Recalculation of CO_2 emissions from biomass use in district heating, combined heat and power plants, direct private wood pellet and firewood consumption in Denmark with 2022 input data

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Indhold

1 Preface

This report and the analyses behind were commissioned by the Danish Energy Agency in August 2023 to address questions about CO_2 emissions related to use of woody biomass for district heat and electricity production, and use of wood pellets and firewood directly consumed in private households. The analytical framework and approach build largely on previous work by Nielsen et al. [1, 2 and 3] and can be compared to the result in [4].

A preliminary version of this report was commented by the Danish Energy Agency by mid November and December 2023.

Niclas Scott Bentsen from Department of Geosciences and Natural Resource Management, University of Copenhagen conducted review and quality control of the report and results before final submission.

The author thanks data providers from the Danish Energy Agency, Utility companies and Niclas Scott Bentsen, for fruitful collaboration and contribution to the report.

The content and conclusions presented here follows the same method and presentation form as in [3] but is the sole responsibility of the author.

2 Abstract

This report is a recalculation with 2022 data of the model output from [3 and 4] which formed the basis of Global afrapportering 2022 and 2023 (GA22 and GA23). Calculations in this report builds entirely on the scientific data and method presented in [3], unless stated otherwise. As such, the changes in results compared to [3 and 4] are solely the effect of using 2022 consumption data and changes stated in the method section of this report.

In this project, data was mainly based on reporting from utility companies and importers to the Danish Energy Agency [9] for wood chips and wood pellets and from [10 and 11] for firewood. Data for wood chips, wood pellets covered 93% and 78% of current total Danish consumption, in the transformation sector and in direct consumption by private households, respectively.

The model calculations include the direct and indirect CO_2 emissions associated with the production of energy in the Danish transformation sector and direct consumption in private households. These include emissions from the production of biomass (forest cultivation, transport, production of wood pellets, etc.), emissions from the combustion of the biomass and indirect emissions (iLUC and iWUC emissions). CO_2 emissions from the construction of plants and facilities are disregarded. Moreover, the CO_2 were not compared to other energy systems, such as plants using coal.

The model calculations also included a dynamic assessment of the changes in the forest carbon stocks in a factual versus a counterfactual situation, where the use of biomass for energy (factual), and how forests and wood would have been managed and treated absent the demand for bioenergy (counterfactuals).

The report focusses on:

1. Analysis of a single year's biogenic and fossil emissions in the supply chain of the Danish use of biomass in the transformation sector and time dependent marginal emissions in a 100-year perspective. Results are reported as cumulative net CO_2 emissions to the atmosphere and Kg CO2/GJ.
2. Analysis of a single year's biogenic and fossil emissions in the supply chain of the Danish use of biomass used directly in private households (wood pellets and firewood) and time dependent marginal emissions in a 100-year perspective. Results are reported as cumulative net CO_2 emissions to the atmosphere and Kg CO2/GJ.
3. Incorporation of consumption and feedstock data, collected by the Danish Energy Agency
4. Revisit and development of key assumptions reported in [3] and a discussion hereof.
5. Discussion of the effect of changes in the data and emission profile compared to results presented in [3 and 4].

The first part of the analysis showed that the use of biomass has decreased in the transformation sector since 2021, where total consumption of biomass in 2020 was 88.1 PJ leading to total emissions of 10,6 million tonnes of CO_2, while in 2022, consumption was

78.3 PJ, leading to total emissions of 9.5 million tonnes CO_2, roughly evenly distributed between wood chips and wood pellets.

Use of biomass directly in households was 10 PJ of wood pellets and 13.8 PJ of firewood, leading to emissions of 1.2 and 1.6 million tons CO2 at the year of combustion, respectively.

After app. 60-95 years only 1% of the additional biogenic emissions from energy production was left in the atmosphere, depending on the category of the biomass.

Of all the biomass used 92% was considered residues either from forest operation or industrial operations, with the remining 8% being biomass attributed with indirect effects, such as iLUC and iWUC.

It was demonstrated that the foremost factor determining the outcome of emissions was whether biomass for energy is truly a residue. Secondly, the decay rate of residues also had a strong effect on the results with transport and other supply chain emissions having lesser but irreversible effects on the outcome.

3 Dansk resume

Denne rapport er en genberegning med 2022-data af modeloutputtet fra [3 og 4], som dannede grundlag for Global afrapportering 2022 og 2023 (GA22 og GA23). Beregninger i denne rapport bygger udelukkende på de videnskabelige data og metoder præsenteret i [3], medmindre andet er angivet. Ændringerne i resultater i forhold til [3 og 4] er derfor alene effekten af at bruge 2022-forbrugsdata og ændringer angivet i metodeafsnittet her.

Inputdata er primært baseret på indberetninger fra forsyningsselskaber og importører til Energistyrelsen [9] for flis og træpiller og på dataindsamling i [10 og 11] for brænde. Data for flis, træpiller dækkede hhv. 93% og 78% af det nuværende samlede danske forbrug i forsyningssektoren og i det direkte forbrug i private husholdninger.

Modelberegningerne omfatter de direkte og indirekte CO2-udledninger forbundet med produktionen af energi i den danske forsyningssektor og direkte forbrug i private husholdninger. Disse omfatter udledninger fra produktion af biomasse (skovdyrkning, transport, produktion af træpiller mv.), udledninger fra forbrænding af biomassen og indirekte udledninger (iLUC- og iWUC). Der ses bort fra CO2-udledninger fra opførelse af anlæg. CO2 udledningerne fra biomassen bliver ikke sammenlignet med udledninger fra andre energikilder, som for eksempel kulværker.

Modelberegningerne indeholder også en dynamisk udvikling i skovenes kulstoflagre i en faktisk versus en kontrafaktisk situation, der viser hvordan udledningerne bliver påvirket af anvendelsen af biomasse (faktisk), sammenlignet med hvordan skove og træets kulstorpuljer ville være blevet behandlet og have udviklet sig uden efterspørgsel efter bioenergi.

Rapporten fokuserer på:

1. Analyse af et enkelt års biogene og fossile CO_2-udledninger i forsyningskæden af den danske anvendelse af biomasse i forsyningssektoren og tidsafhængige marginale udledninger i et100 års perspektiv. Resultater rapporteres som kumulative netto CO_2-udledninger til atmosfæren og kg CO2/GJ.

2. Analyse af et enkelt års biogene og fossile emissioner i forsyningskæden af den danske anvendelse af biomasse anvendt direkte i private husholdninger (træpiller og brænde) og tidsafhængig marginale udledninger i et 100 års perspektiv. Resultater rapporteres som kumulative netto CO_2-udledninger til atmosfæren og kg CO2/GJ.

3. Indarbejdelse af forbrugsdata indsamlet af Energistyrelsen

4. Genbesøg og udvikling af centrale antagelser rapporteret i [3] og en diskussion heraf.

5. Diskussion af ændringer i data- og emissionsprofiler sammenlignet med resultater præsenteret i [3 og 4].

Den første del af analysen viste, at brugen af biomasse er faldet siden 2021. Hvor det samlede forbrug af biomasse i 2021 var 88,1 PJ, hvilket gav en samlet udledning på 10,6 millioner tons CO2, var forbruget i 2022 78,3 PJ, hvilket førte til en samlet udledning på 9,5 millioner tons CO2, nogenlunde ligeligt fordelt mellem flis og træpiller.

Anvendelsen af biomasse forbrugt direkte i husholdningerne var 10 PJ for træpiller og 13,8 PJ for brænde, hvilket førte til udledninger på henholdsvis 1,2 og 1,6 mio. tons CO2.

Efter ca. 60-95 år var der kun 1% af de biogene udledninger fra energiproduktion tilbage i atmosfæren. Hastigheden af konvergensen afhang af biomassens kategori.

Ud af alt den biomasse der blev brugt er det i denne rapport antaget at 92% kommer fra resttræ, hvor de resterende 8% kommer fra træ der giver anledning til indirekte CO_2 udledninger, som for eksempel iLUC og iWUC.

Det blev påvist, at den vigtigste faktor, der bestemmer profilen af CO_2-udledninger, var om biomasse til energi virkelig er et restprodukt. Nedbrydningshastigheden af restprodukter havde også en stærk effekt på resultaterne, hvorimod transport og andre forsyningskædeudledninger kun havde mindre men irreversibel effekt på resultaterne.

4 Description of terms and abbreviations

Abbreviaton/term	English description	Dansk forklaring
Additional harvesting	Harvest of biomass for energy, that is not a residue from harvesting for other products i.e. harvest solely for the purpose of energy.	Hugst af træ til energi der ikke stammer fra en hugstrest, der alligevel var sket som følge af skovproduktion, men udelukkende pga. energimarkedet.
DH	District heating plant	Varmeværk
CHP	Combined heat and power plant	Kraftvarmeværk
Process emissions	Biogenic and fossil CO_2 emissions related to forest operations and production of wood pellets	Biogene og fossile CO2 udledninger som følge af skovdrift og fremstilling af træpiller
Transport emissions	CO_2 emissions related to fossil fuel consumption in the transport sector	Fossile CO_2 udledninger som følge af transport af biomasse
Combustion emissions	Emissions from combustion of wood	Udledninger som følge af afbrænding af træ
Counterfactual	Term that refers to what would have happened to the wood had it not been used for bioenergy	Udtryk der refererer til hvad der ville være sket med træet hvis det ikke blev brugt som bioenergi
Half-life	Term that determines the residence time of carbon in wood products e.g. a natural or non-natural decay rate. The half-life describes the time it will take before half of the wood is decayed and carbon hereby is emitted	Udtryk der beskriver hvor lang tid et stykke træ ville have tage om at frigive halvdelen af kulstoflageret som CO_2 til atmosfæren ved forrådnelse, hvis det ikke var blevet brugt som bioenergi
Indirect emissions	CO_2 emissions related to market pressure from bioenergy demand on other products	CO_2 udledninger der stammer fra markedspres på andre sektorer som følge af efterspørgsel på træ til bioenergi
iLUC	Indirect land use change relating to emissions or uptake from the living forest biomass carbon pool as a consequence of demand for bioenergy	Indirekte CO_2 udledninger eller optag i skovenes levende kulstofpulje, der stammer fra øget pres fra bioenergi forbruget
iWUC	Indirect wood use change, CO_2 emissions related to change in price structure for bioenergy compared to products, leading to consumers switching to more “emission-heavy” products, hereby creating emissions	CO_2 udledninger som følge af at prisstrukturer ændres pga. pres fra bioenergisektoren, som vil lede til øget forbrug af mere udledningstunge produkter, der herved vil udlede CO_2
Residue	Residues from forestry (branches, rotten stems etc.) or residues from wood product industry that under the current market situation does not have an alternative use	Rester fra skovbrug (grene og rådne stammer) eller rester fra træindustrien, der i den nuværende markedssituation ikke har anden anvendelse.
Single pulse emissions:	All CO_2 emissions and forest carbon uptake related to a single year use of bioenergy	Alle CO_2 udledninger, samt optag i skoven som følge af et enkelt års bioenergiforbrug
Weighted average	Refers to results based on weighted average data input to the model for i.e. wood chips, wood pellets and the whole biomass use in the transformation sector	Refererer til resultater baseret på vægtede gennemsnitsdatainput til modellen

1 Introduction

The Paris Agreement deems to keep anthropogenic global warming below a 2°C increase from pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C [5]. Meeting these temperature targets, transitions of the energy, agriculture, land use, industry, and transportation sectors are needed. For the energy sector, the Intergovernmental Panel on Climate Change (IPCC) highlight four transformations required to reach this goal: 1) limits the energy demand, 2) reductions in the carbon intensity of electricity production, 3) increases in the share of electricity, and 4) reductions in the carbon intensity of other energy forms than electricity [6].

Use of biomass in the energy sector has been favoured politically, since the mid-1990s in the transition of the Danish energy sector [7]**,** targeting IPCC's goal 2) and 4) listed above. District heat and electricity production in Denmark has been under substantial transition over the last 30 years from fossil fuel to renewables in the form of biomass, wind, and solar energy [8].

In 2022, renewables made up 75% of both electricity and district heat production, with 24 PJ electricity and 80 PJ district heat being based on biomass (wood chips, wood pellets, straw, and organic waste) corresponding to 22% of renewable electricity and 90% of renewable heat produced, respectively [8].

Wood in various forms e.g. wood chips, wood pellets and firewood makes up 65% of biomass used in the transformation sector and private households.

