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 2023 input data

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Indhold

1 Preface

This report and the analyses behind were commissioned by the Danish Energy Agency in November 2024 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 and 5]. Additionally, parts of the present report is a reproduction of [5] or similar to.

A preliminary version of this report was commented by the Danish Energy Agency in January 2025.

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 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 2023 data of the model output from [3, 4 and 5] which formed the basis of the biomass chapter of Global afrapportering 2022, 2023 and 2024 (GA22, GA23 and GA24). Calculations in this report builds entirely on the scientific data and method presented in [3], unless otherwise stated. As such, the changes in results compared to [3, 4 and 5] are solely the effect of using 2023 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 [10] for wood chips and wood pellets and from [11 and 12] for firewood. Data for wood chips and wood pellets covered app. 90% of the current total Danish consumption.

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) as well as additional harvesting (LUC). CO_2 emissions from the construction of plants and facilities are disregarded. Moreover, the CO_2 emissions were not compared to other ways of producing heat and electricity, e.g., through coal or natural gas combustion.

The model calculations also included a dynamic assessment of the potential changes in the forest carbon stocks in a factual versus a counterfactual situation, including the use of biomass for energy (factual), and how forests and wood would have been managed and treated absent the demand for bioenergy (counterfactual). The method for calculating decay rates of forest and industrial wood residues, and wood products was improved in the present report, leading to significantly more precise predictions of half-lives for decaying wood.

The report focusses on:

1) Analysis of the biogenic and fossil emissions from the supply chain of a single year's 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 the biogenic and fossil emissions from the supply chain of a single year's 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) Revisit and development of key assumptions reported in [3] and a discussion hereof.
4) Discussion of the changes in the methods, data and emission profile compared to methods and results presented in previous reports [3, 4 and 5].

The first part of the analysis showed that the use of biomass has decreased in the transformation sector relative to 2021 and 2022. Total consumption of biomass in 2021 was 88.1 PJ leading to total emissions of 10,6 million tonnes of CO_2, and consumption in 2022

was 78.3 PJ, leading to total emissions of 9.5 million tonnes CO_2. Based on latest data reports, 2023 saw a consumption of 75.5 PJ leading to 9.1 million tonnes CO_2 emissions.

The use of biomass in households was 9.5 PJ of wood pellets and 15.7 PJ of firewood, leading to emissions of 1.15 and 1.9 million tons CO_2 at the year of combustion, respectively. In total 12 mill. tons CO_2 was emitted in 2023 as a consequence of the consumption of 100 PJ of wood biomass.

After app. 60-82 years after consumption, 1% of the original additional biogenic emissions from energy production will be left in the atmosphere, equivalent to 5-10 kg CO_2/GJ, which is somewhat faster than reported in previous assessments [3,4 and 5]. The reason behind this is that in 2023, compared to earlier years, the transformation sector sourced a larger fraction of biomass from harvest residues and a smaller fraction from stem wood.

Of all the biomass used 92.5% was classified as residues either from forest operation or industrial operations, with the remining 7.5% being biomass that can be attributed with indirect effects, such as iLUC, iWUC and LUC because it technically could have had other uses than for energy or would not have been harvested.

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

Comparison of the 2023 results to earlier years', reveals that although changes have been made in data and modelling this has only had minor effects on the results and as such the results are rather robust.

3 Dansk resume

Denne rapport er en genberegning med 2023-data af modeloutputtet fra [3, 4 og 5], som dannede grundlag for Global afrapportering 2022, 2023 og 2024 (GA22, GA23 og GA25). 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, 4 og 5] er derfor alene effekten af at bruge 2023-forbrugsdata og ændringer angivet i metodeafsnittet her.

Inputdata er primært baseret på indberetninger fra forsyningsselskaber og importører til Energistyrelsen [10] for flis og træpiller og på dataindsamling i [11 og 12] for brænde. Data for flis og træpiller dækkede ca. 90% 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) og "additional harvesting" (LUC). 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 (og CO2 udledninger ved naturligt nedbrud) ville være blevet behandlet og have udviklet sig uden efterspørgsel efter bioenergi. Metoden til at bestemme halveringstider for nedbrud i skoven i den kontrafaktiske situation, er i denne rapport opdateret, hvilket har medført en betydelig højere præcision i data for halveringstider.

Rapporten fokuserer på:

1. Analyse af biogene og fossile CO_2-udledninger i forsyningskæden af et enkelt års dansk anvendelse af biomasse i forsyningssektoren og tidsafhængige marginale udledninger i et 100 års-perspektiv. Resultater rapporteres som kumulative netto CO_2-udledninger til atmosfæren og kg CO2/GJ.

2. Analyse af biogene og fossile emissioner i forsyningskæden af et enkelt års dansk 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. Genbesøg og udvikling af centrale antagelser rapporteret i [3] og en diskussion heraf.

4. Præsentation og diskussion af ændringer i metode, data- og emissionsprofiler sammenlignet med metoder og resultater præsenteret i [3, 4 og 5].

Den første del af analysen viste, at brugen af biomasse er faldet siden 2021. Hvor det samlede forbrug af biomasse i forsyningssektoren i 2021 var 88,1 PJ, hvilket gav en samlet udledning på 10,6 millioner tons CO2, og forbruget i 2022 var 78,3 PJ, hvilket førte til en samlet udledning på 9,5 millioner tons CO2, var 2023-årets forbrug på 75.5 PJ, der gav en udledning på 9.1 millioner tons CO2.

Anvendelsen af biomasse forbrugt direkte i husholdningerne var 9.5 PJ for træpiller og 15.7 PJ for brænde, hvilket førte til udledninger på henholdsvis 1,15 og 1,9 mio. tons CO2. I alt blev de rudledt ca. 12 mio. tons CO2 ved et forbrug på 100 PJ.

Efter ca. 60-82 år efter forbrugsåret vil der kun være 1% af de biogene udledninger fra energiproduktion tilbage i atmosfæren, hvilket svarer til en restudledning på 5-10 kg CO2/Gj. Der var en svagt hurtigere konvergens i årets resultater sammenlignet med de forrige år. Dette skyldes at der i årets input data er en større andel af biomassen der stammer fra hugstaffald og en mindre andel der er stammer.

Ud af alt den biomasse der blev brugt er det i denne rapport antaget at 92.5% kommer fra resttræ, hvor de resterende 7.5% 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.

Sammenligningen af dette års resultater med tidligere år viste at de ændringer og forbedringer der er lavet i data og modellen kun har en meget lille effekt på resultaterne og resultaterne kan derfor betragtes som robuste.

4 Description of terms and abbreviations

Abbreviation/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 hugst, der alligevel var sket som følge af skovproduktion, men udelukkende med energiformål.
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 været om at frigive halvdelen af kulstoflageret som CO_2 til atmosfæren, typisk 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 or land areas	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 efterspørglsel på bioenergi.
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 biomass for production.	Alle CO_2 udledninger samt optag i skoven som følge af et enkelt års forbrug af biomasse til bioenergi

1 Introduction

The Paris Agreement deems to keep anthropogenic global warming below a 2ºC increase from pre-industrial levels and pursue efforts to limit the temperature increase to 1.5ºC [6]. 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 [7].

Use of biomass in the energy sector has been favoured politically, since the mid-1990s in the transition of the Danish energy sector [8], 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, waste, and solar energy [9].

In 2023, renewables made up for 298 PJ or 54% of primary energy production in Denmark, with app. 100 PJ being based on woody biomass (wood chips, wood pellets, and firewood) corresponding to 44% of renewable [9], and woody biomass is today the largest group in the Danish renewable energy production. As such, precise estimations of emissions from use of wood in the energy sector are vital for attaining accurate figures of global CO2 emissions related to Danish consumption (see important note in 1.2).

1.1 Aim of this report

The aim of this report is to compile the previous work by Nielsen et al. [3], Nielsen [4] and Nielsen [5] into a full descriptive report containing all details, assumptions and comparisons of results to previous years. Moreover, it is the aim to recalculate CO_2 emissions to the atmosphere over a 100-year period from the use of woody biomass for production of heat and electricity in Denmark in 2023, 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) Revisit and development of key assumptions reported in [3] and a discussion hereof.
4) Discussion of the changes in the data and emission profile compared to results presented in previous reports [3, 4 and 5].

1.2 Important note

The findings presented here cannot and should not be compared to the national inventory report/document 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, 4 and 5] with 2023 data as input to Global afrapportering 2025 (GA25), which is based on the model from [3], that also formed the basis of Global afrapportering 2022, 2023 and 2024 (GA22, GA23 and GA24). Results are based on data from year 2023. Calculations in this report builds on the scientific data and method presented in [3], unless otherwise stated. As such, the changes in results compared to [3] are solely the effect of using 2023 consumption data and changes stated in 2.1.

2.1 Changes from earlier reports

Although the method is the same here as in [3 and 4], this report includes additional analyses and assumptions, the development of these assumptions, data and model improvement are presented below:

1. Data largely origins from the energy sector's reporting to the Danish Energy Agency as described in [10].
2. CO_2 emissions from the consumption of wood pellets and firewood in private households was included in [5] and in this report, but not in [3 and 4], cf. 2.2.
3. A new biomass category "*Energy wood from forests"* was included in the analyses in [5] and in this report, see cf. 2.6. This was in previous years [3 and 4] parts of the categories stems and harvest residues.
4. A new market mediated effect was included for the categories wood from stems and non-forest and waste wood biomass called "*additional harvesting",* cf. 2.5.2. Effects of this is not included in [3 and 4], but in [5] and the present report.
5. The *non forest biomass* category was attributed with 10% additional harvesting due to increasing prices for biomass for energy in [5] and in this report, but not in [3 and 4], cf. 2.6.
6. A new approach to determine half-lives for woody biomass left in the forest is incorporated in this report based on modelling instead of case-study based assumptions. cf. 2.5.1.

2.2 Data input

The data input on consumption of wood pellets and wood chips both from the transformation sector and from household consumption origins from the mandatory reporting to the Danish Energy Agency [10], where all energy producing facilities above 5 MW and importers/producers of above 20.000 tonnes of wood pellets *(changed to 2.5 MW and 5.000 tonnes in July 2023)* are 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) [10]. This reporting data covers 89% 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 [11] (database code KN8Y) to estimate the country from which the firewood imported. The feedstock data for firewood was based on data collection by the Danish Energy Agency [12] and a categorisation hereof cf. 2.6.

All other data input is identical to [3] and [4].

