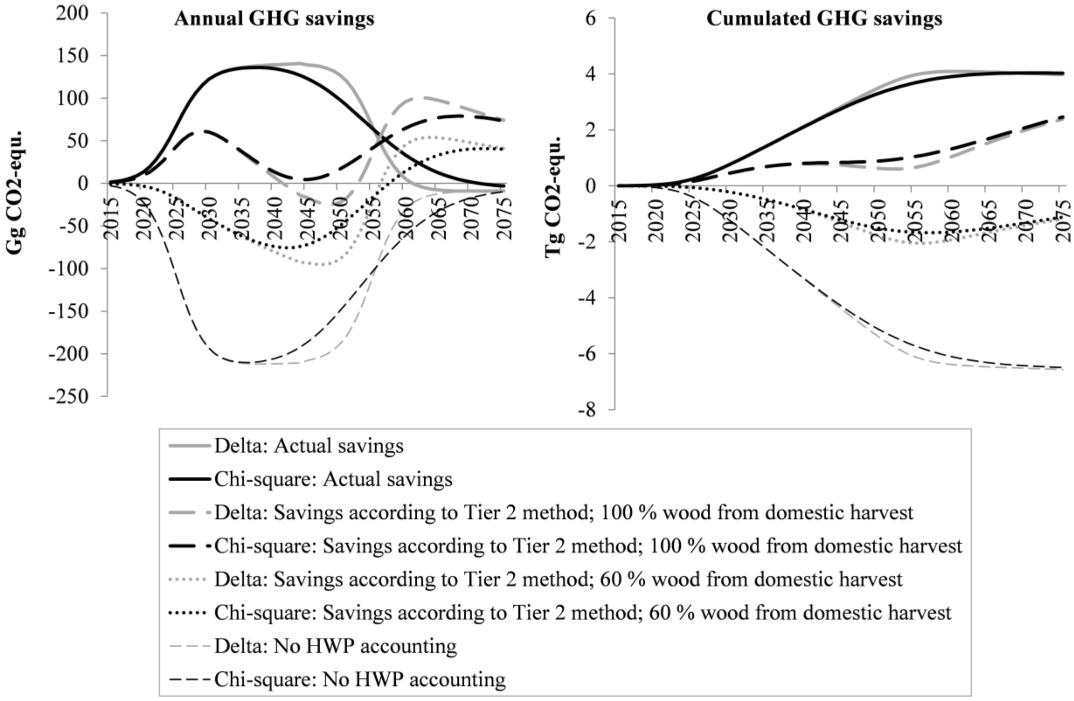


Figure 5. Annual and cumulated GHG savings in the scenario case, assuming different distribution functions (‘delta’ and ‘chi-square’), GHG balancing approaches and shares of domestic raw material

4.1.3 Sensitivity

The results described above are mainly due to the following incontestable facts: Specific GHG emissions caused by wood combustion are clearly higher than those of natural gas, which is definitely the most likely replacement fuel. Cradle-to-gate GHG emissions of all insulating boards are relatively low in comparison to the carbon stored in wood boards (measured in CO_2-equivalents). And third, efficiencies of natural gas facilities are generally higher than those of biomass plants.

Hence, the main findings described above are highly robust to parameter variation. For example, they even hold if cradle-to-gate emissions of wood boards are assumed to be twice as high as the assumed default value (Table S2 in the supplementary material). Long-term cumulated savings would be about 50 % lower than under default assumptions, material substitution would still be preferable to fuel substitution in terms of climate mitigation. Similarly, significantly higher upstream emissions of natural gas (e.g. 40 kg CO_2-equ./GJ instead of the default value 18.82) would result in lower cumulated savings (1.9 Tg CO_2-equ. in 2050), but do not alter the main findings.

A sensitivity analysis regarding product lifetime shows that the longer the mean service life is, the higher the savings are. A lifetime variation of 5 years results in a change of long-term cumulative savings of about 0.7 Tg CO_2-equ (Figure S1).

4.2 CS2: Bio-ethylene

4.2.1 Design and assumptions

Ethylene is a platform chemical for the production of some of the most important polymers, including PVC, PET and polystyrene (Shen, Worrel, Patel, 2010). Bio-ethylene is assumed to be produced from lignocellulosic ethanol (ethanol produced from woody biomass; cf. Wyman, 1994) in this case study. The reference application for ethanol is its use as transport fuel (cf. IEA-ETSAP/IRENA, 2013a). The replacement fuel is gasoline. Unlike CS1, no differences in conversion efficiencies need to be considered. In CS2 it is investigated whether wood-based ethanol used for chemicals production and replacing fossil-based chemicals, is preferable to its utilization as transport fuel.