In 2022, 56 PJ wood was used for electricity production corresponding to 70% of biomass used for electricity production. In 2021 the corresponding figures for district heat was 38 PJ and 63% [8]. As such, precise estimations of emissions from use of wood in the energy sector are vital for attaining accurate figures of CO2 emissions related to Danish consumption (see note in 1.2).

1.1 Aim of this report

The aim of this report is to recalculate previous work by Nielsen et al. [3] and Nielsen [4] to estimate impacts of CO_2 emissions to the atmosphere over a 100-year period from the Danish use of biomass in 2022, focussing on:

1) Analysis of a single year's biogenic and fossil emissions from the supply chain of the Danish use of biomass in the transformation sector and time dependent marginal emissions in a 100-year perspective. Results are reported as cumulative net CO_2 emissions to the atmosphere and Kg CO_2/GJ.
2) Analysis of a single year's biogenic and fossil emissions from the supply chain of the Danish use of biomass used directly in private households (mainly wood pellets and firewood) and time dependent marginal emissions in a 100-year perspective. Results are reported as cumulative net CO_2 emissions to the atmosphere and Kg CO_2/GJ.

3) Incorporation of consumption and feedstock data, collected by the Danish Energy Agency

4) Revisit and development of key assumptions reported in [3] and a discussion hereof.

5) Discussion of the changes in the data and emission profile compared to results presented in previous reports [3 and 4].

1.2 Important note

The findings presented here cannot and should not be compared to the national inventory report to the UNFCCC or to accounting against greenhouse gas emission reduction targets. This analysis builds on a consumption-based model framework, while the inventory reports build on production-based accounting methodology. System boundaries differ between the two methodologies and results are not comparable.

2 Materials and methods

This report is a recalculation of [3] and [4] with 2022 data as input to Global afrapportering 2024 (GA24), which is based on the model from [3], that also formed the basis of Global afrapportering 2022 and 2023 (GA22 and GA23). Results were based on data from year 2022. Calculations in this report builds on the scientific data and method presented in [3], unless stated otherwise here. As such, the changes in results compared to [3] are solely the effect of using 2022 consumption data and changes stated in this chapter.

2.1 Changes from the GA23 report

Although the method is the same here as in [3 and 4], this report includes additional analyses and assumptions:

1. Data largely origins from the energy sector's reporting to the Danish Energy Agency as described in [9].
2. CO_2 emissions from private consumption of wood pellets and firewood used in private households are included in this report, cf. 2.2.
3. A new biomass category "*Energy wood from forests*" was included in the analyses, see cf. 2.5. This was in previous years parts of the categories stems and harvest residues.
4. A new market mediated effect was included for the stem and non-forest and waste wood biomass category called "*additional harvesting*", cf. 2.4.2.
5. The *non forest biomass* category was attributed with 10% additional harvesting due to increasing prices for biomass for energy, cf. 2.5.
6. Key assumptions from [3] are revisited in the material and method section and discussed in the discussion section, cf. 2.3-2.5 and 4.5.

2.2 Data input

The data input on consumption of wood pellets and wood chips both from the transformation and direct consumption sectors origins from the mandatory reporting to the Danish Energy Agency [9], where all energy producing installations above 5 MW and importers/producers above 20.000 tonnes of wood pellets were mandated to report on the amounts of biomass used (tons and energy content), where the biomass origins from (countries), what type of biomass fuel was used (wood chips or wood pellets), what feedstock source of wood the chips and pellets are made from (harvest residues, stems, energy wood from forests, industrial residues, or non-forest and waste wood biomass). This reporting data covers 93% of wood chips and wood pellets used in the transformation sector, and 78% of the wood pellet used in the private sector.

For firewood input data on origin is based on data from www.statistikbanken.dk [10] (database code KN8Y) to estimate the source from which the firewood imported. The feedstock data for firewood was based on data collection by the Danish Energy Agency and Wilke [11] and a categorisation hereof cf. 2.5.

All other data input is identical to [3] and [4]. See [3] for a thorough description.

2.3 Model overview

For assessing cumulative CO_2 emissions, a modelling framework [3] calculates carbon pools and fluxes linked to processes in the supply chain from forest management to heat and electricity production or from chain saw felling in forest to burning in a private wood stove (Figure 1).

Emissions from the construction of CHP/DH plants, private pellet and firewood stoves, machinery and infrastructure were considered outside the system boundaries of this report and thus disregarded.

Direct emissions are emissions from the supply chain of biomass e.g. from forest operations or transportation of biomass or combustion.

Indirect emissions derive from market mediated consequences of the biomass use for energy, i.e. indirect land use change (iLUC), and indirect wood use change (iWUC), or additional harvesting as consequence of changes in the market situation.

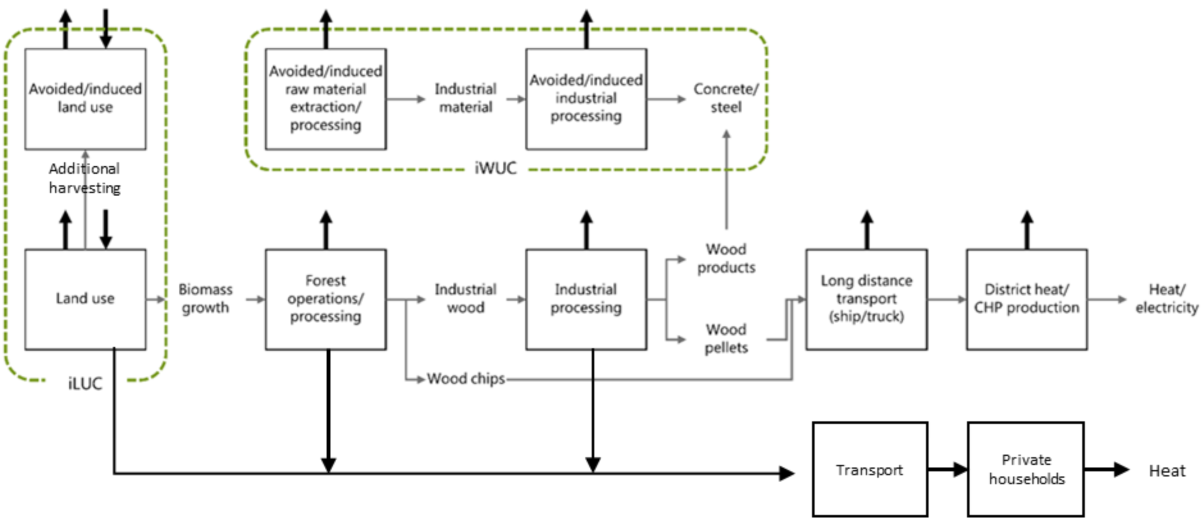

Figure 1. Overview of the model framework.

Assumptions were made regarding background forest systems, forest management, transport, counterfactual of the wood had it not been used for bioenergy, substitution factors and lifetime of forest products, forest growth, decay rated etc. and are stated in the table below (Table 1, see also [3] for more detailed description).

Table 1. Basic assumptions for calculation of the cumulative net carbon emissions (CCE).

No.	Assumption	Source
1	Living and deadwood carbon pools in unmanaged forest are set as the default IPCC values	[39 and 40]
2	The soil carbon pools, including forest floor, in unmanaged forests are in steady state during the whole projection period, and unchanged by use of bioenergy throughout the projection period.	[13, 14]
3	We assume that establishment of forests and growth after intervention, follows existing yield tables and models of for the most common tree species in the region.	[15-17]
4	Living root biomass of all forest management alternatives is assumed to be 20% of the aboveground living biomass.	[18]
5		
6	The half-life of all harvest residues left on the forest floor is 10 years, and 5 years for industrial residues left for decay. For stem wood, the half-life is 15 years.	[21-23]
7	All biomass contains 50% carbon (based on dry weight).	[24]
8	There are no significant emissions along the production chains of other greenhouse gasses than carbon dioxide, nor in the counterfactual system.	Assumption*
9	For forest site operations, we used 2.29 l diesel t^{-1}. For harvest, forwarding and chipping we used 2.31 and 0.87 Kg C m^{-3} and finally for chipping we used 1.85 l diesel t^{-1}. For transport both biomass and coal we used emissions fuel consumption of 1.3, 0.68 and 0.22 for truck, train and ship, respectively	[25-27]
10	Energy use for grinding of wood and pressing to pellets, was assumed to be 152 KWh $tons^{-1}$ pellets assuming natural gas based electricity production.	[26]
11	For drying of wood pellets, an additional 18% use of low-grade biomass (half-life 5 years) was assumed.	[28, 29]
12	The half-life of the wood product pool is 35 years for sawn timber, 25 years for boards and 2 years for paper.	[39]
13	The wood product substitution factor (SF) is set to 1.4 for sawn wood, 1.2 for panels and boards and 1.0 for other products e.g. pulp and paper.	[30]
14	For the biomass categories, stems and industrial residues and energy wood from forests [see 1 and 2], it was assumed that 5% lead to iLUC and 5% lead to iWUC and for the category non-forest and waste wood it was assumed that 10% of the biomass origin from additional harvesting.	Assumption

*Assumption is made as data on other climate gasses is not existing to make meaningful modelling at present.

Key assumptions are presented in more detail in the following chapters.

2.4 Biomass counterfactuals

A counterfactual is to be interpreted as a situation countering the factual situation. The factual situation is the prevailing situation, where a certain amount of biomass is acquired from forests and industries to produce energy, either as wood chips and wood pellets combusted in district heating (DH) and combined heat and power plants (CHP), or as mainly wood pellets or firewood in private households.

The counterfactual situation is to be interpreted as a situation where the market for energy produced from biomass does not exists and the wood currently used for energy assumes a counterfactual fate. The counterfactual depends on the nature of the wood used, ranging from being left in the forest representing a living or dead carbon stock, to wood that would have been used for other purposes. Emissions attributed to the use of biomass for energy is the difference in emission profile between the factual and the counterfactual situation.

2.4.1 Counterfactuals for harvest residues, poor quality stems and wood processing residues; i.e. "residues"

Residues are biomass that in the current market situation cannot be used for other purposes than energy. In this report, residues can be harvesting residues from forest operations, rotten stems or stems of low quality felled during forest harvest but unsuitable or unsellable for other products, or non-commercial tree species. The limit between what is considered harvest residues and stems is a maximum diameter of the wood at 14 cm, a commonly used deposition limit in forestry.

When timber is sawn and further processed, there is also a production of more residues, such as sawdust or shavings etc. Such residues are denoted industrial residues.

The use of residues for energy purposes does not affect land or product markets as it is in surplus. Residual biomass with no other counterfactual than being burned or decaying over time is here denoted 'Residues.'

In modelling the counterfactual of residues, two possible options were assumed:

1. The residues are burned on site.
2. The residues are left to decay naturally.

The decay or burning of forest biomass left on forest floors was assumed to follow a first order exponential decay function with a half-life determining the decay rate.
If residues are burned on site, a half-life of 0.5 year (almost all biomass is burned within the first 2 year after processing) was assumed. If residues are left for natural decay, a half-life of 10 years is assumed [23]. For harvest residues it is assumed that 30% were burned on site and 70% left for natural decay.
For industrial residues left for natural decay (90%) in deposits, a half-life of 5 years was assumed, as these are crushed into small pieces and piled up.
For stems, covering both the stem category and the stem part of firewood, the counterfactual assumption was that 90% was left to decay, with an average half-life of 15 years [31, 32].

The remaining parts (10%) of the stem and industrial residues categories were assumed to be denoted with other counterfactuals (see the following chapters).

For the categories non-forest and waste wood biomass and energy wood from forests, it was assumed that 50% of this was stems and 50% was harvest residues. 10% of this was attributed additional harvest (see next chapter).

The implication of assumptions on counterfactual fates is a shift in timing of CO2 emissions from the wood categories, from an immediate release of the CO_2, when biomass is used for energy to a more or less delayed release, when wood is not used for energy. The difference in timing of CO2 release is determined by the half-lives presented above and the difference is attributed bioenergy production. Use of residues where the counterfactual is decay in forests, will thus reduce the dead biomass carbon pool of utilized forests in the factual situation compared to the counterfactual situation and this reduction will be attributed to the energy production.