2.3 Model overview

For assessing consumption-based cumulative CO_2 emissions, a modelling framework developed in [3], was used to calculate carbon pools and fluxes linked to processes and combustion in the supply chain of biomass for energy used in the Danish transformation sector (wood chips and wood pellets) and in Danish households (wood pellets and firewood).

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

The model calculates CO_2 emissions from processes such as forest management, wood pellet pressing and drying to transport and final heat and electricity production or from chain saw felling in forest to burning in a household wood stove. This situation is denoted as the "factual situation" and should be interpreted as emissions from the use of biomass to energy as it is today (eq. 1. and figure 1).

Even in the absence of a demand for biomass for energy, some CO_2 emissions from forests and wood material occur, e.g., decomposition of harvest residues in the forest floor over time. The model also calculates CO_2 emissions for this situation. This is called the "counterfactual situation for residues", which represents the emissions that would have occurred without the demand for bioenergy. A residue is biomass that is in surplus, without other uses and free to use for energy without any consequences for other biomass markets. The emissions from this are either emissions from burning on site or decomposition of the biomass. These emissions are deducted from the emissions from the factual situation (see eq. 1 and figure 1).

Contrary to emissions from residues, that would have occurred in the absence of a bioenergy demand, the counterfactual can also express an additional emission as a consequence of a market pressure, which is the case when biomass is a non-residue (e.g., biomass which in the current market could have been used for e.g. timber or pulp wood) and consumption of biomass therefore leads to market pressure and indirect effects such as expansion of forestry into unmanaged forest (iLUC) or switch of demand to other products with higher emissions than wood (iWUC). These emissions are then added to total consumption-based CO_2 emissions (see eq. 1 and figure 1 for an overview).

[redacted] eq. 1

The result of the model ("The consumption-based CO_2 emissions for woody biomass fuels") is thus calculated as the factual emissions, deducted the emissions from residues in the counterfactual situation and added the additional emissions from market mediated effects incurred by use of biomass that is not a residue (see overview og emissions in figure 1).

Some of the emissions changes or evolves over time (e.g. decomposition or forest growth). Therefore, the model expresses the consumption-based CO_2 emissions dynamically on a yearly basis over a 100-year period after the combustion takes place.

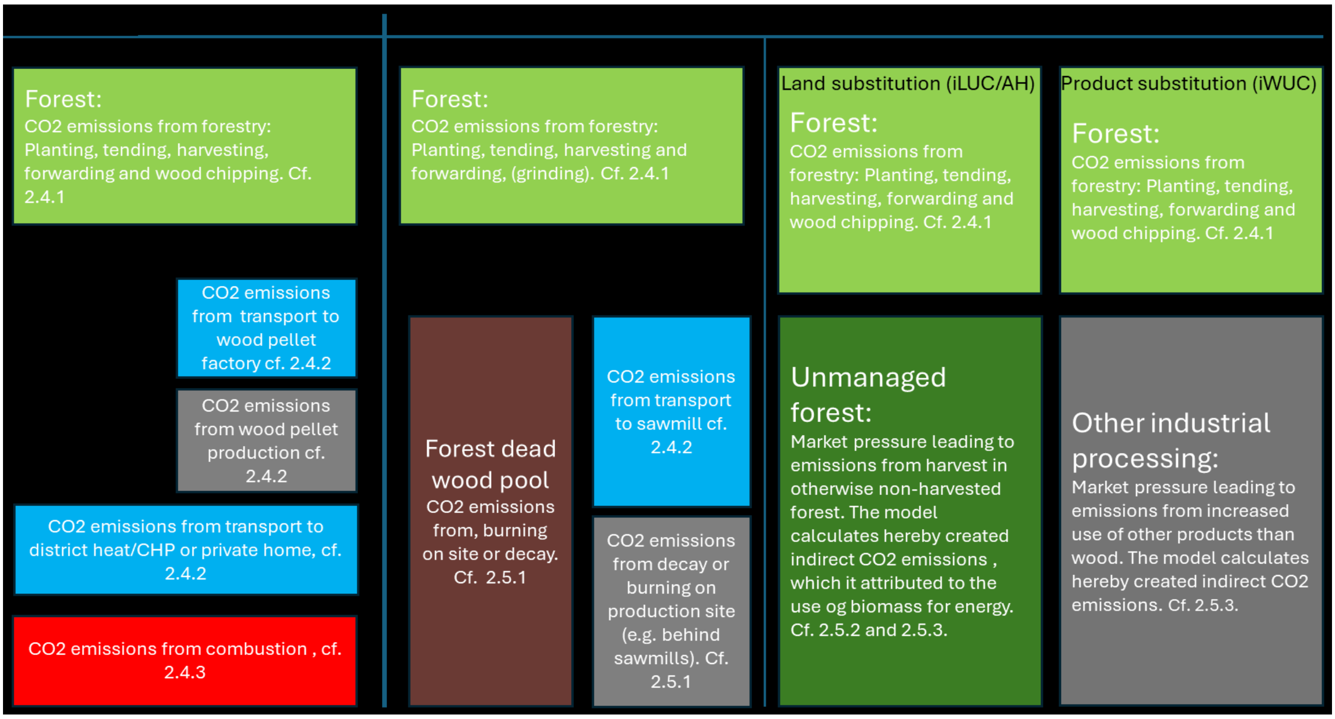

Figure 1. Overview of the model framework. The model calculates the sum of all emissions in the factual situation, deducts emissions from the residual counterfactual and adds market mediated emissions from non-residues.

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 wood products, forest growth, decay rates etc. and are stated in the table 1 below.

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	[40 and 41]
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.	[14, 15]
3	We assume that establishment of forests and growth after intervention follow existing yield tables and models of for the most common tree species in the region.	[16-18]
4	Living root biomass of all forest management alternatives is assumed to be 20% of the aboveground living biomass.	[19]
5	The half-lives of stems and harvest residues was based on the modelling framework presented in Zell et al [43], origin of the wood, climatic data from the origin and the diameter and tree type (conifers vs. deciduous trees).	[43]
6	The half-life of industrial residues was assumed to be 5 years	Assumption
7	All biomass contains 50% carbon (based on dry weight).	[25]
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, the model 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	[26-28]
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.	[27]
11	For drying of wood pellets, an additional 18% use of low-grade biomass (half-life 5 years) was assumed.	[29, 30]
12	The half-life of the wood product pool is 35 years for sawn timber, 25 years for boards and 2 years for paper.	[40]
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.	[31]
14	For the biomass categories stems, 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.

Assumptions and modelling framework are presented in more detail in the following chapters.

2.4 Forest operations, processing and transport related emissions

2.4.1 Forest operations and processing of biomass

Emissions related to forest operations include all aspects of growing trees, including seedling production in nurseries, planting, tending, thinnings, and final harvesting. However, not all these emissions are related to the production of bioenergy as the forest is generally grown to produce timber and these operations would have been performed, also if there was no market for bioenergy. This report consequently only included emissions directly related to the procurement and processing of wood for energy purposes.

Wood chips is a less refined wood fuel derived from harvested biomass, which is chipped directly in the forest or at the user and combusted without further processing. Emissions consequently includes the fuel consumption related to in-forest collection and transport of biomass and to the subsequent chipping of the wood. These emissions were assumed to add up to 3% of the carbon in the wood [44].

Production of wood pellets includes more processing than wood chips. The level of processing depends on the feedstock type, e.g. sawdust, stems, or other residues from timber production. Processes involved include grinding into smaller particles, drying, and pressing into pellets. For drying of wood pellets, the utility companies documented in 2020, that 99% of all pellets were dried with hog fuel (low-grade biomass such as bark), with a use of approx. 180 kg hog fuel per tons pellets [1]. Hog fuel emissions were modelled as for industrial residues with no iLUC (see below).

All values were recalculated into Mg CO_2 Mg^{-1} biomass, using standard emission factors from the IPCC [34].

2.4.2 Transport of biomass

Transport emissions relate to emissions that occur due to transport by either truck, train or ship. To determine the transport emissions, simplifications were made, as these emissions are dependent on the exact location of biomass harvest, collection and processing. The reported data material did not contain such information but only the country of origin and as such simplifications were made based on data collected in [3].

Table 2. Weighted average transport distance for biomass from different regions. The transport distances for Denmark differ from earlier analyses [2] as novel data provided improved basis for the calculations.

Country	Truck	Train	Ship
	Transport distance (km)		
Denmark	57	0	0
Baltic	210	95	943
Belarus	189	0	943
Russia	188	2796	1413
Norway	191	0	450
Sweden	200	0	200
Germany	150	123	255
Ghana	200	0	5000
USA/Canada	252	71	7225
Uspec	200	0	1500
Europe	135	0	1150

*Note that no biomass has been imported from Russia og Belarus after 2022

2.4.3 Combustion and conversion efficiency

Direct CO_2 emissions per unit of energy were calculated for each wood fuel type (pellets or chips), building on standard emissions factors from IPCC [34], and were subsequently aggregated to total wood chip, wood pellet and firewood use.

2.5 Biomass counterfactuals

A counterfactual is to be interpreted as a situation countering the factual situation and describes what would have happened if the wood had not been used for energy. 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 exist and the wood currently used for energy assumes a counterfactual fate. The counterfactual depends on the nature of the wood used as well as the market situation, 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.

2.5.1 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 in this model 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 stem and harvest residue based "residues", two possible options were assumed:

1. The residues are burned on site without energy utilization.
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.
For harvest residues it is assumed that 30% were burned on site and 70% left for natural decay and for stems, it was assumed that for 90% of the mass the counterfactual was to be left for decay.
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.

For all residual biomass directly from forests, with the counterfactual of being left in the forest for decay a model by Zell et al. [43], was used to determine the half-life of the material, by determining the decay constant k and using this in a traditional first order decay function.

The model by Zell et al [43], is a non-linear mixed effect model, that determines decay constant k (equivalent to half-life) for wood from different regions, sizes and different tree species (eq. 2).

$$k(S, CH, MD, t_j, p_y) = \mathrm{e}^{(\beta_0+b_i+\beta_1 I^{CH}+\beta_2 d+\beta_3 I^{MD}+\beta_4 t_j+\beta_5 p_y+\beta_6 p_y^2)} \quad \text{eq. 2}$$

Where k is the decay constant, S is species (disregarded here only distinctionbetween conifers and broadleaves), I^{ch} is an indicator if the tree species is coniferous or deciduous, d is the diameter of the wood left for decay, I^{MD} indicates whether the study calculates mass loss or density loss, t_j is the mean temperature in July at the origin of the biomass, p_y is the year sum of precipitation and $\beta_{1\text{-}6}$ are parameters (see [43]).