Bio-ethylene is chemically identical to petroleum-/naphta-based ethylene (IEA-ETSAP/IRENA, 2013b). This has simplifying implications for the case study: It is not necessary to take further processing steps of the intermediate chemical ethylene into consideration. Furthermore, the choice of probability distribution has no influence on ΔEMI if ‘actual’ savings are considered. Not so if Tier 2 method is applied, because in this case bio-ethylene is assumed carbon-neutral in combustion, but not conventional ethylene. Thus, the time at which products are discarded (determined by probability distributions) has an influence on the temporal distributions of emissions.

Typical lifetimes of ethylene-based products (including short-lived packaging material as well as long-lived products like window frames) vary widely. 5 years is assumed as default value and up to 10 years in sensitivity analyses. As in CS1, cradle-to-gate GHG emissions are assumed to decline (for both types of ethylene to 40 % of the initial value until 2050 and 5 % until 2075).

4.2.2 Results

Fig. 6 shows the main results of CS2 in the default case. As mentioned above, the results for 'actual' savings are unaffected by the choice of distribution function, so only one time series, titled 'actual savings', is shown. In contrast, the results from Tier 2 method depend on the timing of waste combustion and therefore also on the choice of distribution function.

The time series for 'actual' savings indicates that considerable GHG reductions can be achieved through material substitution with bio-ethylene. Despite relatively short assumed mean product lifetimes, the increase in artificial carbon stocks yields positive effects on the GHG balance. But on the longer term, the main contribution to emission savings comes from lower cradle-to-gate emissions of bio-ethylene in comparison to its fossil-based counterpart. Under the default parameter settings, these savings surpass those achieved with ethanol as fuel. The 'actual' savings cumulate to about 2 Tg CO_2-equ. until 2050 and more than 3 Tg CO_2-equ. until 2075. Compared to CS1 the GHG savings per unit of wood consumed are significantly lower.

However, the carbon stock increase in this case study is not accountable under Tier 2 method, as bio-based chemicals/polymers are by default not considered. As a consequence, Tier 2 method results in clearly negative savings; i.e. higher GHG emissions in the scenario (where ethanol is used for ethylene) than in the reference case (where ethanol is directly used as fuel). Due to the comparatively high emission factor of the replacement fuel gasoline, the additional emissions are considerable: they cumulate to more than 4 Tg CO_2-equ. until 2050. The choice of distribution function is of minor importance.

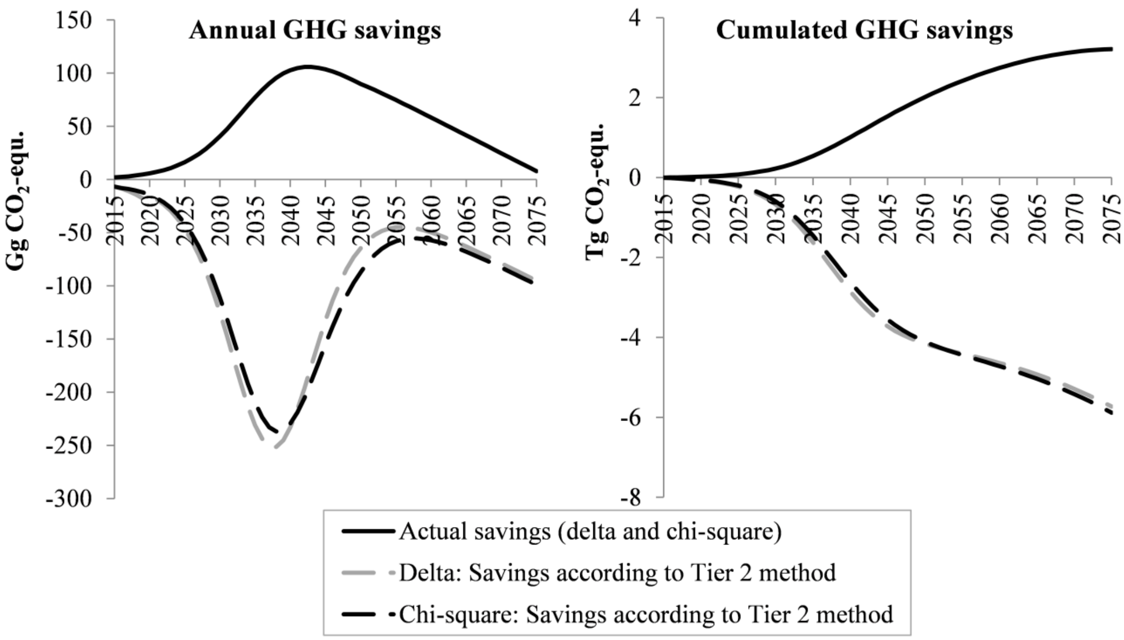


Figure 6. Annual and cumulated GHG savings in the scenario case of CS2 assuming different distribution functions (‘delta’ and ‘chi-square’) and balancing approaches