2.4.2 Counterfactual for wood harvested due to increase prices for biomass - Additional harvesting (Land use change, LUC)

Additional harvest occurs when trees that would not have been harvested are harvested for bioenergy use. An example of this could be a corner of the forest with poor quality trees not suitable or unsellable for timber that is harvested together with a harvest operation in an adjacent forest stand, due to increasing prices for biomass for energy. Here the counterfactual would be that this forest compartment would have been left unharvested. Harvesting for bioenergy (factual) will thus temporarily reduce the living biomass carbon stock compared to the counterfactual.

Additional harvesting can also be small plots of forest in the agricultural landscape that are harvested due to the demand for biomass. This will temporarily lead to a decrease in the landscape carbon stock.

In this report additional harvesting was modelled as the difference in carbon stock on landscape level between a factual situation where the additional harvesting for bioenergy takes place and a counterfactual situation where the plots are left unharvested.

Specifically, a growth model for beech (*Fagus sylvatica*), production class 12 was used as a proxy for the carbon stock in the factual situation $C_{harvested}$, as this is a good proxy growing at a speed close to the average for forests in Denmark. The counterfactual carbon stock for unharvested broadleaf forest $C_{unharvested}$ was modelled with an average carbon stock value for temperate forests Keith et al. [12].

$$Additional\ harvest\ emission = C_{unharvested} - C_{harvestedt},$$

2.4.3 Counterfactual for wood with indirect change in land and product use (iLUC and iWUC)

Biomass currently used for energy may have an alternative use, that lead to a different emission pattern than residues. If the biomass could have been used for something else, using it for bioenergy leads to market-mediated reactions linked to the land market (iLUC) or the product market (iWUC). This could for example occur if price for biomass for energy exceed the price for pulp wood and pressed pulp mills to source from other previously unmanaged forests, or by the price of pulp products increasing so consumers will use other products instead of pulp. Such market-mediated reactions may lead to additional emissions or emission savings as elaborated below.

Counterfactual by indirect land use change

iLUC can affect emissions and forest carbon stocks in three different ways:

1. Expansion of forest management into previously unmanaged forests (most often leading to a carbon stock decrease).

2. Intensification in existing managed forests (carbon stock increase or decrease),
3. A reduced supply of wood products (here treated as iWUC - see 2.4.5).

Ad. 1 Expansion into unmanaged forests - iLUC

The situation, where management of forest expands into previously unmanaged forests was modelled similar to the method developed by Schmidt et al. [33].

In natural forests, although fluctuations can occur, carbon stocks in living and dead biomass as well as in the soil are quite stable over time as a result of an equilibrium between carbon sequestration by photosynthesis and emissions from respiration [34]. When such forests are taken into management, the carbon stock is affected on several parameters:

1. Harvest removes carbon from the forest, why the carbon stock in living biomass will be reduced compared to the unmanaged forest.
2. Input to the dead wood carbon pool is reduced, as mortality from competing trees is reduced and part of the biomass is extracted for products or energy.
3. In some cases, the soil carbon pool is also affected due to lower input, induced by increased extraction or emissions from increased turnover of soil carbon.

For the carbon pool in unmanaged forest ($C_{unm,t}$) (counterfactual situation, without bioenergy) a default carbon stock for boreal forests given by Keith et. al., [12], was assumed.

The carbon stock in the managed forest ($C_{man,t}$)is modelled with Norway spruce, production class 14 as a proxy for the carbon stock in the managed forest ($C_{man,t}$).

Finally, iLUC emissions were calculated as:

$$iLUC = C_{unm,t} - C_{man,t},$$

Both additional harvesting and expansion into unmanaged forests will lead to decreased carbon stocks in forests, which is considered as a CO_2 emission attributed to the use of biomass for energy.

Ad. 2 Intensified forest management- iLUC

Increased demand for bioenergy can also lead to increased investments in forest management leading to intensified or *improved management practices*, with two potential effects on forest carbon stocks and emissions.

Forest managers may replant cleared forest stands partly with nurse trees (fast growing trees species), leading to faster recovery of the forest carbon stock after felling compared to the counterfactual situation.

Moreover, the economic incentive provided by the bioenergy demand makes particularly early thinnings more profitable, which may incentivise forest managers to practice timely thinning and hereby increase the quality of the remaining forest stand, leading to a better assortment with higher timber shares. In the counterfactual situation, this kind of thinning is considered unprofitable.

While the specific long term effect on timber quality induced by e.g. timely thinning driven by a bioenergy demand remains unknown, the use of nurse trees such as poplar, birch and larch species can increase the average forest carbon stock of up to 10-20% over the forest rotation under Danish conditions [35]. In this report this was not considered, as no data on the amount of e.g. nurse trees is available.

Ad. 3 Reduced supply of wood products - iWUC

In economic theory, when the supply of industrial wood is under pressure from an increased demand for bioenergy and hence increased biomass price, the price of industrial wood also increases. Increasing prices leads to decreasing wood consumption, as shifts to other products becomes more economically favourable, hereby changing the emission profile. When demand for bioenergy drives the price increase on other products, these emissions are attributed to bioenergy.

In this report it is assumed that the overall demand for goods and services e.g. buildings, paper and furniture is not affected by increased use of wood for energy [33]. Therefore, the increased price on industrial wood will shift the consumption towards use of alternatives to industrial wood, e.g., concrete, steel, or plastic.

Here we assumed that all demand not additionally supplied through additional harvesting or iLUC (expansion of managed forest area) is shifted to other products such as steel, concrete or plastic i.e. full substitution.

Such shifts, lead to increased emissions as many of these products have higher supply chain emissions than wood [36]. Commonly this effect is reported as a substitution factor (SF) that expresses the amount of CO2 emissions for the alternative product as a factor of the amount of carbon in the wood product which is substituted:

$$SF = \frac{C_{non-wood} - C_{wood}}{WU_{wood} - WU_{non-wood}},$$

where $C_{non\text{-}wood}$ and C_{wood} are the carbon emissions from the use of non-wood and wood alternatives and WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in wood and non-wood alternatives [48].

Leskinen et. al., [30], finds that the mean substitution factor for wood products on average is 1,2 to 1,6 but varies substantially.

Here a substitution factor of 1.4 (iWUC for stems) for structural timber and non-structural parts was assumed 1.2 (iWUC for industrial residues) for panels and boards produced from industrial residues. Hence, for each tonne of wood carbon not being a residue or denoted with iLUC, 1.4 and 1.2 tonnes of carbon were added to the emissions for bioenergy in the factual situation.

Specifically, the shares of biomass not considered a residue in this report, was attributed 50% with iLUC emissions and 50% iWUC emissions for stems and industrial residues and 100% additional harvesting for energy wood from forests and non-forest biomass.

2.5 Biomass categories and counterfactuals

The biomass that was used in Denmark in 2022 was categorized into five groups: *harvest residues, stems, industrial residues, energy wood from forests and non-forest and waste wood biomass [41]*. The counterfactual assumptions to bioenergy for each category are described below.

***Harvest residues* from forestry** is biomass from tops and branches as well as from early thinnings, which is normally left on site for natural decay or burned after a harvest or thinning operation. As the counterfactual for harvest residues, it was assumed that 30% were burned directly on the forest floor with a half-life of 0.5 years and 70% was left in the forest for natural decay. All harvest residues are considered residues in the current market situation and therefore no indirect emissions were assumed for this type of biomass. With 30% being burned and 70% being left for decay, the mean half-life for harvest residues is assumed 7.15 years.

Figure 2: Example of harvest residues. Here tops from Norway spruce with a deposition limit of 14 cm.

Stems used for energy is a broader category which typically contains undersized stems, stems with rot, bend stems, and stems from non-merchantable tree species. For 90% of the stems, it was assumed that the counterfactual to energy production was to be left on site, for natural decay (100%) during forest harvest with no alternative use, i.e. no indirect emissions. However, the stem category can contain stems that could have been used for pulp and paper or wood products, which leads to iLUC and/or iWUC emissions. It was assumed that 10% of stem biomass should be attributed indirect emissions, with 5% as iLUC emissions and 5% as iWUC emissions.

Figure 3: Example of stem wood for energy. The wood is the bottom of Norway spruce stems with substantial root and bud rot.

Industrial residues are mainly sawdust, bark, slabs, edgings, off-cuts, veneer clippings, and particleboard trimmings, planer shavings, and sander dust (see figure 4 for examples).

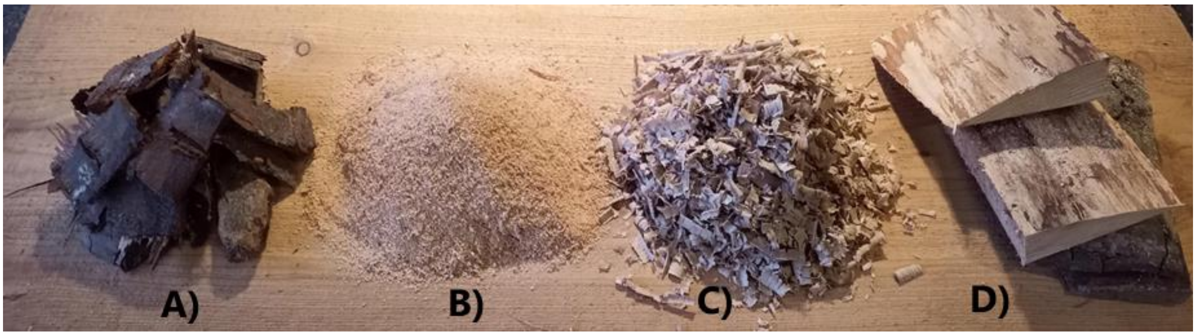

Figure 4: Typical examples of industrial residues. A) Bark (Hog fuel), low quality, typically used for drying of wood pellets. B) Sawdust from sawmills, high quality clean wood, typically used for wood pellets. C) Planer shavings, from furniture production, high quality clean wood, typically used for wood pellets. D) Shells from sawmills, varying quality, typically used for wood chips or wood pellets.

Depending on the sawmill or production unit, and the type of residue, the counterfactual can be everything from burning or decaying on site to solid wood products such as particle boards or paper, from which indirect emissions may occur. For 90% of the industrial residues a counterfactual of decay was assumed with a half-life of 5 years. For the remainder 10%, a counterfactual leading to indirect emissions with 5% attributed to iLUC and 5% attributed to iWUC was assumed.

Energy wood from forests is biomass originating from tree stands harvested solely for the purpose of energy production. For the part of this category with no counterfactual other than being left on the forest floor, this was modelled as 50% stems and 50% harvest residues, which was treated as described for harvest restudies and stems above. There are typically three types of harvest of energy wood from forests.

1. Dedicated energy plantations, mostly containing tree species with rapid juvenile growth, such as birch, willow, alder, eucalyptus or poplar. Such plantations will have a negative effect on iWUC, as they take up space for industrial wood production. However, they also have a positive effect as they restore the carbon stock much more rapidly compared to wood producing tree species. In some cases, the rapid growth by dedicated energy plantations overrules the loss of wood product production, see e.g. [37], in other cases not. Here the effect is assumed neutral, leaving only decay left as counterfactual.

2. Harvest of unproductive stands in corners and edges of forests, which in the absence of bioenergy would have been left unharvested. Harvesting of these stands will have a negative effect on the forest carbon stock, compared to the counterfactual situation and is modelled as additional harvest.

3. Clearing of invasive species and unwanted tree growth in nature conservation areas, where the counterfactual fate of wood material is to be left for decay is modelled as harvest residues.

Overall, the category of *Energy wood from forest* can both have positive and negative effects on the forest carbon stock. The proportion of the three above mentioned types is not known.

However, as a precautionary principle it is conservatively assumed that there is a small overweight of the negative effect, leading to 10% additional harvesting (reduction in forest carbon stock) due to the increasing prices for bioenergy observed in 2022.

Figure 5: Examples of energy wood from forests. A) A monoculture with poplar, planted solely for energy production. B) An unproductive corner of the forest with poor quality non-commercial tree species, here red alder. C) Removal of invasive species from nature areas.

Non-forest and waste wood are merged into one category that includes waste from gardens, used for firewood, harvesting of shelterbelts, harvesting of tiny forest plots in agricultural fields etc. As there is no difference between the biomass categories *non-forest biomass* and *wood waste and municipal wood waste,* model wise, these categories were merged in the non-forest and waste wood biomass category. The waste wood considered here is however only wood from gardens used for firewood.

Figure 6: Typical examples of non-forest and waste wood biomass. A) A shelterbelt can be used for wood chips B) Trees from gardens used for firewood. C) A game remise can be used for wood chips.