The diameter for harvest residues was assumed to be 7 cm on average, where for stems the mean diameter was assumed to be 20 cm. The stems and harvest residues where then further divided into 3 regions.

1. In the <u>boreal region</u>, climate data from the city Tartu in Estonia was used as input to the model, with the July temperature being 18.3 C and the year sum of precipitation is 650 mm. Estonia was used as a large part of the boreal biomass origins from this region. Moreover, it was assumed that 75% of the biomass in the boreal region originated from conifers and 25% from deciduous trees. In total 41,5% of the biomass in the 2023 data origin from the boreal region.
2. For the <u>temperate region</u>, climate data from Aarhus in Denmark was used as input to the model, with July temperature being 18.1 C and a year sum of precipitation being 780 mm. Denmark was used as data input as the majority of the biomass origins from here. For the temperate region it was assumed that the share of conifers and deciduous trees was 50/50%. In total 45.3% of the biomass in the 2023 data origin from the temperate region.
3. In the <u>tropic/subtropic region</u> climate data from Charleston in South Carolina, USA was used as input to the model, with July temperature being 28 C and the year sum of precipitation being 1180 mm. South Carolina was chosen as input as most of the biomass not coming from the boreal or temperate regions, origins from this region. Here an equal share of conifers and deciduous trees was assumed, as for the temperate region. In total 13.2% of the biomass was from this region in the 2023 data.

Based on the share between regions, climate data and assumptions on the size of the biomass, the model yielded an average half-life at 12.2 years for harvest residues and 14.0 years for stems, for all data included. For the specific sectors, fuel types etc., different, but similar half-lives were determined.

For industrial residues 90% was assumed to be left for decay in deposits, a half-life of 5 years was assumed, as these are crushed into small pieces. The model by Zell et al [43] in not calibrated to estimate decay rates for industrial residues af it only deals with decay in natural ecosystems and therefore the assumption on a 5 year half-life was kept as in [3, 4 and 5]. The remaining parts (10%) of the stem and industrial residues categories were assumed to be denoted with other counterfactuals than decay or burning on site (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 and was treated as described above. The remaining 10% of stems and industrial was assumed to have the counterfactual of being additional harvest (see next chapter).

The implication of assumptions on counterfactual fates is a shift in timing of CO_2 emissions from the different 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 shift in timing of CO_2 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 in forests where biomass is harvested in the factual situation compared to the counterfactual situation and this reduction will be attributed to the energy production.

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

Additional harvest occurs in managed forests or tree plots in agricultural fields, when trees that would otherwise 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 permanently change the living biomass carbon stock dynamics compared to the counterfactual, without harvest, leading to additional emissions.

Additional harvesting can also be small plots of forest in the agricultural landscape that are harvested due to the demand for biomass. This will permanently change the landscape carbon stock dynamics as well.

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 and regrowth of new trees takes place in the factual situation 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 forest growth and carbon stock developments in the factual situation $C_{harvested}$, as it is representative of the average forest growth in Denmark. The counterfactual carbon stock for unharvested broadleaf forest $C_{unharvested}$ was modelled with an average carbon stock value for temperate forests, see [12].

$$Additional\ harvest\ emission = C_{unharvested} - C_{harvestedt}, \qquad \text{eq. 3}$$

2.5.3 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 biomass in the current market could have been used for something else, such as boards or panels, 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 the price for biomass for energy exceeds the price for pulp wood and thereby 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 for products (here treated as iWUC - see 2.4.5, leading to increased emissions from use of other materials).

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. [34].

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 and decomposition [35]. 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., [13], was assumed.

The carbon stock when converted to 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:

$$iLUC = C_{unm,t} - C_{man,t}, \qquad \text{eq. 4}$$

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 respond to increased demand for biomass for energy production and replant cleared forest stands partly with nurse trees (fast growing trees species) and a higher plant number, leading to faster recovery of the forest carbon stock after felling compared to the counterfactual situation. In the first 20 years this can lead to a 3-4 timer larger forest carbon stock.

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] and up to 4 times larger the first 20 years. In this report these effects were not considered, as no data on the amount of e.g. nurse trees or additional plant numbers is available.

Ad. 3 Reduced supply of wood products - iWUC

In economic theory, when the supply of e.g. 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 (steel, concrete, plastic etc.) becomes more economically favourable, hereby changing the overall emission profile. When demand for bioenergy drives the price increase and hereby shift to other products, the additional emissions from the use of these other products are attributed to bioenergy, denoted iWUC.

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 [34]. 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 iLUC (expansion of managed forest area) is shifted to other products i.e. full substitution.

Such shifts, lead to additional emissions as many of these products have higher supply chain emissions than wood [37]. Commonly this effect is reported as a substitution factor (SF) that expresses the amount of CO_2 emissions for the alternative product supply chain as a factor of the amount of carbon in wood product which is substituted:

$$SF = \frac{C_{non-wood} - C_{wood}}{WU_{wood} - WU_{non-wood}}, \qquad \text{eq. 5}$$

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 [31].

Leskinen et. al., [31], 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 for non-structural parts a substitution factor 1.2, was assumed (iWUC for industrial residues) for panels and boards produced from industrial residues.

Specifically, the shares of biomass not considered a residue in this report (10% of *stems, industrial residues and energy wood from forests*), 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.

2.6 Counterfactuals for biomass categories

The biomass that was used in Denmark in 2023 was categorized into five groups: *harvest residues, stems, industrial residues, energy wood from forests and non-forest and waste wood biomass [42]*. The assumptions on counterfactuals for each biomass category are described below.

***Harvest residues* from forestry** is biomass from tops and branches as well as from early thinnings, which, before they found a use for energy, was left on site for natural decay or burned after a harvest or thinning operation to make room for regeneration/planting. As the counterfactual for harvest residues, it was assumed that 30% would have been burned on site with a half-life of

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

0.5 years and 70% would have been 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 was calculated to 8.69 years.

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 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).

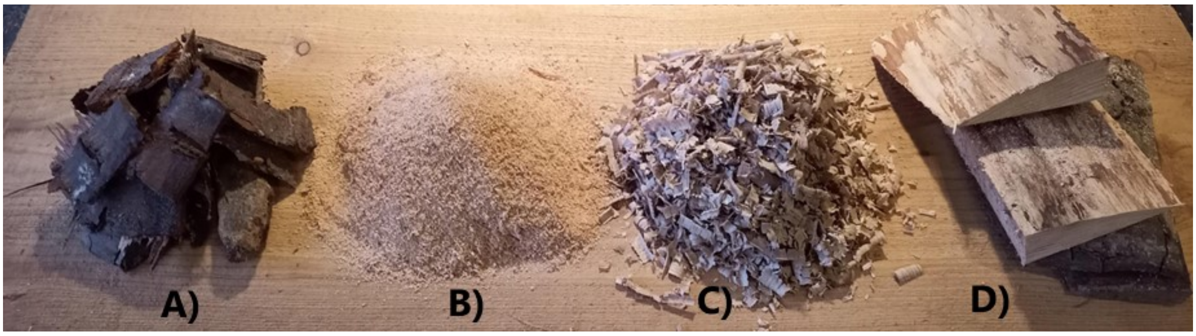

Figure 4: Typical examples of industrial residues. A) Bark (Hog fuel), low quality, typically used for drying of wood pellets. B) Sawdust from sawmills, high quality clean wood, typically used for wood pellets. C) Planer shavings, from furniture production, high quality clean wood, typically used for 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 as in previous reports. 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 (without iLUC and iWUC) and 50% harvest residues, which was treated as described for harvest residues 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 timber producing tree species. In some cases, the rapid growth by dedicated energy plantations overrules the loss of wood product production, see e.g. [38], 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 harvesting.
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 here 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 (resulting in a reduction in forest carbon stock) due to the increasing prices for bioenergy observed in 2023.

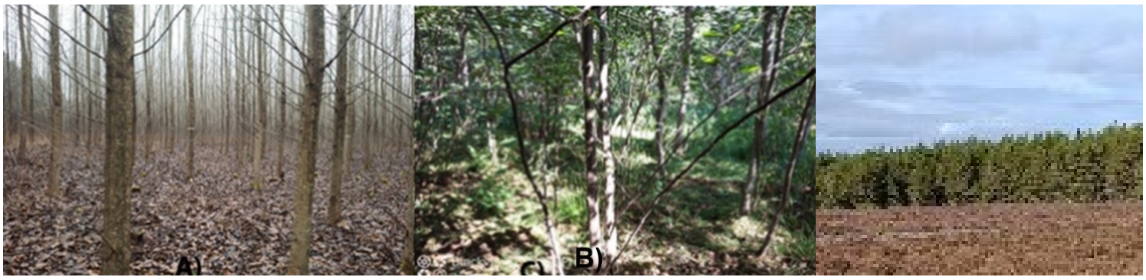

Figure 5: Examples of energy wood from forests. A) A monoculture with poplar, planted solely for energy production. B) An unproductive corner of the forest with poor quality non-commercial tree species, here red alder. C) Removal of invasive species (Pinus contorta) from nature areas (heathlands).

Non-forest and waste wood are here merged into one category that includes waste wood 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 in the model as 50% harvest residues piled in the forest for decay (35%) or burned on site (15%), with a mean half-life at 8.69 years, as much of this biomass typically has a small diameter, and 50% as stems with a half-life at 14.2 years, as these types also has some degree of stem parts. Moreover, due to the increasing prices on biomass observed in 2023, this category was attributed with 10% additional harvesting as some areas previously unprofitable for harvest has now become 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 [12], 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.

2.7 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 year of energy production (here, 2023), 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 an overview, see cf. 2.3 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).