4.2.3 Sensitivity

The amount of cumulated GHG savings in this case study is on the long term determined by the differences in production emissions. Any assumptions about long-term developments of these parameters are highly uncertain. In the case of wood-based bioethanol and ethylene, technological progress and the use of renewable process energy might result in considerable reductions. On the other hand, upstream emissions of fossil gasoline will be affected by changes in main crude oil supply regions, refinery configurations etc. (EC, 2015). A sensitivity analysis regarding these parameters illustrates that the outcomes of this case study are highly dependent on the assumed gross effects on upstream/cradle-to-gate emissions. The default case is based on constant upstream emissions of bioethanol and gasoline and decreasing cradle-to-gate emissions of both ethylene types. For Sensitivity analysis A in Fig. 7 it is assumed that only bio-ethylene production will become increasingly efficient in terms of GHG emissions. Under this assumption, annual GHG savings increase to about 250 Gg CO_2-equ. until 2050 and remain relatively stable thereafter. The cumulated savings amount to 10.5 Tg CO_2-equ. in 2075. In contrast, Sensitivity analysis B shows a projection where – due to upstream emissions of fossil gasoline increasing by a factor of 1.5 until

2050 – it becomes preferable to use bioethanol as fuel rather than chemical feedstock after 2045.

To conclude, there are high uncertainties related to the climate efficiency of material substitution in the chemical industry. For the particular case of ethylene from lignocellulosic ethanol, LCA data in literature indicate that material substitution is presently more efficient than fuel substitution; but the robustness of this result is low in the context of long-term technological and market developments.

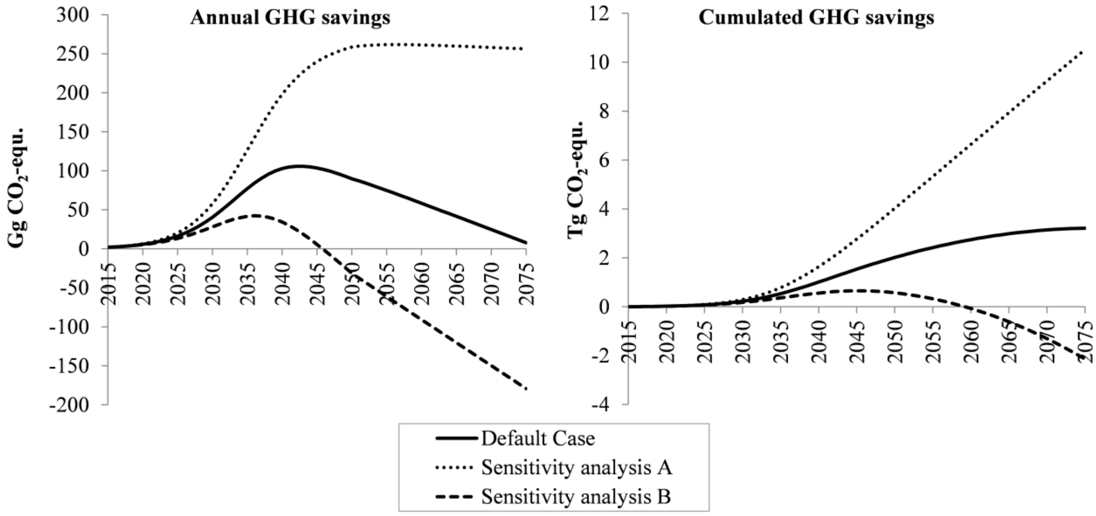


Figure 1. Sensitivity analysis regarding LCA parameters: Annual and cumulated GHG savings under different parameter settings

Regardless of these uncertainties, a further sensitivity analysis, regarding product lifetimes, was evaluated under Tier 2 method. It was found that increasing lifetimes (of products not considered in HWP accounting) have an adverse effect, because the GHG savings from bio-based wastes being combusted (carbon-neutrally) and replacing fossil-based ones, occur at a later point of time (cf. Fig. S2). Hence, the disincentive to material substitution is especially relevant for long-lived products.

4.3 Summary and conclusions

Two case studies have been investigated to quantify potential GHG savings from material substitution in comparison to fuel substitution with biomass, to facilitate a better understanding of potential benefits under different accounting methods and identify crucial parameters. There are fundamental differences between these case studies: In the first one, wood is converted to a long-lived product with a relatively simple process, instead of being directly used for energy. The emissions from this conversion process – as well as of the conventional counterparts – are rather insignificant. What is decisive is that carbon stored in wood is transferred to an artificial long-term carbon pool, and that the combustion of natural causes significantly lower CO_2 emissions per energy unit gained than wood combustion. Hence, in this case material substitution yields high GHG savings in comparison to fuel substitution, and the results are highly robust to uncertain future developments. However, the benefits in respect to GHG mitigation do not fully materialize under the Tier 2 method currently applied for Austria's (and many other countries') GHG inventory report. First, because of the characteristic of the exponential decay function applied in HWP accounting. And second, because only products originating from domestic harvest are accountable, while no such differentiation exists for biomass used for energy.