In the basic assumptions, non-forest and waste wood biomass was treated as 50% harvest residues piled in the forest for decay (70%) or burned on site (30%), with a mean half-life at 7.15 years, as much of this biomass typically has a small diameter, and 50% as stems with a half-life at 15 years, as these types also has some degree of stem parts. Moreover, due to the increasing prices on biomass observed in 2022, this category was attributed with 10% additional harvesting as some areas previously unprofitable for harvest now becomes profitable, leading to a decrease in landscape carbon stock.

Firewood is composed of a mixture of the above-mentioned biomass categories, based on the study in [11], where firewood is categorised as:

1. Wood from gardens, here treated as non-forest and waste wood biomass.

2. Directly from forests, here treated as 90 stems and 10% harvest residues.
3. Firewood packed on pallet towers, here treated as stems.
4. Firewood from other dealers, here treated as stems.
5. Firewood from residues from wood processing industry, here treated as industrial residues.
6. Other materials, here treated as industrial residues.
7. Don’t know, here treated as non-forest and waste wood biomass.

Although transport modes differ compared to wood chips and wood pellets used in the transformation sector, assumptions on transport were the same for firewood (and wood pellets consumed in private households) as for wood chips and wood pellets [see 1 and 3].

2.6 The single pulse curve and marginal time dependent effect

A single pulse curve is used to present the cumulative net carbon emissions from a single production year (here 2022), in a 100-year perspective.

The curve is a function of upstream emissions from forest management, harvesting, transport, processing added to direct combustion emissions from energy production plus emissions from indirect land use change, indirect wood use change and additional harvesting and finally deducted the recapture of CO2 in forests and trees recovering after harvest, compared to had the biomass suffered a counterfactual fate (fate of biomass if not used for energy) decay or unharvested. For a thorough model description, see [3] and figure 1.

The curve (Figure 7, lines) represents the time dependent marginal difference between the factual situation (biomass being used for energy) and the counterfactual situation (biomass being left for decay, avoided iLUC etc, x-axis on the figure, expressed in tons of CO_2.

For residues with a counterfactual being decay, the CO2 bound in the wood will eventually end up in the atmosphere, both in the factual and counterfactual situation. However, in the counterfactual situation this will occur slower, as the decay process is slower than the burning process. This slower process in the counterfactual situation function as a bottleneck that will make a larger amount of CO2 being stored in decaying wood, than in the factual situation, where the wood is burned, and the CO2 is released to the atmosphere immediately. The difference in forest floor carbon stocks between burning for energy and decay is determined by the half life of the decaying wood. Biogenic CO2 emissions from wood with a fast decay (harvest residues), will thus converge to 0 faster compared to wood with longer half-life (stems) (Figure 7).

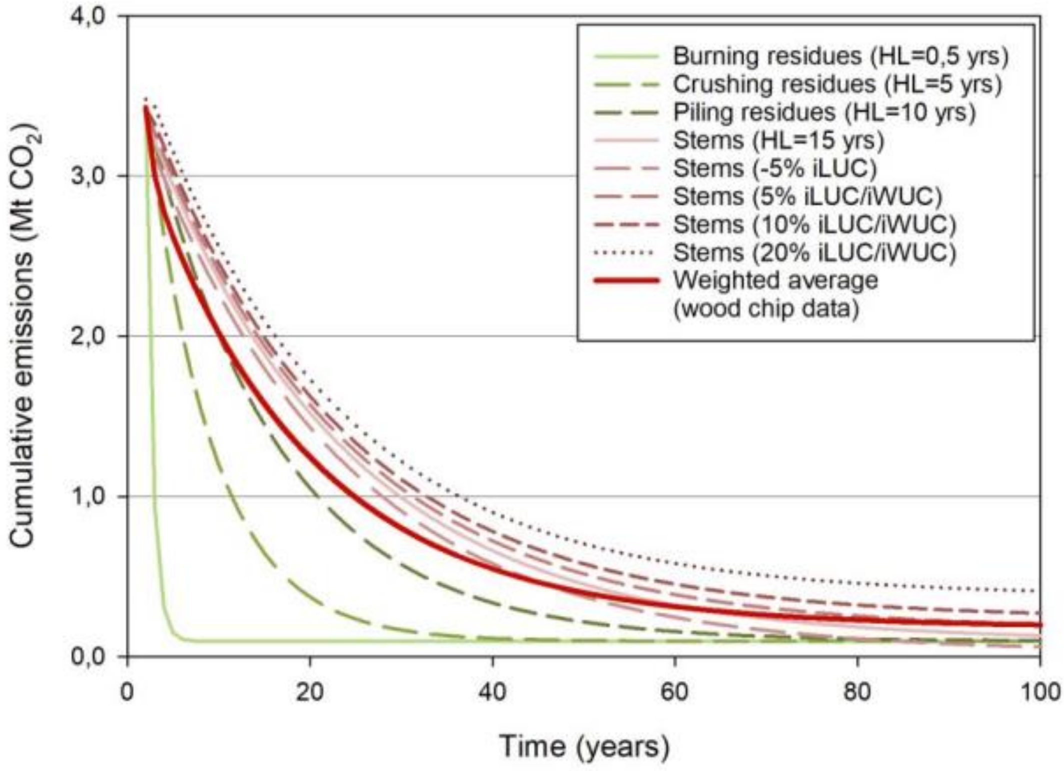

Figure 7: Typical shapes of the single pulse curve, with different counterfactuals, e.g., half-life (HL), amount of wood with iLUC and iWUC. Reproduction from [3].

The single pulse curve is thus at its highest the year of combustion where the difference between factual and counterfactual is largest. In time the CO2 in the decaying wood in the counterfactual situation will also be emitted to the atmosphere and the single pulse curve will, regarding the time dependent biogenic emission, converge towards 0 (0 is the counterfactual situation), as the difference between factual and counterfactual becomes smaller.

However, as there are fossil fuels used in transport, processing of biomass and iWUC emissions, together with permanently reduced forest carbon stocks iLUC, the single pulse curve will not converge to 0 (Figure 6). The magnitude of the beforementioned effects will determine the level of convergence of the single pulse curve.

There are roughly four ways the single pulse curve can be affected by changes in consumption data (see figure 8).

1. The curve shifts parallelly upwards or downwards if consumption changes, equivalent to the emissions imposed by the shift in consumption, meaning that larger consumption leads to larger emissions.
2. Changes in the composition of the sourced biomass (stems, harvest residues, industrial residues etc) as these have different decay rates in nature or as products . Slower decay rates lead to longer residence times of the carbon in the decaying wood, and hence to a slower convergence of the single pulse.

3. The single pulse curve can be affected by the use of fossil fuels in the supply chain or related to iWUC. Changes in this will lead to a parallel shift in the curve equal to the emissions from the fossil fuels.
4. The single pulse curve can be affected as by permanently increased or decreased carbon stocks induced by additional harvest and iLUC. This will lead to a parallel shift up or down in the curve, like for fossil fuels.

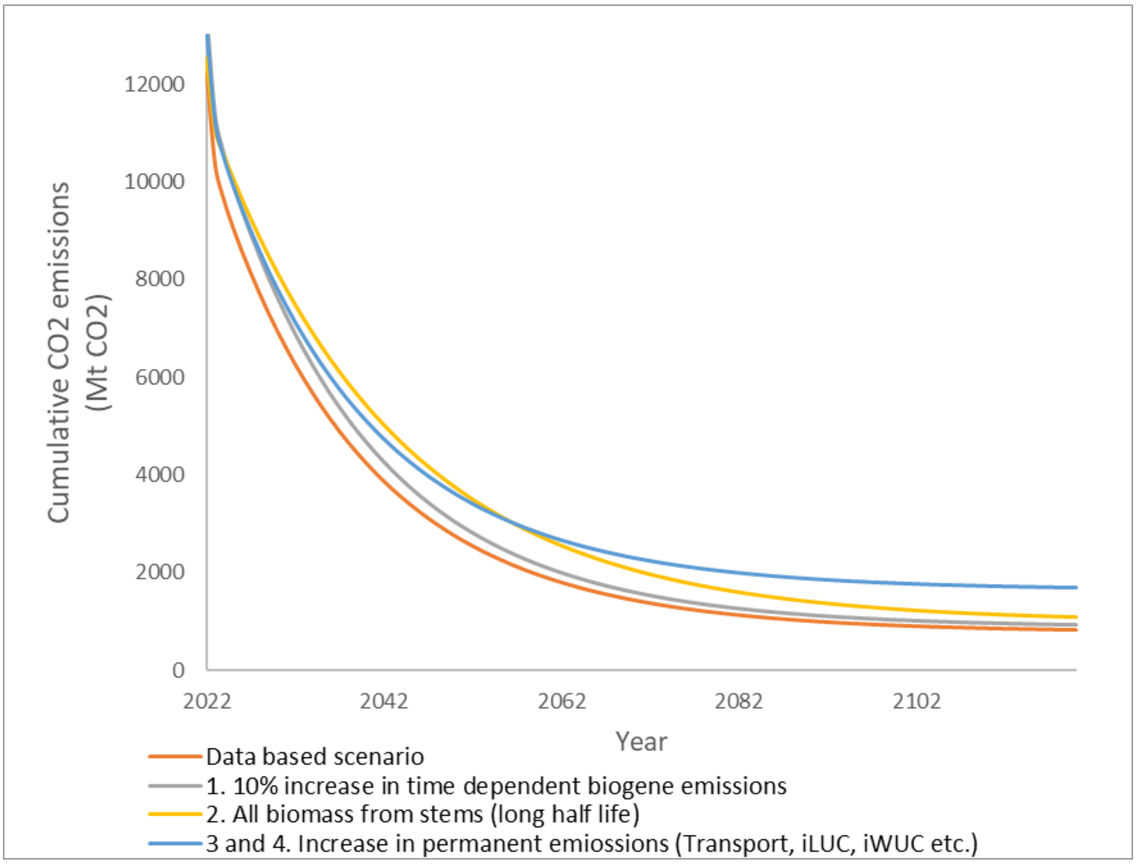

Figure 8: Examples corresponding to point 1 to 4, cf. 2.6.

2.7 Analyses carried out in this report

The single pulse curve is here used to present how the biomass used in 2022 by the transformation sector and in private households affect the atmospheric CO2 from 2022 and 100 years into the future. Analyses were made by sector and fuel type and aggregated to a national level.

Emissions factors (Kg CO2/GJ) was derived from the single pulse curve. Finally, emission factors were split up on different parts to demonstrate the magnitude of the above-mentioned factors.

3 Results

3.1 The data basis for the Danish wood chip, wood pellet and firewood consumption in 2022

In 2022, the total primary energy supply to the Danish CHP and DH production [8] of wood chips and wood pellets, was 78.3 PJ. Of the 78.3 PJ, 41 PJ was wood chips, and 37.3 PJ was wood pellets (Table 2). These consumption data were used in the subsequent analyses. The private households consumed 10 PJ wood pellets and 13.8 PJ firewood (Table 2).

Table 2. Biomass consumption in district heating and combined heat and powerplants as well as in private households from different fuel types in 2022. Data source: Energistatistik 2022 [8].

	Wood pellets transformation	Wood chips transformation	Wood pellets private	Firewood private	Total
ENS (PJ)	37.3	41.0	10.0	13.8	102.1
Share (%)	36.6	40.2	9.7	13.4	100

In the transformation sector, feedstock for wood chips production is mostly harvest residues followed by stems and a smaller fraction of industrial residues. Wood pellets are based primarily on industrial residues (sawdust etc.), but also on a large proportion of stems and only minor amounts from the other categories (Table 3).

In direct consumption in private households, wood pellets were almost solely based on industrial residues and a small proportion of stems. Firewood was assumed to be mainly based on stems and non-forest and waste wood feedstock, (Table 3).

Table 3. Feedstock for wood chips, wood pellet and firewood production as reported by utility companies and wood pellet importers and from [11] for 2022. 0,0% indicates a very small amount, where empty cells indicate 0%.

Fuel type	Harvest residues	Stems	Energy wood from forests	Industrial residues	Non forest
			%		
Wood chips	44,3%	25,1%	9,1%	13,9%	7,6%
Wood pellets transformation	6,2%	43,2%	0,5%	50,1%	0,0%
Wood pellets private	0,0%	5,8%	0,0%	94,2%	0,0%
Fire Wood private*	0,6%	41,4%		2,5%	54,8%
Weighted average	19,2%	32,2%	3,6%	33,6%	11,3%

*Source [11] and calculations cf. 2.5

Overall, industrial residues and stems each covered a third of the consumption, where harvest residues covered roughly 20%, non-forest and waste wood biomass covered 11.3% and energy wood from forests covered 3.6%.