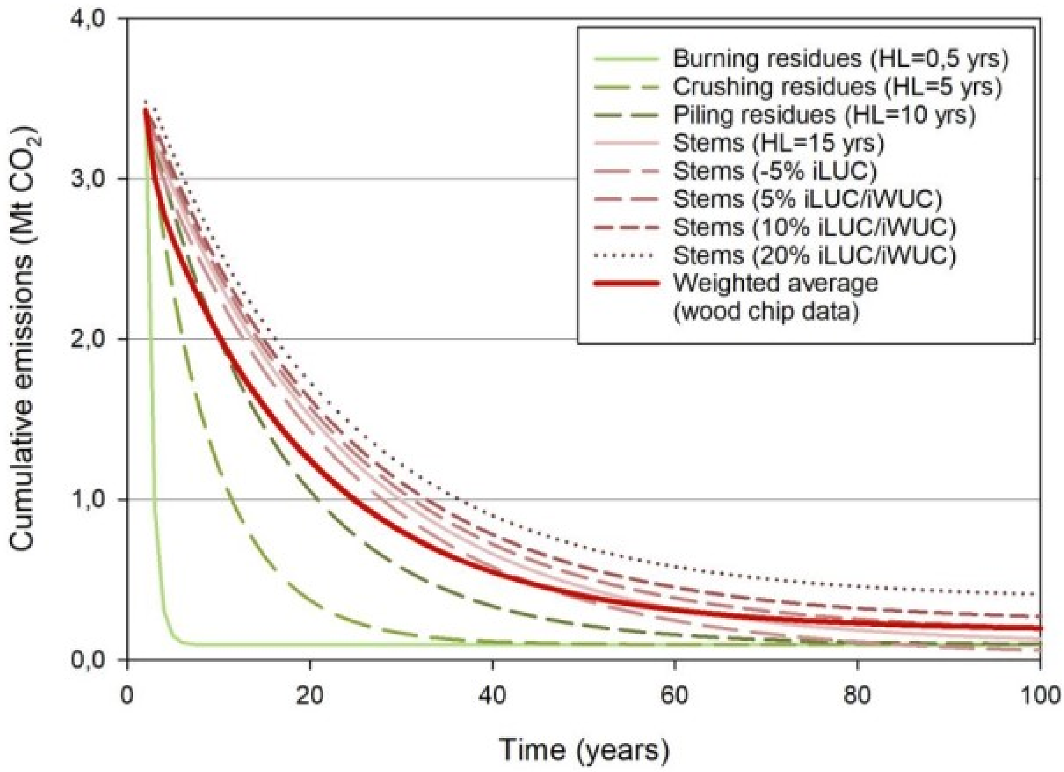

Figure 7: Typical shapes of the single pulse curve, with different counterfactuals, e.g., half-life (HL), amount of wood with iLUC and iWUC. Reproduction from [3].

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 CO_2 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 i,e.. emissions without use of woody biomass), as the difference between factual and counterfactual becomes smaller.

However, as there is fossil fuels used in transport, processing of biomass and iWUC emissions, together with permanently reduced forest carbon stocks, in iLUC and additional harvest, the single pulse curve will not reach 0 (Figure 7). 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 in year 1 if consumption increases or decreases but the composition and origin of the feedstock remain unchanged. The curve converges at the fossil and iLUC emissions at a 10% higher level, compared to the data-based scenario.
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 upwards or downwards in the curve equal to the emissions from the fossil fuels.
4. The single pulse curve can be affected as by permanent increases/decreases of carbon stocks in forests, induced by additional harvest and iLUC. This will lead to a parallel shift up or down in the curve, like for fossil fuels.

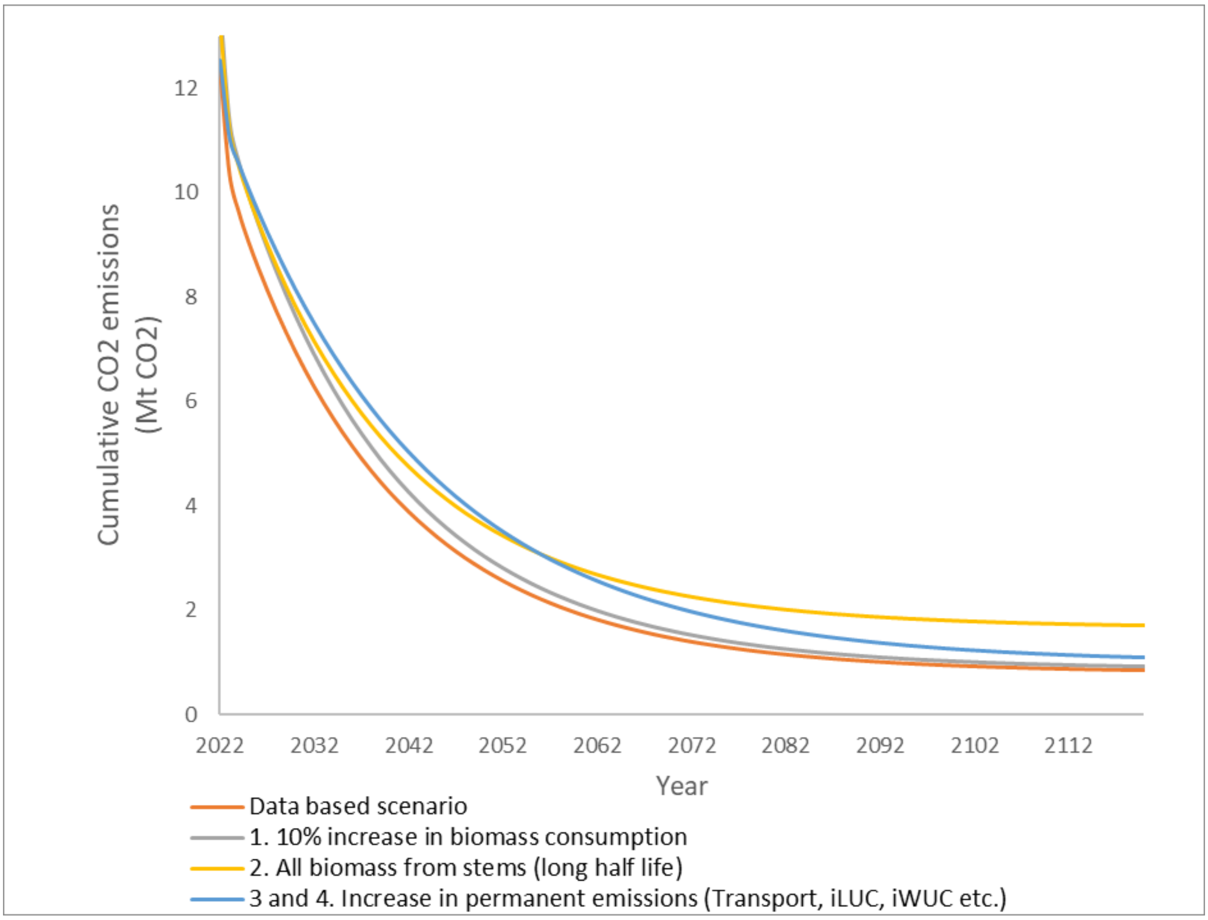

Figure 8: Examples corresponding to point 1 to 4, cf. 2.7.

2.8 Analyses carried out in this report

The single pulse curve is here used to present how the biomass used in 2023 by the transformation sector and in private households affect the atmospheric CO_2 from 2023 and 100 years into the future. Analyses were made by sector and fuel type and aggregated to a total level.

Emissions factors (Kg CO_2/GJ) were derived from the single pulse curve. Additionally, emission factors were split up on different factors to demonstrate their contribution to the total emission.

Finally, a comparison of emission profiles from the different data years was carried out to assess their development over time. Specifically, emission profiles from GA22-GA25 were compared for the transformation sector and emission profiles from GA24 and GA25, were compared for the total wood consumption emissions.

3 Results

3.1 The data basis for the Danish wood chip, wood pellet and firewood consumption in 2023

In 2023, the total primary wood fuel supply to the Danish CHP and DH production [9] of wood chips and wood pellets, was 75.5 PJ. Of the 75.5 PJ, 40.9 PJ was wood chips, and 34.6 PJ was wood pellets (Table 3). These consumption data were used in the subsequent analyses. The private households consumed 9.5 PJ wood pellets and 15.7 PJ firewood (Table 3).

Table 3. Woody biomass consumption in district heating and combined heat and powerplants as well as in private households from different fuel types in 2023. Data source: Energistatistik 2023 [9].

	Wood pellets transformation	Wood chips transformation	Wood pellets private	Firewood private	Total
ENS (PJ)	34.6	40.9	9.5	15.7	100.7
Share (%)	34.3	40.6	9.4	15.6	100

In the transformation sector, feedstock for wood chips production was mostly harvest residues followed by stems and a smaller fraction of industrial residues. Wood pellets were based primarily on industrial residues, but also on a large proportion of stems and only minor amounts from the other categories (Table 4).

For consumption in private households, wood pellets were almost solely based on industrial residues and a small proportion of harvest residues. Firewood was mainly based on stems and non-forest and waste wood feedstock (Table 4).

Table 4. Feedstock for wood chips, wood pellet and firewood production as reported by utility companies and wood pellet importers and from [12] for 2023. 0,0% indicates a very small amount, where empty cells indicate 0%. Weighted average is calculated as weighted average between all fuel types.

Fuel type	Harvest residues	Stems	Energy wood from forests	Industrial residues	Non-forest
			%		
Wood chips	49,5%	24,5%	6,4%	11,5%	8,1%
Wood pellets, transformation	10,1%	39,7%	0,2%	50,1%	0,0%
Wood pellets, private	20,7%	1,0%	0,0%	78,3%	0,0%
Firewood, private*	1,5%	50,0%		7,2%	41,4%
Weighted average	25,8%	31,1%	2,5%	30,3%	10,4%

*Source [12] and calculations cf. 2.6

Overall, industrial residues and stems each covered 30% of the consumption, where harvest residues covered roughly 26%, non-forest covered 10.4% and energy wood from forests covered 2.5%.

Of the total biomass used, 92.6% were considered residues, where the remaining 7.4% was considered wood attributed with indirect emissions, such as iLUC or iWUC c.f. 2.5.

Wood chips in the transformation sector mostly came from Denmark, covering 48.6% of the use, followed by the Baltic countries (21.2%). Other large contributors of wood chips were Norway, Germany and Brazil, with the rest sourced broadly from Europe (Table 5).

Wood pellets for the transformation sector were mainly sourced from the Baltic countries covering app. 67%. USA and Canada covered 21% and the rest was sourced more broadly in European countries (Table 5).