In CS2 more advanced conversion technologies are considered. The biomass feedstock is lignocellulosic ethanol made from wood, which has a similar (well-to-wheel) emission factor as its replacement fuel gasoline. Mean product lifetimes are assumed to be significantly shorter than in CS1. In consequence, potential GHG savings are mainly due to lower cradle-to-gate emissions of bio-based ethylene as compared to its conventional counterpart. The uncertainties related to these parameters are, however, considerable, and the presented long-term assessments of potential GHG savings are actually quite speculative. HWP accounting is not applicable for bio-based polymers under Tier 2 method, so the respective carbon stock increase is entirely disregarded. Thus, material substitution in this field is not an option for improving GHG balances if the current method is maintained.

The size of savings achievable by diverting biomass from energy to the material uses considered here is relatively small in the context of Austria's total emissions: The sum of average annual savings from both case studies in the timeframe 2015 to 2050 is equivalent to less than 0.2 % of Austria's base year emissions under the Kyoto Protocol. But these are only two examples for a huge range of possible applications, and there is evidence that wood/bio-based products perform even better in other applications (cf. Sathre and O'Connor, 2010).

5 Discussion in the context of climate policy

Despite the fact that material substitution can be a highly efficient way of reducing

GHG emissions, there is currently no incentive to promote it as climate mitigation strategy. This has to do with inadequacies of the currently applied HWP accounting method, which generally favours the use of imported biomass for energy over material substitution. HPW pools being calculated on the basis of domestic production rather than actual consumption, the assumption of exponential decay instead of more realistic distribution functions, and the fact that certain bio-based products are not considered under default Tier 2 method is creating distorted incentives.

It is expressly permitted to use distribution functions to estimate HWP pool changes under a Tier 3 method (IPCC, 2014), but either way inflows are confined to the proportion derived from domestic harvest. And as long as the production approach is permitted, there is no reason for Austria to apply a more realistic ‘country-specific method’ which better reflects the real carbon pool changes in the inland. With regard to the EU’s long-term commitment to establish a bioeconomy until 2050 (European Commission, 2012), these are serious drawbacks that need to be addressed in future revisions of accounting rules.

Another relevant aspect in connection with material substitution is that emissions from production processes are included in the producer country’s GHG balance and not the country where products are consumed. Hence, GHG savings from reducing production emissions by replacing carbon-intensive materials for biomass do not necessarily materialize in the country where material substitution takes place. Quite the contrary: establishing a bio-economy to substitute carbon-intensive imported products and materials for bio-based alternatives is likely to have an adverse impact on the national GHG balance, even if the global effect is clearly positive.

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– Supplementary material –

Contents

6.1.1 IPCC rules for bioenergy and default HWP accounting

According to IPCC Guidelines (IPCC, 2006) CO_2 emissions from biomass combustion are not to be included in the national total of GHG emissions. This has sometimes led to the assumption that bioenergy is generally considered as carbon neutral (cp. Sedjo, 2013). In fact they are not included because net GHG emissions or removals are estimated in the context of ‘agriculture, forestry and land use’. Imported biomass is, however, indeed a carbon neutral fuel for the importing country because the carbon fluxes are considered in the exporter’s GHG balance.

It was originally (1996 Guidelines) assumed that all carbon removed in wood and other biomass from forests is oxidized in the year of removal (Grêt-Regamey et al., 2008). As a consequence, it made no difference whether wood was used for energy (and indeed oxidized shortly after harvesting) or converted to products (so that oxidation was actually not taking place for a possibly long period of time).

Recognizing that the dynamics of artificial carbon pools in the form of long-lived wood products are actually quite relevant, HWP accounting was introduced; by default for sawnwood, panels and paper. HWP accounting should reflect the fundamental difference between energy and material uses of wood with regard to the timing of CO_2 fluxes to the atmosphere.