Of the total biomass used 92% was considered residues, where the remaining 8% was considered wood attributed with indirect emissions, such as iLUC or iWUC.

Wood chips in the transformation sector mostly came from Denmark, covering 36% of the use, closely followed by the Baltic countries (app. 30%). Other large contributors of wood chips to the transformation sector were Sweden, Germany and Brazil, with the rest sourced broadly from Europe (Table 4).

Wood pellets in the transformation sector was mainly sources from the Baltic countries covering more than 50%. USA covered 21,4% and the rest was sourced more broadly in Denmark, Sweden, and other European countries (Table 4).

Table 4: Origin of different biomass for energy categories. 0,0% indicates a vary small amount, where empty cells indicate 0%. Note that origin of industrial residues does not reflect where the wood has grown, but only where the wood industry, from which the biomass was sources is located.

Country	Share of wood chips Transformation sector	Share of wood pellets Transformation sector	Share of wood pellets direct private consumption	Share of fire-wood direct private consumption*	Overall share of biomass for energy
			%		
Belgium	0,2%	0,0%			0,1%
Belarus		0,1%	0,1%	0,1%	0,1%
Bosnien-Hercegovina				0,0%	0,0%
Brazil	6,7%	1,5%			3,1%
Canada		1,1%	3,8%		0,8%
Denmark	36,0%	7,1%	5,8%	92,0%	30,5%
Estonia	3,1%	27,8%	7,2%	1,3%	12,5%
Finland	0,1%	0,1%	4,8%	0,0%	0,5%
France	0,2%			0,1%	0,1%
Germany	8,8%	2,9%	1,6%	0,3%	4,5%
Great Britain	0,2%	0,0%			0,1%
Italy				0,0%	0,0%
Latvia	25,1%	21,9%	4,3%	1,4%	18,2%
Lithuania	1,2%	2,1%	0,7%	2,2%	1,6%
Norway	5,2%	2,9%	0,7%	0,0%	3,1%
Poland		3,0%	4,1%	1,1%	1,7%
Portugal	0,1%	0,5%	2,6%		0,5%
Russia**	0,2%	1,7%	27,0%	0,0%	3,5%
Serbia				0,0%	0,0%
Slovenia				0,0%	0,0%
Spain	0,3%			0,0%	0,1%
Sweden	12,6%	6,0%	29,3%	0,9%	10,1%
Ukraine				0,5%	0,1%
USA		21,4%	8,1%		8,8%

*Source [10], **Sourcing from Russia stopped in 2022 due to sanctions following the Ukraine war.

In the direct consumption in private households the largest contributor to wood pellets was Sweden with app 29%, closely followed by Russia with 27%. App. 12% was sourced from the US and Canada, with the remainder sourced broadly from European countries (table 4). Firewood was mainly sourced in Denmark, covering 92% of the consumptions and the largest import countries being the Baltic countries and Sweden and the remainder sourced broadly from Europe.

Overall, the largest contributor to the Danish use of woody biomass for energy was the Baltic countries, covering app 37% of the use. Roughly 30% was sourced in Denmark. Sweden and the US covered each a bit above 10% and the rest was covered broadly in Europe, Brazil and Russia (Table 4).

3.2 2022 woody biomass CO_2 dynamics in the transformation sector

3.2.1 Wood chips

The use of wood chips in 2022 with a consumption of 41.0 PJ emitted 4.85 Gt CO_2 in 2022. However, over time the difference between the factual and counterfactual situation converges (Figure 9). After 79 years only 1% of the time dependent biogenic emissions induced by using wood chips for energy in 2022 compared to the counterfactual of not using biomass, were left in the atmosphere. CO_2 emissions do not converge towards zero, as there are fossil emissions related to the supply chain e.g. forest operations, transport, and indirect emissions e.g. reduced forest carbon stock induced by additional harvesting and iLUC, and fossil emissions from iWUC.

Permanent indirect emissions, such as iLUC and iWUC accounted for app. 2% of the emissions in year 1 and 40% in year 100, and fossil transport and process emissions accounted for 2.5% in year 1 and 52% in year 100.

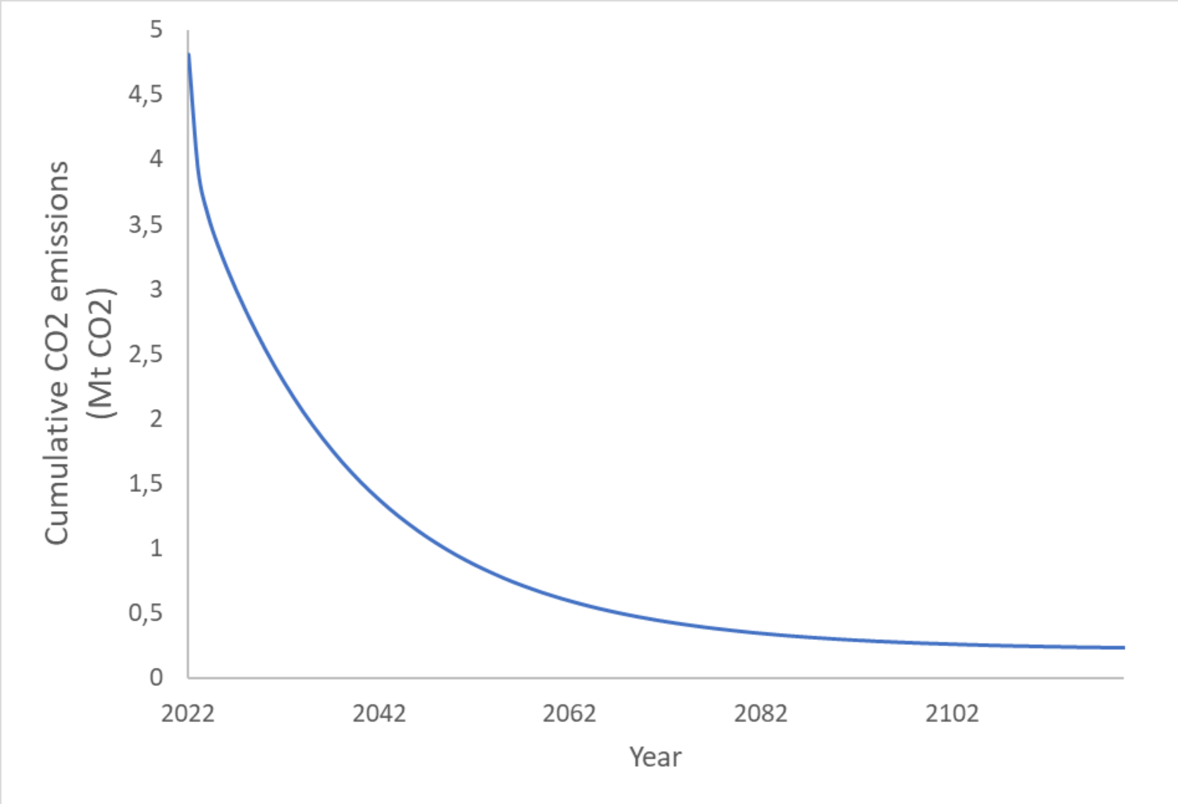

Figure 9. Cumulative emissions for 2022 consumption of wood chips for energy production in the Danish transformation sector, for production of 41.0 PJ using the "weighted average wood chip data".

The emissions factor for wood chips in year one is higher than for coal due to a higher energy density per tons C of coal. After few years (1-3), the emission factor falls to a lower level than for coal (Table 5). In year one the emission factor for wood chips was 117.2 Kg CO_2/GJ, where after 30 years, the emissions are 22.2 Kg CO_2/GJ. 100 years after combustion, only emissions equivalent to the fossil part of the emissions and permanent reduction in the forest carbon stocks following iLUC and additional harvesting remains in the atmosphere, being 5.7 Kg CO_2/GJ. Comparable CO_2 emissions from coal and natural gas would be 107 and 65 Kg CO_2/GJ respectively, regardless of the time perspective (Table 5).

Table 5: CO2 emissions (Kg/GJ) for different fuel sources used for wood chips and for the weighted average wood chip data

Year after consumption	*1*	*10*	*20*	*30*	*50*	*70*	*100*
Weighted average wood chip data	**117,2**	**58,6**	**35,1**	**22,2**	**10,9**	**7,2**	**5,7**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

3.2.2 Wood pellets

For wood pellets in the transformation sector with a consumption of 37,4 PJ, direct emissions were slightly lower compared to wood chips (4.6 GtCO2), mainly due to the lower input of wood pellets, compared to wood chips. As for wood chips, the emissions converge towards up-stream fossil process, transport and indirect emissions within a certain period. Less than 1% of biogenic emissions remain after 66 years (Figure 10). The convergence is slightly faster than for wood chips due to larger proportion of industrial residues (short half-lives) in wood pellet production. Moreover, the convergence is at a higher level due to longer transport distances, more processing, accounting for 5.6% in year 1 and 52% in year 100, and the fact that indirect emissions here accounts for 3.9% in year 1 and 44% in year 100 (Figure 10) with the remaining emissions, being residual time dependent biogenic emissions.

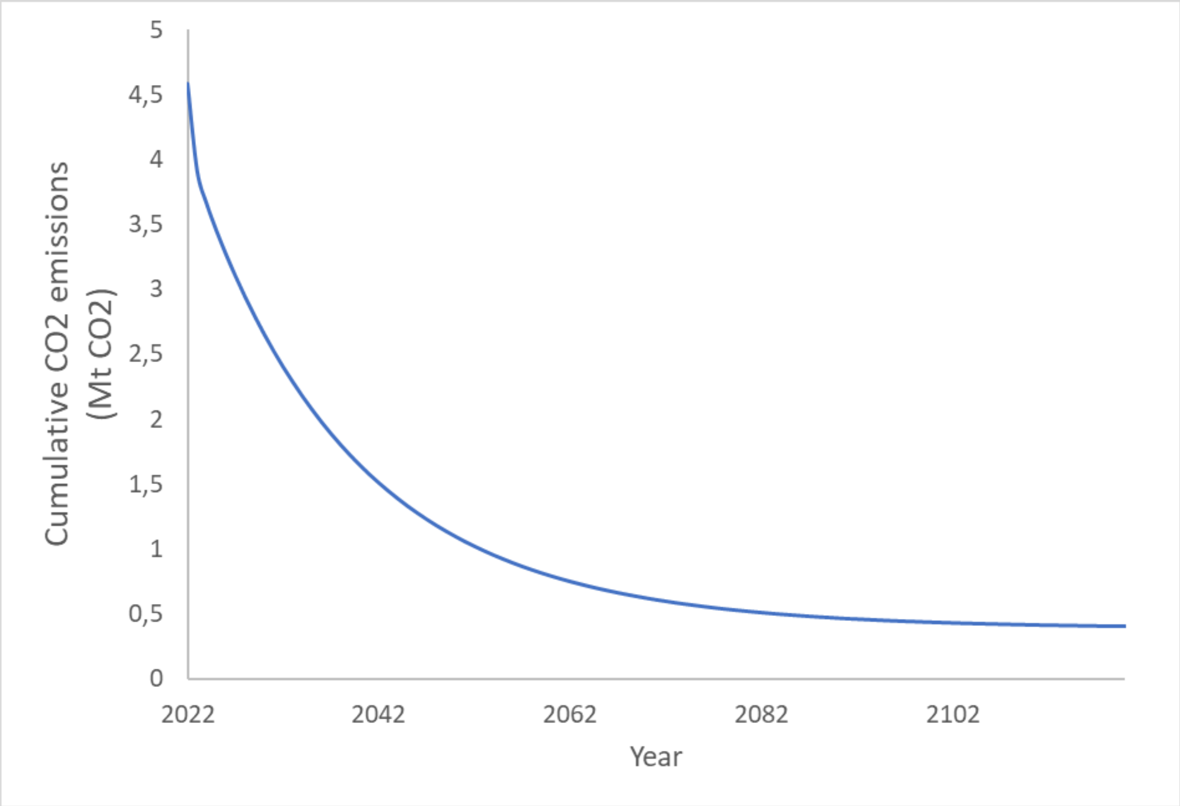

Figure 10. Cumulative net CO_2 emissions 2022 use of wood pellets in the transformation, with a consumption of 37.3 PJ wood pellets, for the current biomass sourcing as described for the "weighted average wood pellet data" from the transformation sector.