Table 5: Origin of different biomass for fuel categories. 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	Share of wood pellets	Share of wood pellets	Share of firewood	Overall share of biomass
	Transformation sector		Direct private consumption		All sectors
			%		
Belgien	0.8%	-	-	0.2%	0.1%
Brazil	7.1%	-	-	-	3%
Canada	-	3.9%	5,0%	-	2%
Denmark	49%	0.8%	15.1%	89.8%	36%
Estonia	5%	35.3%	7.9%	0.3%	14%
Finland	0.1%	0.2%	0.2%	-	0.1%
France	1.1%	-	-	0.1%	0.1%
Ireland	-	-	-	0.4%	0.1%
Latvia	15.3%	28.1%	11.5%	1.1%	17%
Lithuania	1.4%	3.7%	4.1%	5.1%	3%
New Zealand	-	-	0.1%	-	0.1%
Norway	6.9%	1.5%	0.8%	-	3%
Poland	-	0.1%	2.9%	1.6%	1%
Portugal	-	6.2%	0.8%	-	2%
Romania	-	0.0%	-	0.1%	0.1%
Russia	-	0.1%	-	-	0.1%
Spain	1.2%	-	-	-	0.1%
Great Britain	2.0%	-	-	-	1%
Sweden	2.8%	1.6%	21.3%	0.6%	4%
Germany	8.4%	1.6%	1.5%	0.2%	4%
Ukraine	-	-	0.0%	0.5%	0.1%
USA	-	17.0%	28.8%	-	9%
Vietnam	-	-	-	-	0.1%

In private households the largest contributor to wood pellets was USA with app. 29% and Sweden, Latvia and Denmark covering app. 45%, with the remainder sourced broadly from

European countries (table 5). Firewood was mainly sourced in Denmark, covering 90% of the consumptions and the largest import countries being the Baltic countries and Poland and the remainder sourced broadly from Europe.

Overall, the largest contributor to the Danish use of woody biomass for energy was Denmark, covering app. 36% of the use. Roughly 34% was sourced in the Baltic countries. USA and Canada covered 11% and Germany and Sweden covered each 4%. The rest was covered broadly in Europe and from Brazil (Table 5).

3.2 2023 woody biomass CO_2 dynamics in the transformation sector

3.2.1 Wood chips

The use of wood chips in 2023 with a consumption of 40.9 PJ emitted 4.79 Gt CO_2 (Figure 9). However, over time the difference between the factual and counterfactual situation converges towards a steady state (Figure 9). After 75 years only 1% of the time dependent biogenic emissions induced by using wood chips for energy, compared to the counterfactual of not using biomass, were left in the atmosphere. CO_2 emissions do not converge towards zero, as there is 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, iLUC, iWUC and additional harvesting, accounted for app. 1.8% of the emissions in year 1 and 39% in year 100, and fossil transport and process emissions accounted for 2.4% in year 1 and 52% in year 100, with the remaining being residual biogenic emissions.

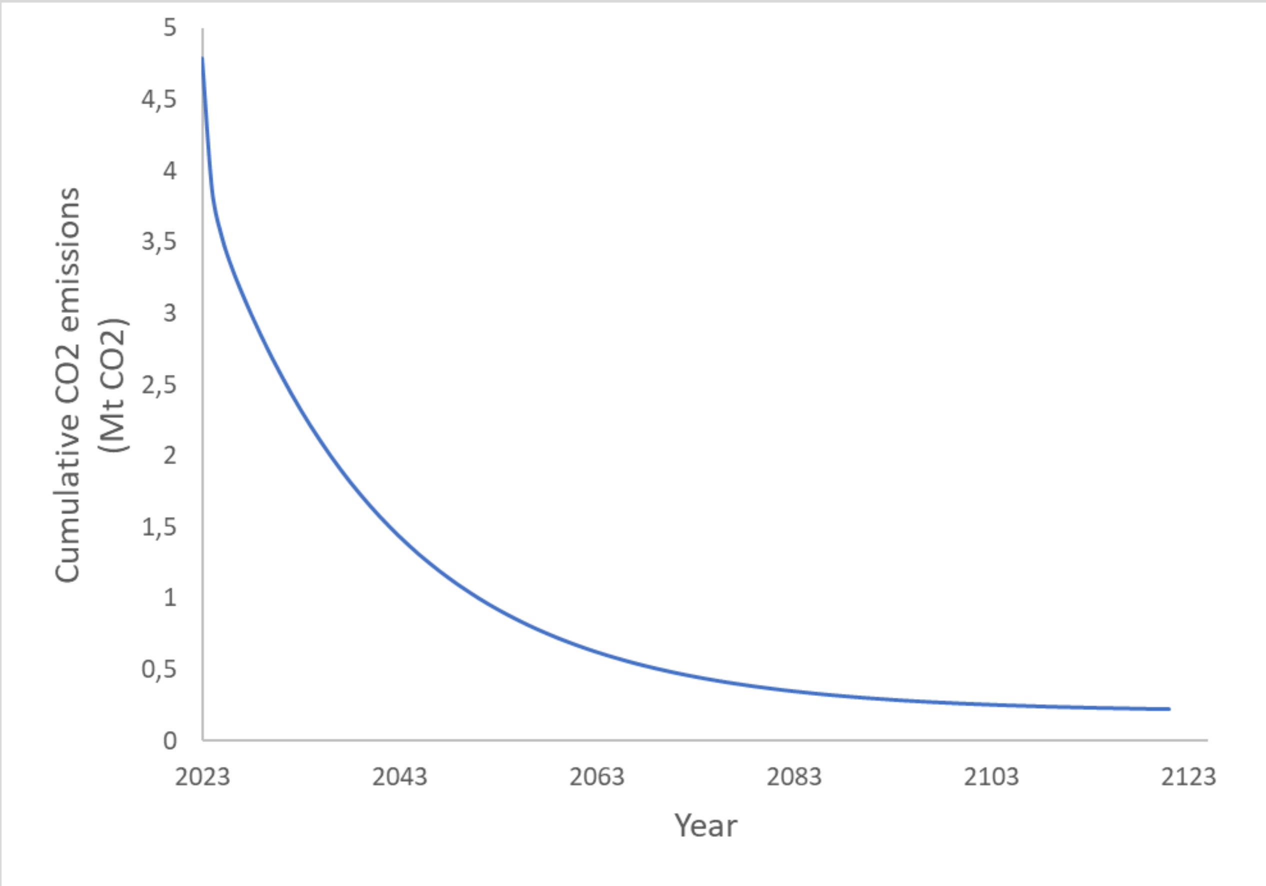

Figure 9. Cumulative emissions for 2023 consumption of wood chips for energy production in the Danish transformation sector, for production of 40.9 PJ using the "weighted average wood chip data".

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 117.0 Kg CO_2/GJ, where after 30 years, the emissions are 23.4 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 5.4 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 6).

Table 6: CO2 emissions (Kg/GJ) for different fuel sources used for wood chips and for the weighted average wood chip data

Years after consumption	1	10	20	30	50	70	100
Weighted average wood chip data	**117,0**	**59,6**	**36,7**	**23,4**	**11,2**	**7,1**	**5,4**
Coal – reference	107,1	107,1	107,1	107,1	107,1	107,1	107,1
Natural gas – reference	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 34,6 PJ, emissions in year 1 were somewhat lower compared to wood chips (4.24 MtCO2), mainly due to the lower consumption 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 in the atmosphere after 72 years (Figure 10). The convergence is slightly faster than for wood chips due to larger proportion of industrial residues (short counterfactual half-lives) in wood pellet production. Moreover, the year 100 value is at a higher level than for wood chips due to longer transport distances, more processing, accounting for 4.6% in year 1 and 53% in year 100, and the fact that indirect emissions here account for 3.8% in year 1 and 44% in year 100 (Figure 10), with the remaining emissions, being residual time dependent biogenic emissions.

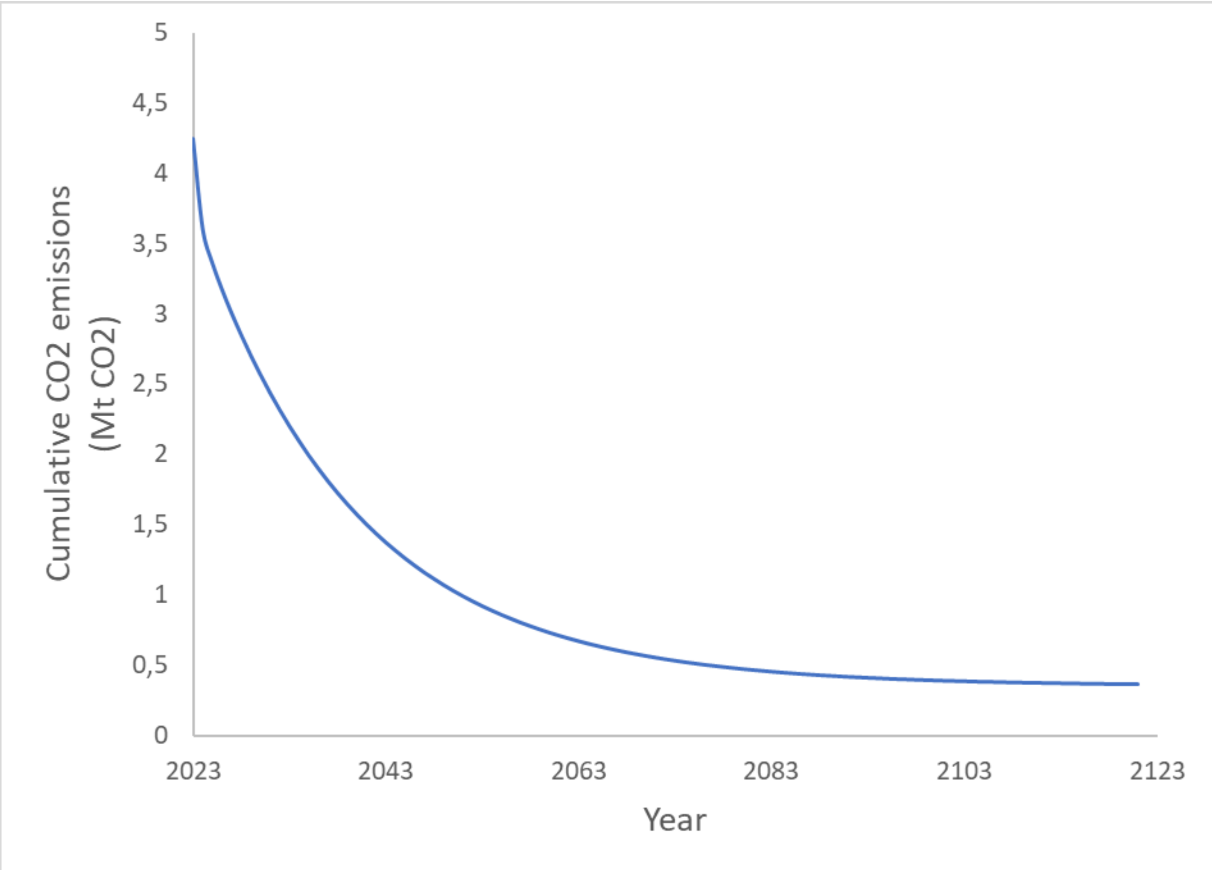

Figure 10. Cumulative emissions for 2023 consumption of wood pellets for energy production in the Danish transformation sector, for production of 34.6 PJ using the "weighted average wood pellet data".