Different system boundaries may be selected for Tier 2 method. In Austria's latest inventory report the most common, so-called 'production approach' was applied. In countries like Austria, where wood supply is based on managed forests rather than deforestation, the approach involves the following steps (IPCC, 2014; Pilli, Fiorese, Grassi, 2015):

1. The fraction of raw material originating from domestic sources is estimated based on production and foreign trade statistics (Equ. 2.8.1 and 2.8.2 in IPCC, 2014). The result is of high importance as only the share of wood products originating from domestic raw material is considered in HWP accounting.
2. Inflows to and outflows from the carbon pool are calculated on an annual basis. The domestic production of wood products multiplied by the factor determined in step 1 and respective conversion factors represents the inflow. Wood product imports and exports are disregarded in the production approach.
3. Outflows from the pool are estimated by applying a first-order (exponential) decay function with default decay factors for each commodity group. The default half-lives for sawnwood, panels and paper are 35, 25 and 2 years, respectively.
4. Based on inflows and outflows, the carbon stock change and according CO_2-emissions or removals are calculated.

Results of the production approach do not actually reflect developments in HWP consumption in the inland; they are determined by production quantities and strongly influenced by the share of domestic raw material used. Thus, economic cycles and random variations in raw wood supply (caused by windfall calamities, for example) are directly reflected in HWP pool changes, regardless of actual HWP *consumption* developments. The GHG emissions or removals calculated with this default Tier 2 approach are more determined by the situation of raw wood markets than by actual stock changes in the respective country.

The production approach is one among several accounting approaches (cf. Pingoud et al., 2003; Pingoud et al., 2006; Grêt-Regamey et al., 2008). Austria, as a net exporter of wood-based products, is benefitting from considering production quantities instead of inland consumption, for example.

6.1.2 *Detailed description of the modelling approach*

The model has been developed to quantify potential benefits of material substitution in terms of GHG mitigation. All calculations are performed on an annual basis. The basic idea is to compare a scenario with increasing material substitution with a reference case, where the same amount of biogenic feedstock is directly used for energy (cf. Fig. 2 in the main article):

$$BFC^{Scen}(t) \triangleq BFC^{Ref}(t) = BFC(t) \tag{8}$$

BFC stands for biogenic feedstock consumption. Variables are generally denoted with the superscript 'Scen' for the scenario case and 'Ref' for the reference case. Superscripts are omitted if equations apply to both cases.

The development in material substitution scenarios, described by the consumption of the respective wood product in the scenario case (PC_{bio}^{Scen}) over time, is assumed to follow an S-shaped market diffusion curve (logistic function):

$$PC_{bio}^{Scen}(t) = BFC(t) \cdot cf = \frac{MP}{1+e^{-\alpha(t-t_{50\%})}} \tag{9}$$

MP is the market potential of the wood product (expressed in mass units), $t_{50\%}$ the year when 50 % of the market potential is assumed to be exploited and α a parameter determining the steepness of the curve. These parameters are set for each case study individually, based on expectations and estimates about of possible future market developments. cf is a factor used for converting quantities of biomass feedstock into the respective product (from kg wood into m^3 insulation material, for example). Only case studies where it is valid to assume that all carbon stored in the feedstock material ends up in the product or that processing rejects are directly used for energy generation are considered here. Processing rejects (for example in insulating board production) do not result in deviations from the reference case as long as they can be assumed to be used for energy; so it is methodically correct to disregard these material streams.

In the reference case, the functional equivalent of wood products consumption is consumed in the form of conventional products. In situations where wood products replace a mix of conventional products, the consumption of each type of conventional product (index 'i') in the reference case is calculated based on its market share (ms_i). Functional equivalence between wood and conventional products is established by introducing replacement factors (rf_i). The consumption of the conventional product i in the reference case is calculated as:

$$PC_i^{Ref}(t) = PC_{bio}^{Scen}(t) \cdot \frac{ms_i}{rf_i} \tag{10}$$

Replacement factors of insulating boards are for example determined by the thermal conductivity of conventional ones in relation to that of wood insulating boards.

$$rf_i = \frac{\lambda_{WIB}}{\lambda_i} \tag{11}$$

For chemically or functionally equivalent products (e.g. ethylene from wood and naphta in Case Study 2), replacement factors are equal to 1.

Besides Equ. 1, a second condition for direct comparability between the scenario and the reference case is that energy produced within the system boundaries is equal in each year:

$$FES^{Scen}(t) \triangleq FES^{Ref}(t) \tag{12}$$

Energy is measured in terms of final energy supply (FES) to account for eventual differences in conversion efficiencies. In Case Study 1 different efficiencies are assumed for bioenergy, waste incineration and natural gas plants. In Case Study 2 no such conversion is necessary because ethanol can be assumed to be a direct substitute for gasoline.

In a general case final energy supply from bioenergy in the reference case is calculated from the consumption of biogenic feedstock:

$$FES_{BE}^{Ref}(t) = BFC(t) \cdot LHV_{bio} \cdot \eta_{BE} \tag{13}$$

η denotes the conversion efficiency and LHV_{bio} the lower heating value of the respective biobased feedstock.