The emission factor for wood pellets is slightly higher in year 1 compared to wood chips. The need for drying, the longer transport distance, and the larger proportion of wood carrying indirect emissions, leads to a higher emission factors for wood pellets compared to wood chips in the transformation sector (Table 6). The larger amount of fossil fuels used in the wood pellet supply chain and more permanent indirect emissions are also evident by the higher level of convergence (difference between factual and counterfactual) in year 100, compared to wood chips (Table 5 and 6).

Table 6. CO_2 emissions coefficients (Kg/GJ) for the weighted average wood pellet data in the transformation sector

Year after consumption	*1*	*10*	*20*	*30*	*50*	*70*	*100*
Weighted average wood pellet data	**122,5**	**67,5**	**42,1**	**28,3**	**16,3**	**12,4**	**10,8**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

After 100 years, emissions from the 2022 pellet-based biomass use in the transformation sector are approximately 10% and 17% respectively of the emissions had the energy been produced by coal or natural gas.

3.2.3 Total wood consumption emissions in the transformation sector

Consumption of wood pellets and wood chips used in the Danish transformation sector in 2022 (78.3 PJ), lead to emissions in year 1 of app. 9.5 million tons CO_2 (Figure 11). Emissions, however, rapidly decline over the first 40 years after consumption and reach 1% of the initial time dependent biogenic emissions remaining after 77 years.

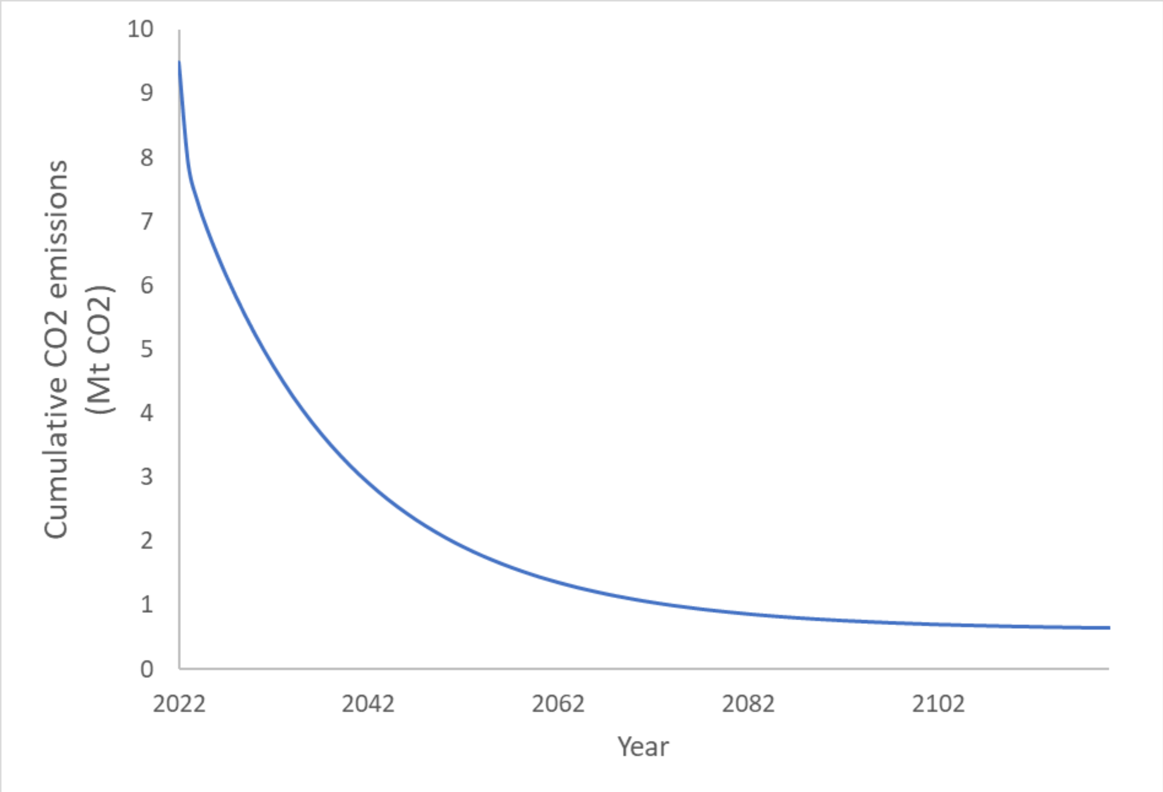

Figure 11. Cumulative net CO_2 emissions of a single year use with a weighted average consumption of wood pellets and wood chips in Danish DH and CHP of 78.3 PJ.

The emissions per GJ are somewhat in between the results for wood chips and wood pellets (Table 7).

Table 7. CO_2 emissions coefficients (Kg/GJ) for the weighted average wood chips and wood pellet data in the transformation sector

Year after consumption	*1*	*10*	*20*	*30*	*50*	*70*	*100*
Weighted average data	**121,0**	**63,4**	**38,8**	**25,3**	**13,5**	**9,7**	**8,2**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

In year 1, direct biogenic emissions from combustion of biomass accounts for 85% of the total emissions. Biogenic process emissions (hog fuel for wood pellet drying) accounts for 8.6%, iWUC/iLUC for 2.9% and fossil process emissions including transport accounts for 3.5% of the total emissions. The convergence between factual and counterfactual is reflected in the change in emission factors over time. Emissions are lower than coal already few years after combustion, while for natural gas the emissions are higher for about 10 years but lower hereafter (Figure 12).

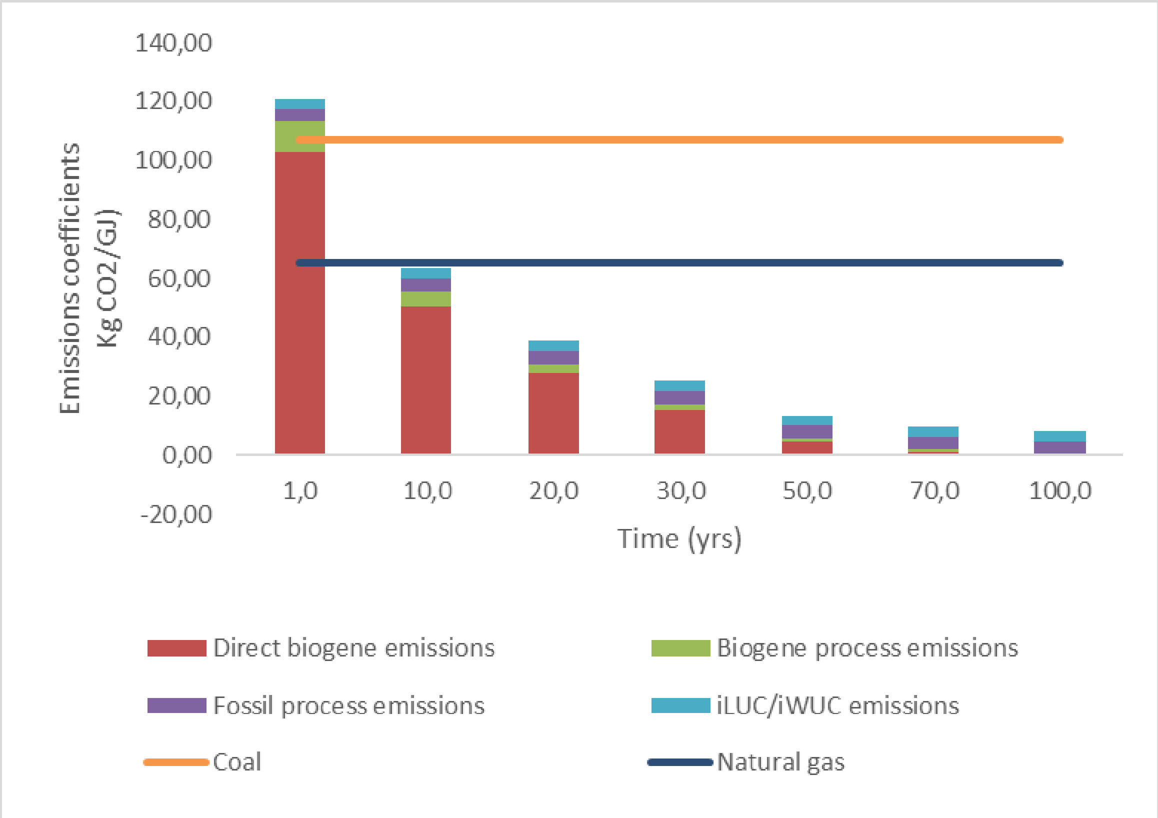

Figure 12. Emission coefficients for Danish district heating and CHP wood consumption and fossil energy sources (coal and natural gas) over time. Importantly, the biogene emissions are reduced over time due to convergence between factual and counterfactual.

It should be noted that iLUC, iWUC and fossil supply chain emissions are irreversible, while biogenic process and direct biogenic emissions are time dependent and reversible.

3.3 2022 biomass CO_2 dynamics in direct consumption in households

3.3.1 Wood pellets

Direct use of wood pellets in the private households with a consumption of 10 PJ leads to emissions of 1.26 Mt CO_2 in year one (Figure 13). Fossil process and transport emissions accounted for 5,7% of the emissions in year 1 and indirect emissions accounted for 4.1%. In year 100 transport and process accounted for 57.7% and indirect emissions for 41%, with the remaining emissions, being residual time dependent biogenic emissions.

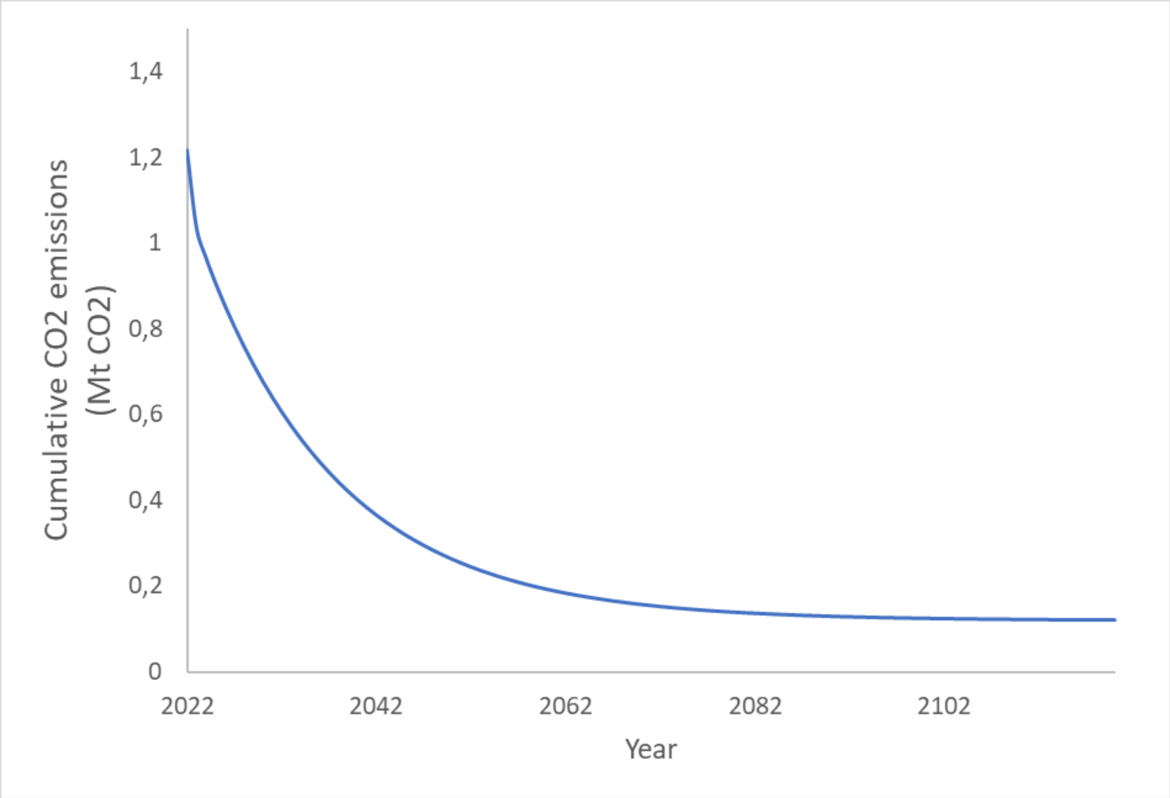

Figure 13. Cumulative emissions for one-year consumption of wood pellets for energy consumption by wood pellets consumed directly in private households 2022, for production of 10.0 PJ.