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 factor for wood pellets compared to wood chips in the transformation sector (Table 7). 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 6 and 7).

Table 7: CO2 emissions (Kg/GJ) for different fuel sources used for wood pellets and for the weighted average wood pellet data

Years after consumption	1	10	20	30	50	70	100
Weighted average wood pellet data	**122,4**	**66,8**	**41,4**	**27,6**	**15,7**	**12,0**	**10,6**
Coal – reference	107,1	107,1	107,1	107,1	107,1	107,1	107,1
Natural gas – reference	65,4	65,4	65,4	65,4	65,4	65,4	65,4

After 100 years, emissions from the 2023 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 2023 (75.5 PJ), lead to emissions in year 1 of app. 9.1 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 73 years.

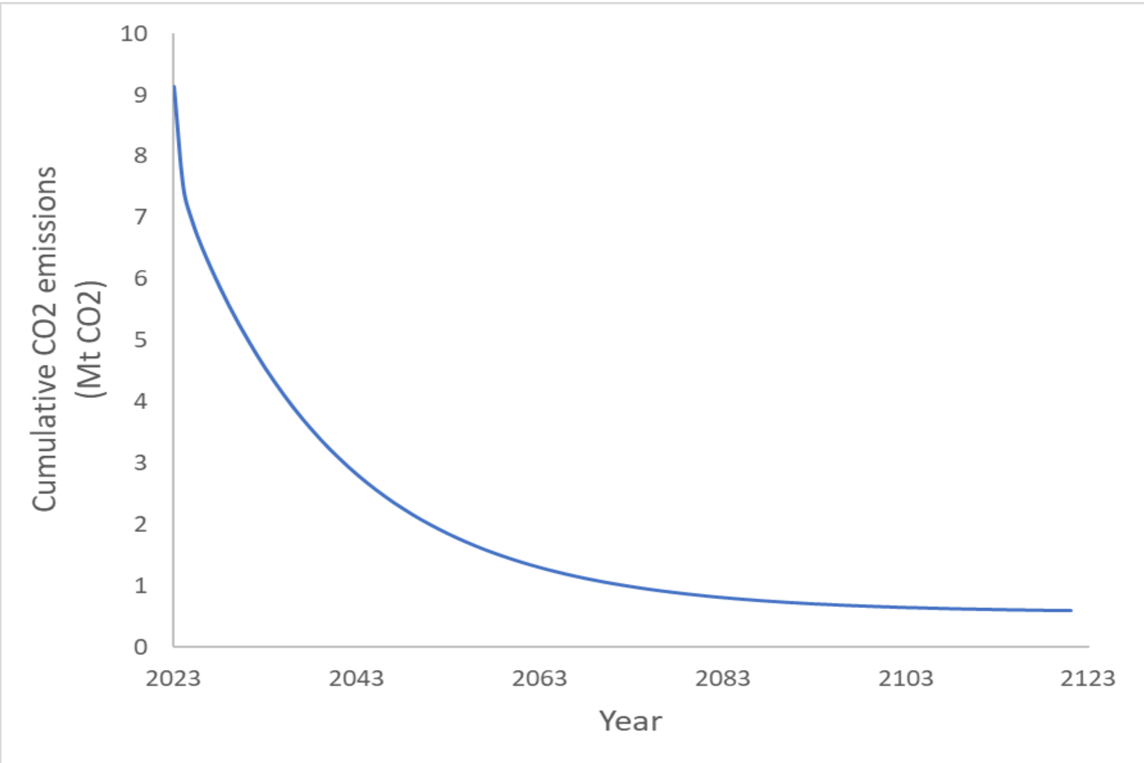

Figure 11. Cumulative net CO_2 emissions of a single year use with a weighted average consumption of wood pellets and wood chips in Danish DH and CHP of 75.5 PJ.

The emissions per GJ are somewhat in between the results for wood chips and wood pellets (Table 8).

Table 8: CO_2 emissions (Kg/GJ) for different fuel sources used in the Danish transformation sector

Years after consumption	1	10	20	30	50	70	100
Weighted average data	**120,9**	**63,1**	**38,9**	**25,3**	**13,2**	**9,3**	**7,8**
Coal – reference	107,1	107,1	107,1	107,1	107,1	107,1	107,1
Natural gas - reference	65,4	65,4	65,4	65,4	65,4	65,4	65,4

In year 1, direct biogenic emissions from combustion of biomass accounted for 86% of the total emissions. Biogenic process emissions (hog fuel for wood pellet drying) account for 7.9%, iWUC/iLUC for 2.7% and fossil process emissions including transport account for 3.4% of the total emissions. The convergence between factual and counterfactual is reflected in the change in emission factors over time. Remaining 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). It should be noted that iLUC, iWUC, additional harvesting and fossil supply chain emissions are considered irreversible, while biogenic process and direct biogenic emissions are time dependent and reversible.

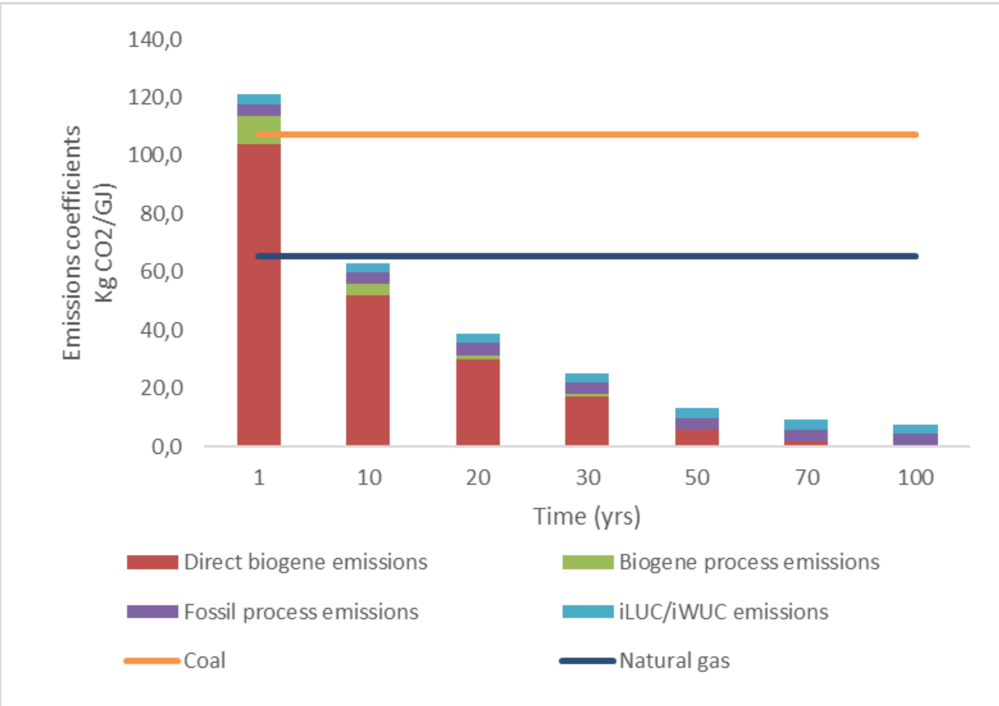

Figure 12. Emission coefficients for Danish district heating and CHP wood consumption and reference fossil energy sources [See 2] (coal and natural gas) over time. Importantly, the biogenic emissions are reduced over time due to convergence between factual and counterfactual.

3.3 2022 biomass CO_2 dynamics in direct consumption in households

3.3.1 Wood pellets

The use of 9.5 PJ wood pellets in private households, leads to emissions of 1.15 Mt CO_2 in year one (Figure 13). Fossil process and transport emissions accounted for 5% of the emissions in year 1 and indirect emissions accounted for 3.2%. In year 100 transport and process accounted for 60% and indirect emissions for 39%, with the remaining emissions, being residual time dependent biogenic emissions.

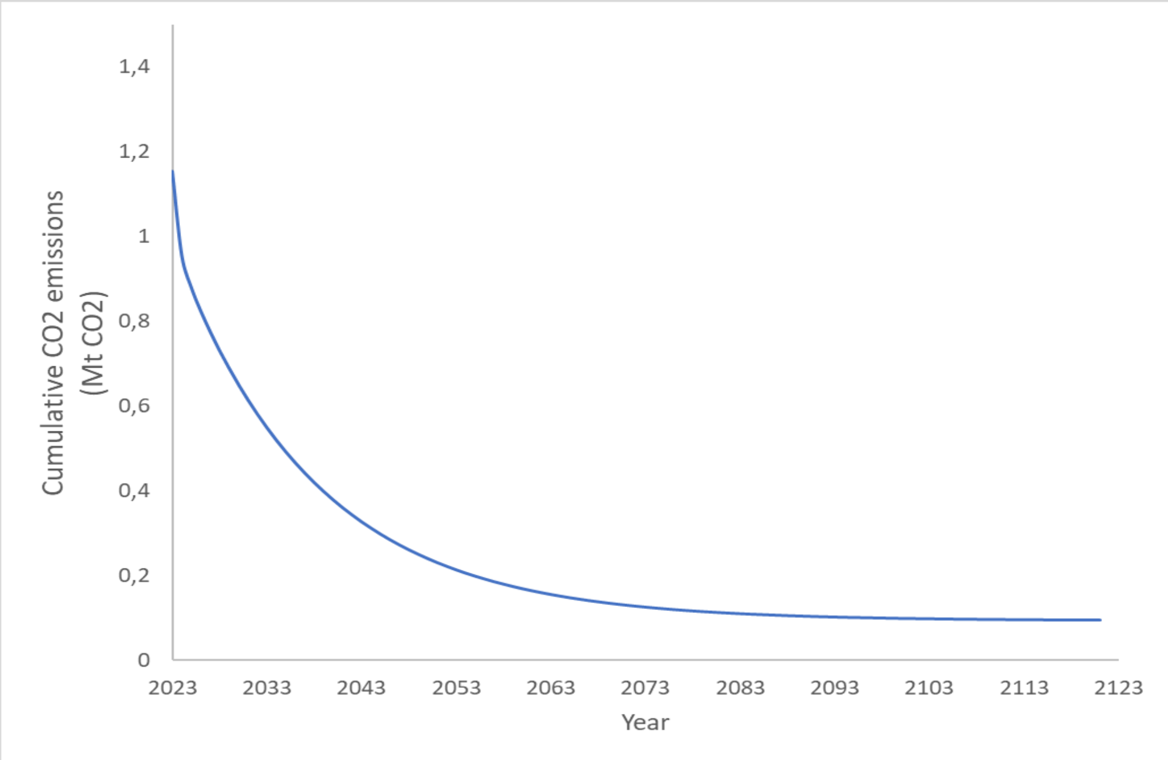

Figure 13. Cumulative emissions for one-year consumption of wood pellets for energy consumption by wood pellets consumed directly in private households 2023, for production of 9.5 PJ.