Total final energy supply in each year is the sum of bioenergy, energy from waste combustion and from a 'replacement fuel':

$$FES(t) = FES_{BE}(t) + FES_{WST}(t) + FES_{RF}(t) \tag{14}$$

Final energy from waste incineration and replacement fuels is calculated analogously to Equ. 6 (indices are 'BE' for bioenergy, 'WST' for waste and 'RF' for replacement fuel). The heating values of reference products ending up as waste are denoted as LHV_i. For non-combustible products composed of inert materials, which are usually landfilled (such as glass and rock wool boards in Case Study 1; Huber, 2013), the LHV is set to zero.

Replacement fuel is needed to compensate differences in final energy supply between the scenario and the reference case. In Case Study 1 the replacement fuel is assumed to be natural gas and in Case Study 2 gasoline. Direct use of biogenic feedstock in the scenario case is zero, as well as replacement fuel consumption in the reference case:

$$FES_{BE}^{Scen}(t) = 0 \text{ and } FES_{RF}^{Ref}(t) = 0 \quad (15; 16)$$

Hence, final energy from replacement fuel in the scenario case can be calculated as:

$$FES_{RF}^{Scen}(t) = FES_{BE}^{Ref}(t) + FES_{WST}^{Ref}(t) - FES_{WST}^{Scen}(t) \quad (17)$$

For determining the amount of waste material being used for energy – and thereby emitting greenhouse gases – in each year, the delta function or the chi-squared distribution are assumed. (The results from both probability distributions are later compared.) Assuming the chi-squared distribution, the amount of waste from discarded bio-based products in the scenario case is

$$WST_{bio}^{Scen}(t) = \sum_{t'=t_0}^{t-1} \chi^2(t-t';\tau) \cdot BFC(t') \quad (18)$$

for all years $t > t_0$, where t_0 is the first year of the scenario analysis (2015 in the case studies presented in this paper). Waste from conventional products in the reference case is calculated analogously; for each type of reference products (i) individually, if the bio-based product replaces a mix of conventional counterparts:

$$WST_i^{Ref}(t) = \frac{1}{cf_i} \sum_{t'=t_0}^{t-1} \chi^2(t-t';\tau) \cdot PC_i^{Ref}(t') \quad (19)$$

Assuming the delta function, the quantities of waste in the year t correspond to the feedstock consumption in the year (t-τ):

$$WST_{bio}^{Scen}(t) = BFC(t-\tau) \quad (20)$$

$$WST_i^{Ref}(t) = \frac{PC_i^{Ref}(t-\tau)}{cf_i} \quad (21)$$

As recycling is not considered, all wastes are assumed to be used for energy generation (or landfilled, if thermal utilization is not applicable). Final energy from waste incineration is

$$FES_{WST}^{Scen}(t) = WST_{bio}^{Scen}(t) \cdot LHV_{bio} \cdot \eta_{WST} \quad (22)$$

in the scenario case and

$$FES_{WST,i}^{Ref}(t) = \sum_i \; WST_i^{Ref}(t) \cdot LHV_i \cdot \eta_{WST} \quad (23)$$

in the reference case.

GHG emissions considered in the model include emissions from biomass feedstock combustion, from the production of conventional and biobased products (index 'PE' for production emissions), from combustion of waste and replacement fuel.

$$EMI(t) = EMI_{BE}(t) + EMI_{PE}(t) + EMI_{WST}(t) + EMI_{RF}(t) \quad (24)$$

Emission factors of fuels are the sum of direct emission (from combustion) and indirect (upstream) emissions. In contrast to the IPCC approach, biomass is not assumed to be oxidized in the year of removal (with the exception of wood ending up in wood product pools according to HWP accounting). Instead, GHG emissions from biomass combustion are treated just like those from fossil fuels and non-renewable wastes. Carbon sequestration during wood growth is not within the scope of the model; this is legitimate because biomass inflows to the system boundaries in the scenario and reference case are by definition equal each year, and only the difference in GHG emissions between the two cases is considered.

Production emissions are calculated from cradle-to-gate emissions according to life cycle analyses (LCA) in literature.

$$EMI_{PE}^{Scen}(t) = PC_{bio}^{Scen}(t) \cdot e_{LCA,bio} \tag{25}$$

$$EMI_{PE}^{Ref}(t) = \sum_i \; PC_i^{Ref}(t) \cdot e_{LCA,i} \tag{26}$$

For emissions from bioenergy and replacement fuel combustion, it is important to consider direct emissions (index ‘dir’) as well as relevant upstream emissions (index ‘ups’):

$$EMI_{BE}^{Ref}(t) = \frac{FES_{BE}^{Ref}(t)}{\eta_{BE}} \left(e_{BE,dir} + e_{BE,ups}\right) \tag{27}$$

$$EMI_{RF}^{Scen}(t) = \frac{FES_{RF}^{Scen}(t)}{\eta_{RF}} \left(e_{RF,dir} + e_{RF,ups}\right) \tag{28}$$