For wood pellets consumed directly in private households, the emissions factor in year one is 122.3 Kg CO_2/GJ, where after 30 years, the emissions factor is 25.4 Kg CO_2/GJ, and after 100 years only emissions equivalent to the fossil part of the emissions remains in the atmosphere adding up to 12.1 Kg CO_2/GJ (Table 8). The high level of convergence (large difference between factual and counterfactual in year 100) is due to the large proportion of biomass origin from Russia, and USA, with long transports, leading to a larger part of the emissions being irreversible.

Less than 1% of the time dependent biogenic emission remained in the atmosphere after only 65 years. The rapid convergence is due to the large proportion of industrial residues used here with the short half-life of 5 years, leading to a faster convergence of the time dependent biogenic emissions.

Table 8: CO2 emissions (Kg/GJ) for wood pellets used in direct consumption in private households

Year after consumption	*1*	*10*	*20*	*30*	*50*	*70*	*100*
Weighted average wood chip data	**122,3**	**64,3**	**38,4**	**25,4**	**15,5**	**12,9**	**12,1**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

3.3.2 Firewood

A firewood consumption of 13.8 PJ emitted 1.62 Mt CO_2 in 2022 (Figure 14). Due to the large amount of stems in the firewood category the convergence of the single pulse curve is somewhat slower than for the other biomass types, as stems in the counterfactual has a slower decay rate and the time to reach 1% of biogenic emissions being left in the atmosphere was here 96 years. However, the level of convergence (difference between factual and counterfactual in year 100) is lower than the other biomass types, as the transport in the supply chain for firewood is much shorter, compared to e.g. wood pellets, leads to a lower level of permanent emissions.

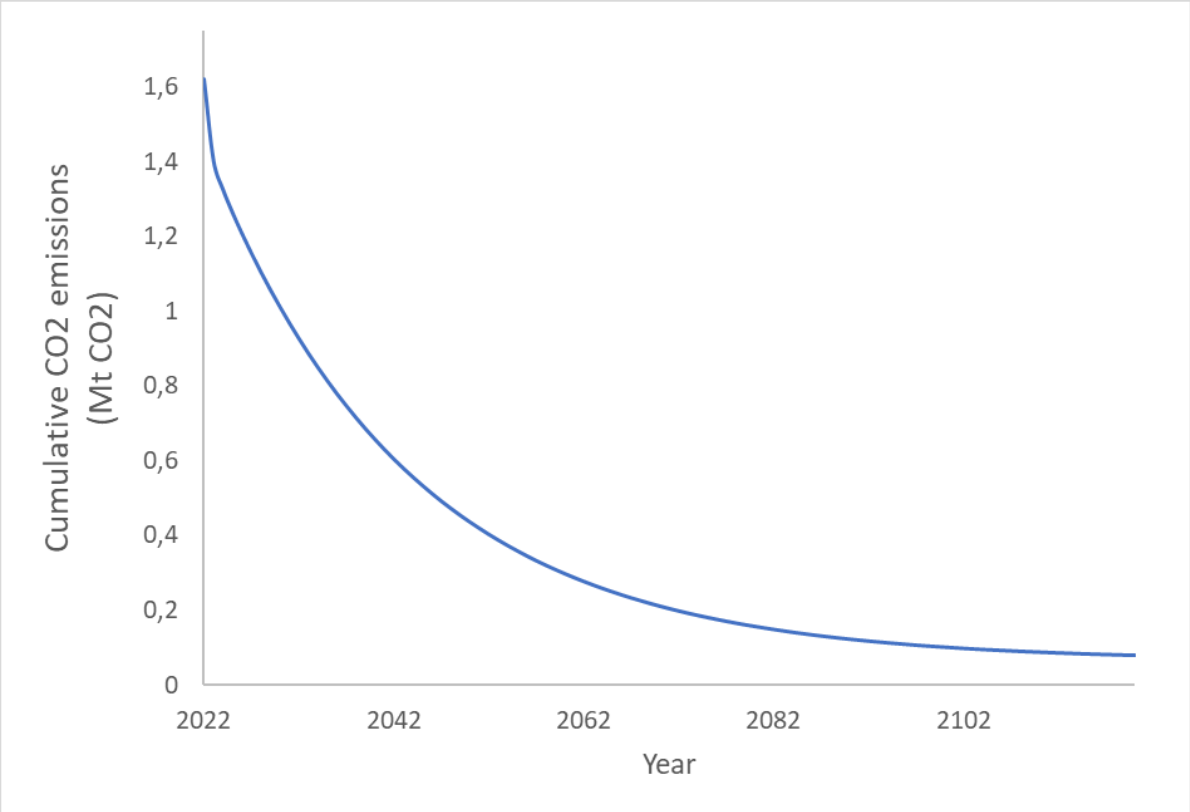

Figure 14. Cumulative emissions for one-year direct consumption of firewood in private households in 2022 in Denmark, for production of 13.8 PJ.

The emissions factor for firewood in year one was 117.7 Kg CO_2/GJ, which is comparable to wood chips and ends up at 5,7 Kg CO_2/GJ (Table 9).

Table 9: CO2 emissions (Kg/GJ) for different fuel sources used for wood chips and for the weighted average wood chip data

Year after consumption	*1*	*10*	*20*	*30*	*50*	*70*	*100*
Weighted average wood chip data	**117,7**	**70,2**	**45,7**	**30,4**	**14,8**	**8,7**	**5,7**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

In year 1 transport and processing accounted for 1.5% of the emissions and 31% in year 100. Indirect emissions accounted for 2.5% in year 1 and 51% in year 100.

3.4 CO2 emissions from total national woody biomass use for heat and electricity (main results)

For the entire consumption of wood pellets, wood chips and firewood used in the Danish transformation and household sectors in 2022 (102.1 PJ), the emissions in year 1 are app. 12.4 million tons CO_2 (Figure 15). Time dependent biogenic emissions converge to less than 1% after 81 years. In year 1 and year 100 fossil transport and processing emissions accounted for 3.5% and 52.9% respectively. Indirect emissions (fossil and permanent biogenic) in accounted for 2.9% and 42.8% in year 1 and 100, respectively.

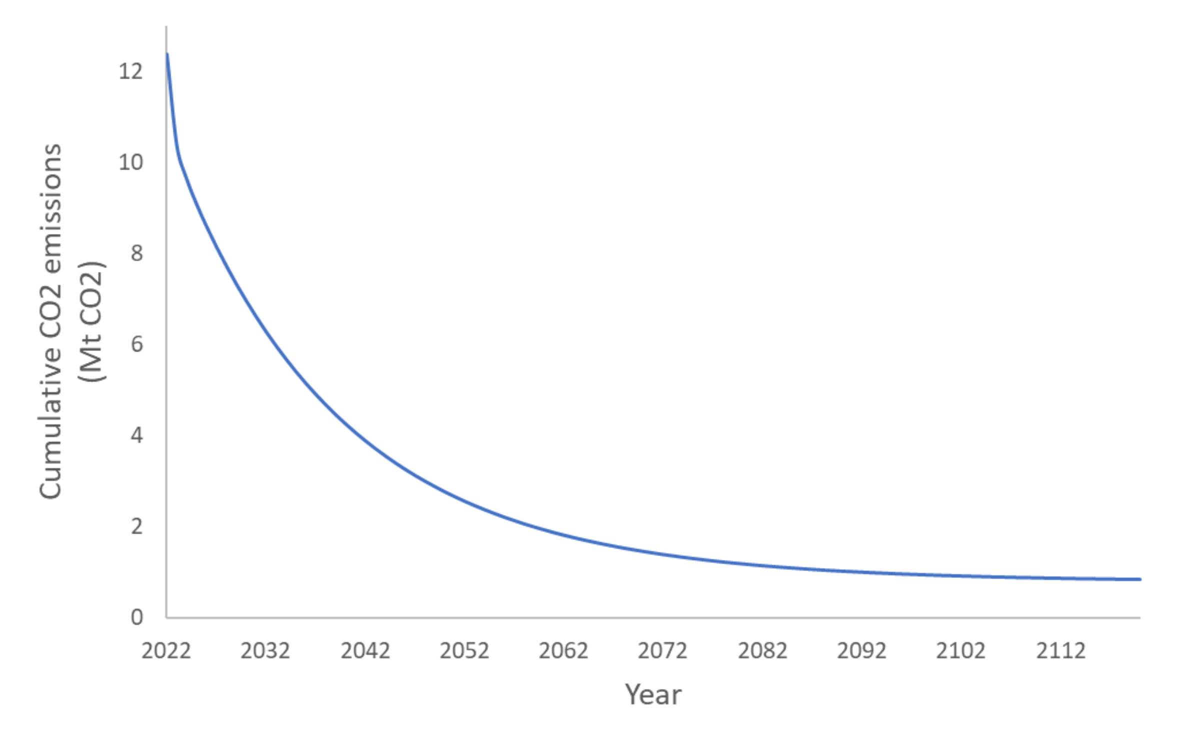

Figure 15 Cumulative net CO_2 emissions from total national consumption of woody biomass for energy in 2022, by use of wood chips, wood pellets and firewood with a total biomass consumption of 102.1 PJ.

Not surprisingly, the emissions factors fall in between all the different fuel and consumption types when merged to national consumption with weighted average data (Table 10).

Table 10: CO2 emissions (Kg/Gj) for all woody biomass used for energy in Denmark in 2022

Year after consumption	*1*	*10*	*20*	*30*	*50*	*70*	*100*
Weighted average data	**121,2**	**64,7**	**39,8**	**26,0**	**13,9**	**9,9**	**8,3**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

In year 1 direct time dependent biogenic emissions from combustion accounts for 85,3% (103.3 Kg CO_2/GJ), time dependent biogenic process emissions (hog fuel for wood pellet drying) for 8.4% (10.1 Kg CO_2/GJ) of the emissions, fossil transport and process emissions covered 3.5% (4.2 Kg CO_2/GJ) of the emissions and indirect emissions (additional harvesting, iLUC and iWUC, i.e. permanent biogenic carbon stock change and fossil emissions accounted for 2.9% (3.5 Kg CO_2/GJ) (Figure 16).

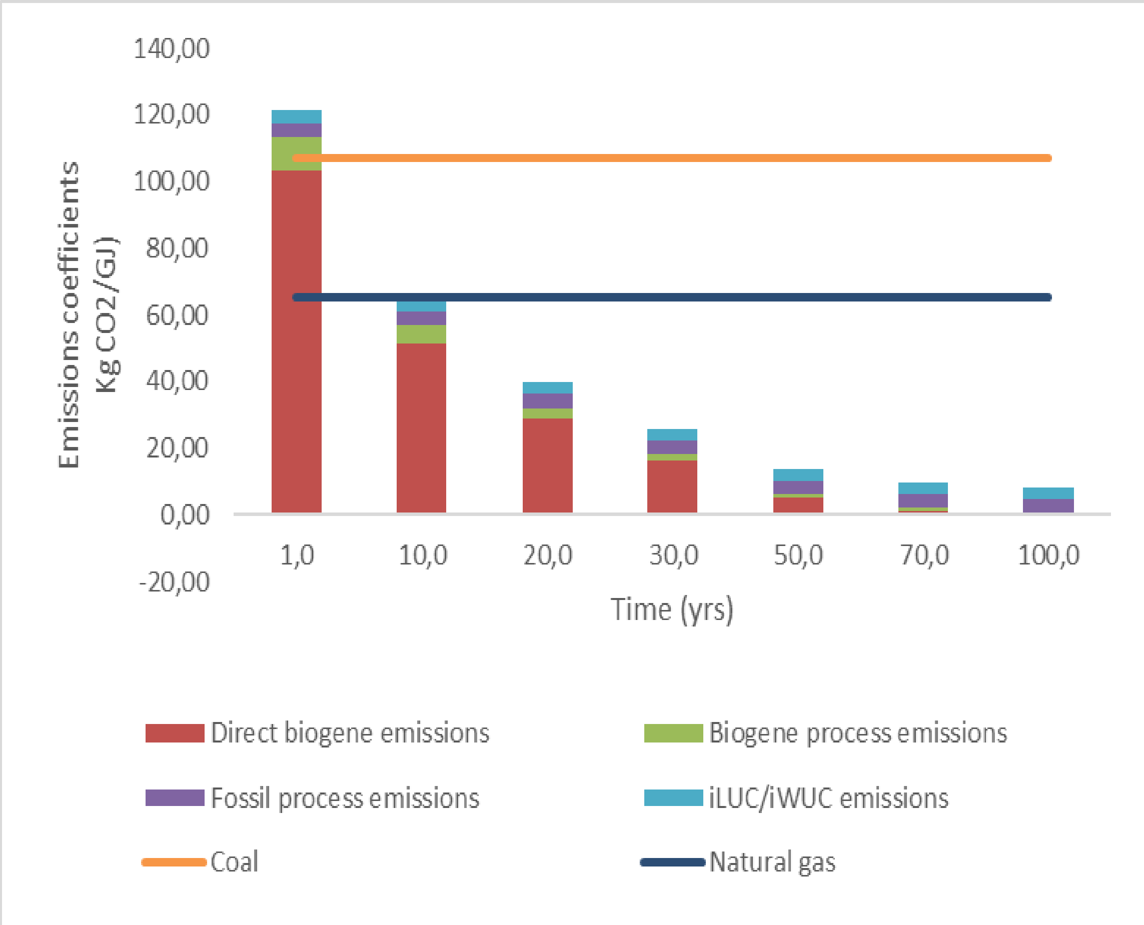

Figure 16. Emission coefficients for wood consumption in Danish district heating and CHP as well as the direct consumption in private households and reference fossil fuel sources (coal and natural gas) over time. Importantly, the biogenic emissions are reduced over time due to convergence among factual time dependent biogenic emissions and counterfactual of the emitted CO_2.