The emission factor for wood pellets used in private households is 121.6 Kg CO_2/GJ in year one. After 30 years, the emissions factor is 23.5 Kg CO_2/GJ, and after 100 years only emissions equivalent to the fossil and permanent biogenic part of the emissions remains in the atmosphere adding up to 10.1 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 originating from USA, with long transport distances, 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 64 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 9: CO_2 emissions (Kg/GJ) for different fuel sources used for wood pellets used for private consumption

Years after consumption	1	10	20	30	50	70	100
Weighted average wood pellet data (private)	**121,6**	**61,2**	**36,2**	**23,5**	**13,6**	**10,9**	**10,1**
Coal - reference	107,1	107,1	107,1	107,1	107,1	107,1	107,1
Natural gas - reference	65,4	65,4	65,4	65,4	65,4	65,4	65,4

3.3.2 Firewood

Firewood consumption of 15.7 PJ emitted 1.91 Mt CO_2 in 2023 (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 situation would have had a slower decay (longer half-life) and the time to reach 1% of biogenic emissions being left in the atmosphere was here 82 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.

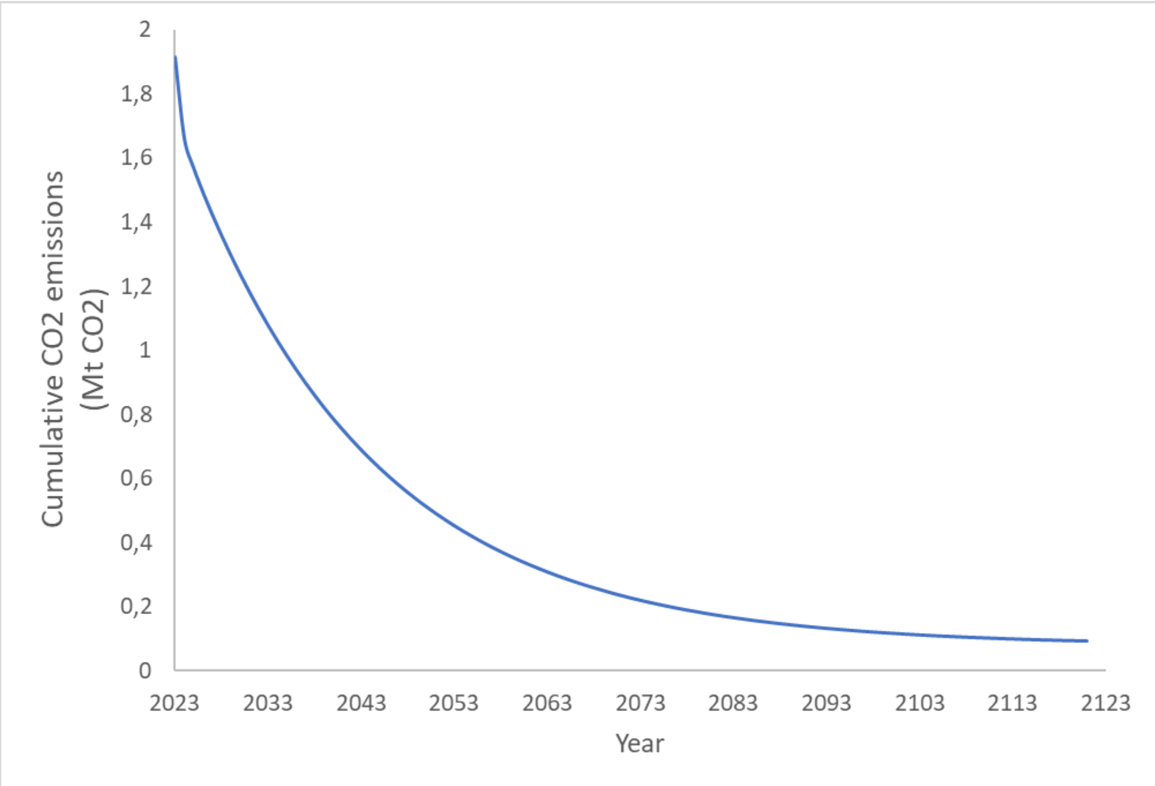

Figure 14. Cumulative emissions for one-year direct consumption of firewood in private households in 2023 in Denmark, for production of 15.7 PJ.

The emissions factor for firewood in year one was 117.8 Kg CO_2/GJ, which is comparable to wood chips and ends up at 6,0 Kg CO_2/GJ in year 100 (Table 10).

Table 10: CO_2 emissions (Kg/GJ) for firewood used by Danish consumers

Years after consumption	1	10	20	30	50	70	100
Weighted average firewood data	**121,9**	**71,9**	**45,9**	**30,1**	**14,5**	**8,7**	**6,0**
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 one transport and processing accounted for 1.5% of the emissions and 27% in year 100. Indirect emissions accounted for 3.2% in year 1 and 59% in year 100.

3.4 CO2 emissions from total 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 sector and households in 2023 (100.7 PJ), the emissions in year 1 are 12.0 million tons CO_2 (Figure 15). Time dependent biogenic emissions decline to less than 1% after 74 years. In year 1 and year 100 fossil transport and processing emissions accounted for 3.2% and 51% respectively. Indirect emissions (fossil and permanent biogenic) accounted for 2.8% and 44% in year 1 and 100, respectively.

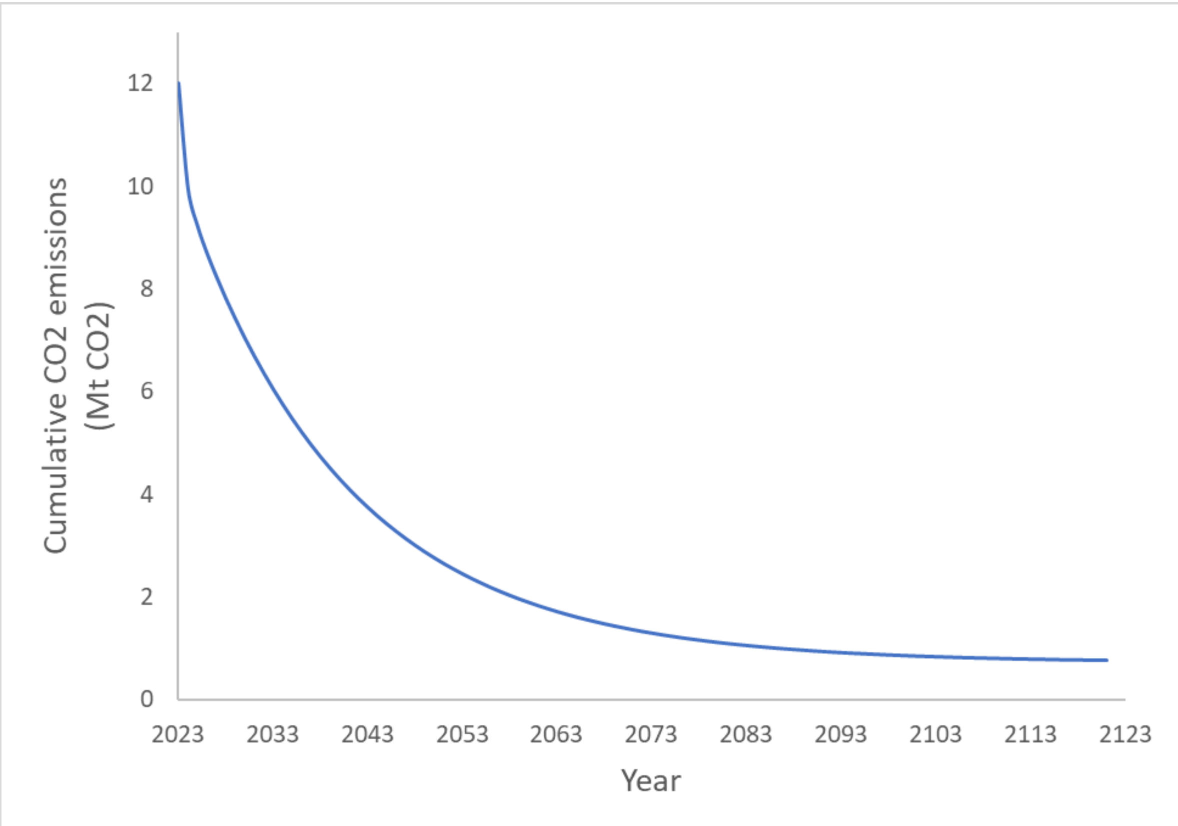

Figure 15: Cumulative net CO_2 emissions from total consumption of woody biomass for energy in 2023, by use of wood chips, wood pellets and firewood with a total biomass consumption of 100.7 PJ.

Not surprisingly, the emissions factors fall in between all the different fuel and consumption types when merged to total consumption with weighted average data (Table 11).

Table 11: CO_2 emissions (Kg/GJ) for all woody biomass used for heat and electricity in 2023

Years after consumption	1	10	20	30	50	70	100
Weighted average data	**119,3**	**63,2**	**38,9**	**25,3**	**13,2**	**9,2**	**7,6**
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 86% (102.7 Kg CO_2/GJ), time dependent biogenic process emissions (hog fuel for wood pellet drying) for 7.9% (9.4 Kg CO_2/GJ) of the emissions, fossil transport and process emissions covered 3.2% (3.8 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 2.8% (3.3 Kg CO_2/GJ) (Figure 16).