Finally, the temporal development of the difference in GHG emissions between the scenario and the reference case is analysed; once assuming chi-square- and once assuming delta-distribution. ΔEMI denotes the GHG savings in the scenario case:

$$\Delta EMI(t) = EMI^{Ref}(t) - EMI^{Scen}(t) = EMI_{BE}^{Ref}(t) + EMI_{PE}^{Ref}(t) - EMI_{PE}^{Scen}(t) + EMI_{WST}^{Ref}(t) - EMI_{WST}^{Scen}(t) - EMI_{RF}^{Scen}(t) \tag{29}$$

The savings according to Tier 2 method are calculated as follows:

$$\Delta EMI_{Tier2}(t) = \Delta C(t) + EMI_{PE}^{Ref}(t) - EMI_{PE}^{Scen}(t) + EMI_{WST}^{Ref}(t) - EMI_{RF}^{Scen}(t) \tag{30}$$

ΔC(t) is the carbon stock change of the HWP pool during year t according to Equ. 2.8.5 in (IPCC, 2014). Production and upstream emissions are assumed to occur in the inland. Following the IPCC approach for bioenergy, emissions from biomass or biowaste combustion are not considered, as wood removals are equal in the scenario and the reference case.

6.1.3 Data tables

Table S1. Scenario parameters for market development in the two case studies

	Market potential		Shape parameters	
Symbol (Unit)	MP (Gg)	MP (m^3)	α	$t_{50\%}$
Case Study 1: Wood insulating boards	209	1,200	0.44	2025
Case Study 2: Bio-ethylene	500	-	0.24	2035

Table S2. Material properties, emission factors and market shares of insulating boards (Values in this table are rounded; replacement factors are based on exact values)

	Thermal conduc-tivity	Density	Cradle-to-gate GHG emissions (assumed for 2015)	Replace-ment factor rf_i	Heating value	GHG emission factor (combus-tion)	Market share
Unit	W/mK	kg/m^3	kg CO_2-equ./kg	1	GJ/m^3	kg CO_2-equ./kg	1
Sources	Baubook (2016), UBA (2016), IBU (2016)				Patel et al. (2006), Mötzl (2009), IPCC (2006)		Assump-tion based on KFP (2016)
Wood-fibre insulating board	0.043	174	0.52	1.00	2.57	1.68	-
Rock wool board	0.038	114	1.63	1.11	-	-	20%
Glass wood board	0.034	28	2.03	1.25	-	-	35%
PIR/PUR board	0.024	30	4.49	1.78	0.89	2.44	5%
XPS board	0.037	36	4.23	1.16	1.69	3.48	5%
EPS board	0.038	18	4.17	1.12	0.73	2.95	35%

Abbreviations: PUR: polyurethane, PIR: polyisocyanurate, EPS: expanded polystyrene, XPS: extruded polystyrene

Table S3. Fuel parameters and upstream GHG emissions relevant for Case Study 1

	Heating value	GHG emission factor (combustion)	Upstream GHG emissions	Carbon content
Unit	MJ/kg	kg CO2-equ./GJ	kg CO2-equ./GJ	kg C/kg
Sources	based on IPCC (2006)		EC (2015)	IPCC (2006)
Natural gas	-	56.2	18.82	-
Wood residues	14.75	113.9	-	0.45

Table S4. Parameters for Case Study 2

	Heating value	GHG emission factor (combustion)	Upstream GHG emissions (fuels)	Cradle-to-gate GHG emissions (chemicals; 2015)	Carbon content
Unit	MJ/kg	kg CO_2-equ./GJ	kg CO_2-equ./GJ	kg CO_2-equ./kg	kg C/kg
Sources	IPCC (2006)/based on Patel et al. (2006), Mötzl (2009), Arvidsson and Lundin (2011)		EC (2015), Patel et al. (2006)	Patel et al. (2006), IEA-ETSAP/IRENA (2006)	IPCC (2006)/based on Patel et al. (2006)
Gasoline	44.30	69.5	9.23	-	0.84
Ethanol (feedstock: wood)	27.00	71.0	7.41	-	0.52
Bio-Ethylene (feedstock: wood)	43.00	73.6	-	0.50	0.86
Ethylene (feedstock: naphta)	43.00	73.6	-	1.30	0.86

6.1.4 Sensitivity analyses

The following figures show the results of sensitivity analyses to CS1 (Fig. S1) and CS2 (Fig. S2) regarding product lifetimes.