4 Discussion and conclusion

4.1 Data input

In [Nielsen et al 3] the data collection covered 96% and 69% of the wood pellet and wood chip consumption in the transformation sector, respectively and 0% in direct consumption in households, while in [Nielsen 4] the coverage for wood pellets and wood chips only covered 75 and 53% of the total consumption of the wood chip and wood pellets used in in the transformation sector and =% of the private consumption in households.

In the present report the data coverage for the wood pellet and wood chips used in the transformation sector was 93% for both fuels. Thus, this report is more certain on the data side compared to [3] and [4]. Moreover, consumption in private households was included in this report which gives a much closer estimate on the national emissions from woody biomass in 2022 compared to previous years. Data on consumption in private households is however a bit more uncertain as for example import of firewood was based on data from official trade statistics [10].

4.2 Origin of biomass

Contrary to [Nielsen et al., 3] where the origin of biomass was based on data collection with overrepresentation of large utilities and [Nielsen, 4] where the origin of biomass was based on official trade statistics, the data input on consumption of wood pellets and wood chips both from the transformation and direct consumption sectors origins from the mandatory reporting to the Danish Energy Agency [9]. Here all energy producing installations above 5 MW and importers/producers above 20.000 tonnes of wood pellets were mandated to report the biomass origins from (countries). The data collected for the present report covered 93% of wood chips and wood pellets used in the transformation sector, where in [3] 84% was covered and in [4] 65% was covered. In the private consumption in households, 78% of the wood pellet used, was covered in this report where in [3 and 4] 0% was of this was covered. Moreover, this report also covered use of firewood which the other reports did not cover at all. As such, the data quality of the present report has been substantially improved in the present report.

For wood pellets directly consumed in private households a very large proportion was sourced overseas or in Russia, leading to large transport emissions. Contrary, the transport distances for firewood consumed in private households was very short as 92% was sourced locally. Moreover, assumptions on transport for wood pellets and firewood neglects that there may be a short transport by private cars for biomass consumed in private households. However, as this has a very limited effect on the results and as there is no data available on this, this was disregarded in the present report.

4.3 Sourcing strategy and the single pulse curve

Data from 2022 reporting showed that the lions share of the wood chips was sourced from harvest residues and also an increased share of industrial residues and with a smaller share sourced from stem compared to 2021 data [4]. This explains the faster convergence of the single pulse curve observed for 2022 in this report compared to [4]. The level of convergence in year 100 did not differ here compared to [4].

For wood pellets used in the transformation sector the sourcing strategy differed by 2022 data having a larger amount of stems compared to 2021 [4], and a smaller amount of industrial residues. These two effects have opposite effects on the convergence of the single pulse curve and thus only small differences were observed. The level of convergence (difference between factual and counterfactual in year 100) is slightly lower for 2022 data, which most likely is due to a smaller proportion being sourced from Russia, which is substituted by sourcing a larger proportion from the Baltic states, with shorter transport distances as a consequence.

For wood pellets consumed directly in private households the sourcing was almost solely based on industrial residues. This is also evident on the single pulse curve converging much more rapidly compared to all other types of consumption of biomass for energy in Denmark. The level of convergence is however at a much higher level compared to all other biomass consumption types. The high level of convergence origins from transport emissions being much higher for this type of biomass, as a large proportion (57%) is sourced from either Russia, Canada or USA, with long transport distances and hence higher fossil emissions.

Firewood was sourced mostly from stems, and non-forest and waste wood biomass of which 70% was modelled as stems adding up to app. 58% stem wood in total. This lead to a slower convergence of the single pulse curve compared to the other biomass fuel types. On the other hand, the level of convergence is at a low level mainly due to the short transport distances, as 92% of the firewood was sourced domestically.

The difference in the single pulse curve between wood pellets and firewood consumed directly in private households demonstrates the effect of using two very different sourcing strategies, with wood pellets being sourced by industrial residues with short a half-life, but sourced from distant places (fast convergence to a high level), and firewood based mainly on stems with long a half-life sourced mainly domestically (slow convergence to a low level). Comparison of results from [3] and [4], should be handled with care as results in [3] and [4] does not contain specific data for wood pellets consumed in private households and firewood was not included at all. This will lead to higher emissions solely for this reason. Non the less, comparing the emission factors reveals that there are only limited differences compared to previous years. There is however a tendency to a faster convergence of time dependent emissions in year 2022 compared to earlier years, which is a consequence of the larger proportion of stems in the total mix previous years. The level of convergence is however similar, around 8 Kg CO_2/GJ.

4.4 Data uncertainties and improvements

As mentioned in [Nielsen 4], data improvement on origin of the biomass improved in 2021, and in 2022 data will be further improved, by also containing origin of firewood and smaller importers of wood pellets. But as for the results presented in [3 and 4], the counterfactuals, natural or product decay rates (half-lifes), are the main determinants of the speed convergence of the single pulse curve compared to the counterfactual situation. Data on this are still limited with only a few scientific reports covering this. As such, more data on the actual decay rates in forests mainly in Denmark and the Baltic countries will significantly improve the accuracy and precision of the results presented here and in [3 and 4].

iLUC/iWUC and fossil process and transport emissions determine the fraction of emissions not being offset by forest carbon sequestration and does not differ in this report compared to [3 and 4], except for the transport emissions for wood pellets consumed in private households, which was much higher. These emissions, especially indirect emissions may vary considerably and can have significant effect on the results [1,2,3 and 4] and more research on the effect on the marked for other wood-based products from use of bioenergy would make results more precise. For a thorough discussion see [3].

4.5 Biomass counterfactuals and effects on the single pulse curve

The results showed in this report are based on numerous assumptions, all of which has influence on the outcome of the single pulse curve (Figure 17). The foremost factor determining the results, is whether the biomass is a true residue or has a counterfactual as another product. As such, the most important factor is to be sure that the biomass used for energy is not taken from other markets, which then has to switch to other products (iWUC) or expand the managed forest area into unmanaged forests (iLUC).

While the price for timber still remains much higher than the price for energy wood, the net prices of pulp, paper, and wood fuel assortments overlapped in 2022 [38] and may have favoured the sale of wood in pulp and paper quality for fuel purposes, here creating a market-based risk of iLUC/iWUC. However, the half-life of paper and cardboard is 2 years [29], meaning that, in a carbon footprint perspective using pulp and paper wood for energy has lesser influence on the emission profile than had it been saw logs used for energy.

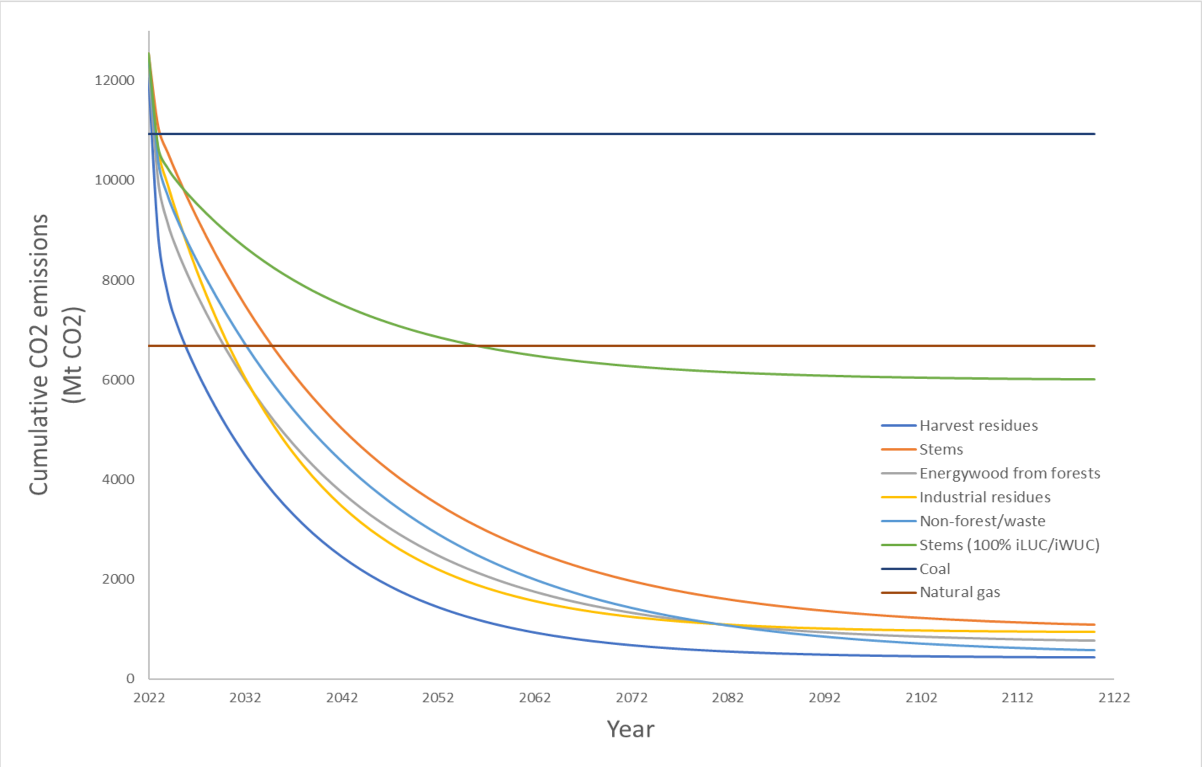

Figure 17 Conceptual figure demonstrating effects of different biomass categories and the entire outcome space for emissions from biomass for energy, based on national 2022 data.

Second, to the large market related effects presented above comes the decay rate of the biomass category for the part that are true residues. For example, the use of harvest residues only ads up to 61% of the emissions in year 10, compared to stems and thus using harvest residues instead of only stems represents a 39% reduction in the short run.

Thirdly comes the transport distance. As reported in [3] this can vary from 1-10% of the total emissions depending on the country of origin (Denmark or USA). Moreover, this emission is irreversible and persists in the atmosphere for centuries, as it is fossil.

The final effect in the results is the forest operations and other processing in the supply chain, which has minor effects on the results.

4.6 Conclusions

All in all, the results presented here did not differ substantially from the results presented in [3 and 4], except that direct consumption of wood pellets and firewood in private households was included here. The inclusion of these biomass types demonstrated a somewhat different trajectory of the single pulse curve for both types. The difference came from a different sourcing strategy compared to the transformations sector, where the wood pellets in direct private consumption was almost solely based on industrial residues with a large proportion coming from distant places, while for firewood the proportion of stems was high, but the sourcing was mostly domestically based.

It was demonstrated that the counterfactual iWUC/iLUC/additional harvesting were the foremost factors that has the potential to alter the results and parallel shift the emissions by an increase in the permanent emissions. the second largest factor was the decay rate (half-life) of the biomass in the counterfactual situation which is strongly determining the trajectory of the convergence of the time dependent biogenic emissions The third largest factor was the transportation distances and finally other processing and forest operations.

The foremost data improvements that can be made are better determination of the decay rate in different forest ecosystems, and documentation that the wood used is truly a residue, that is not competing with other markets.

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