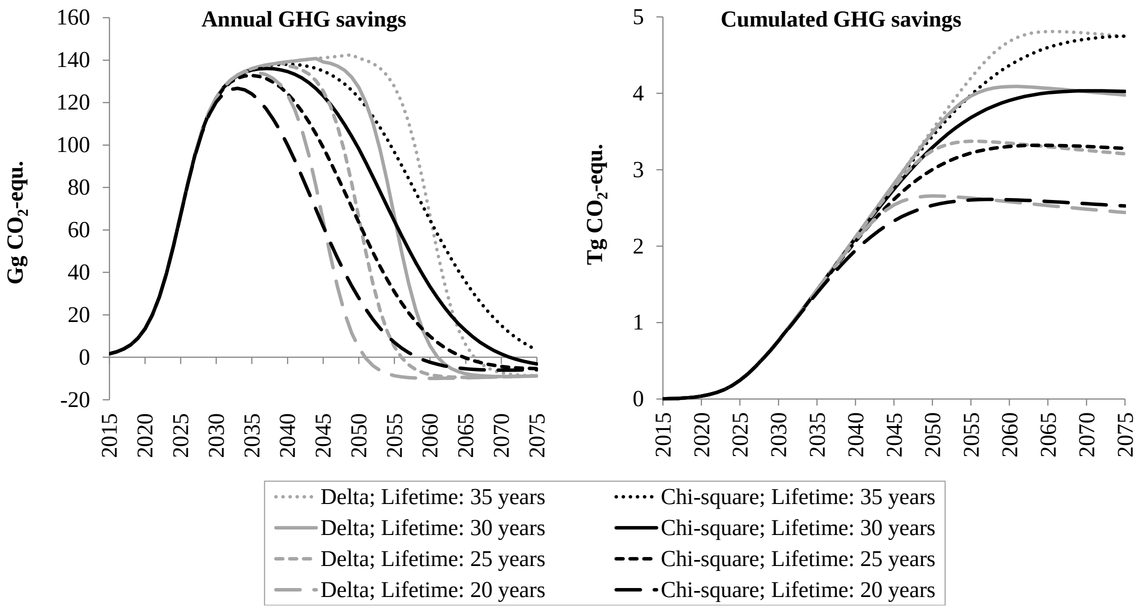

Figure S2. Cumulated 'actual' GHG savings in the scenario case, assuming different mean lifetimes of insulating boards

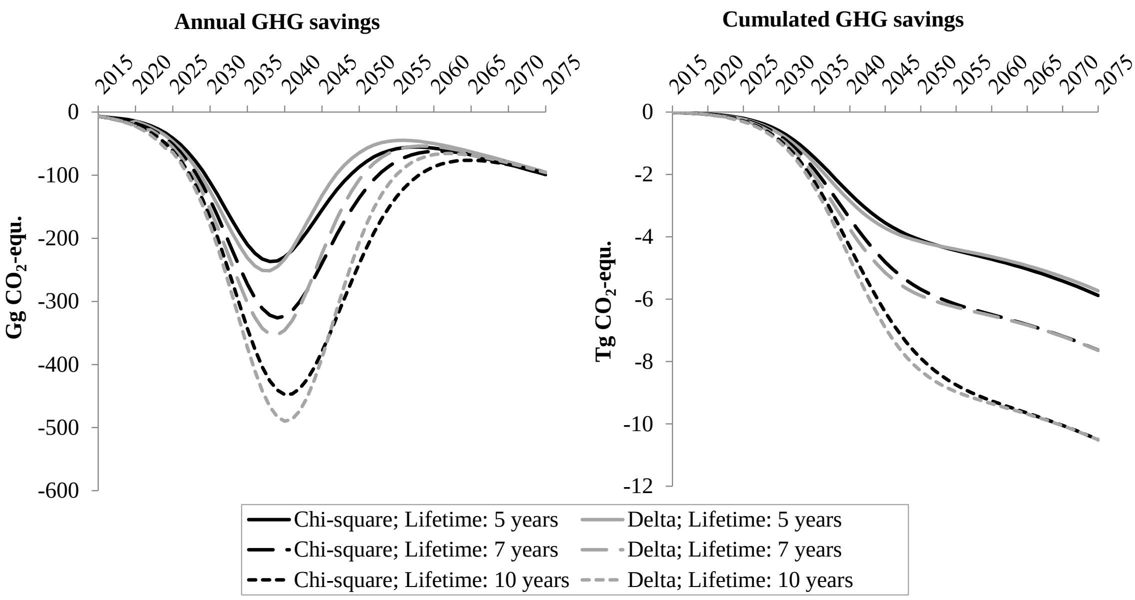

Figure S3. Sensitivity analysis regarding mean product lifetimes in CS2: Savings under default Tier 2 HWP accounting, which does not consider biobased chemicals/bio-polymers

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