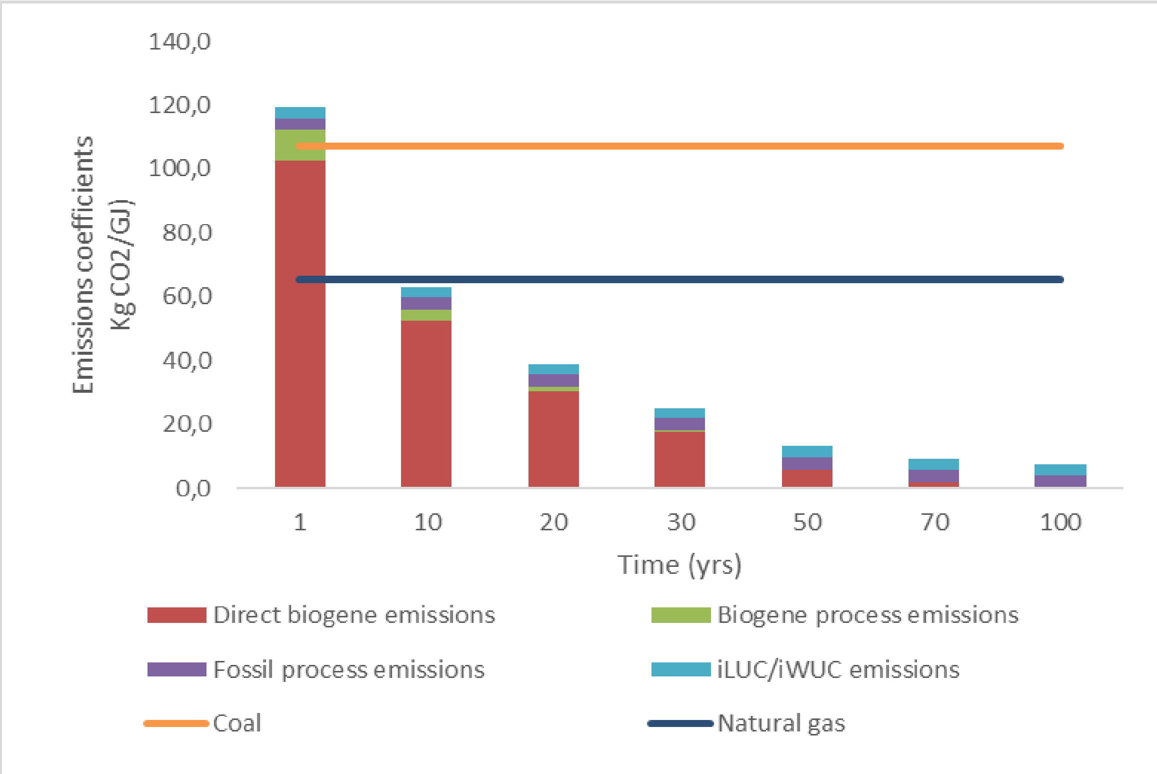

Figure 16. Emission coefficients for wood consumption in Danish district heating and CHP as well as the direct consumption in private households and reference fossil fuel sources (coal and natural gas) over time. Importantly, biogenic emissions are reduced over time due to convergence among factual time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

3.5 Comparison of results from year 2020-2023

In the transformation sector there was a significant development in the results between the different reports (GA22-GA25). In the GA22 results (Figure 17), the emissions are much lower compared to the other years, which is mainly due to the data collection in GA22 (year 2020) being only based on the largest powerplants and therefore not including emissions from the smaller plants. The GA22 results are therefore not comparable to the other years.

The higher emissions in GA23 are a direct consequence of the larger consumption in 2021 (where the data origin). While the use of wood chips were somewhat comparable consumption levels between years, wood pellet consumption in the year 2021 is app. 45% higher in 2021 than in 2020, 2022 and 2023, and therefore the higher emissions is observed in GA23 results. The trajectory of the curves seems similar, although updates to the model have been made continuously (Figure 17).

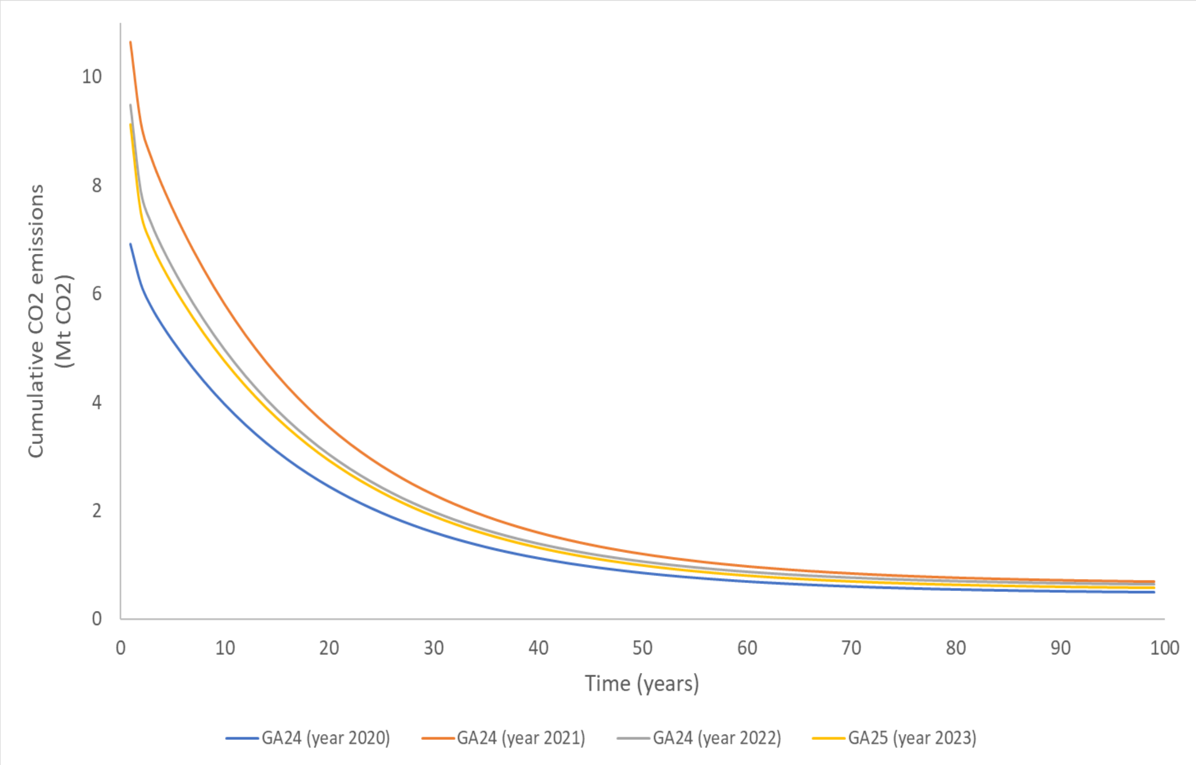

Figure 17: Comparison of GA results from 2022-2025, from the transformation sector

While comparison between years seems difficult with exception of what comes from increased/decreased use, the emissions factors (kg CO2/GJ) is directly comparable between years.

Although there are minor differences in the trajectory of the emissions factors between the years, it seems that the development in assumptions and model updates only has a minor effect on the results (Figure 18), and the observed differences between e.g. GA22 and GA 25 is mainly due to the fact that in GA22 there was 47% stems, while in GA25 there is only app. 31% stems and a much higher amount of harvest residues.

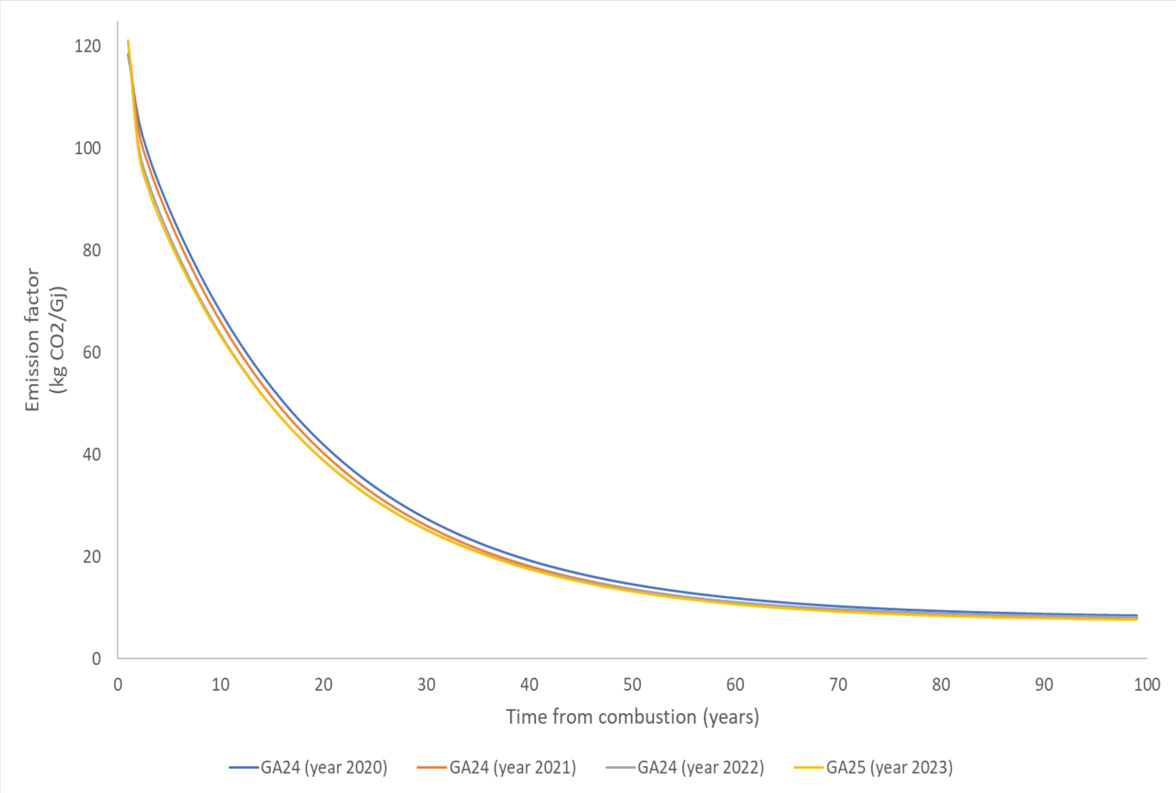

Figure 18: Comparison of GA results from 2022-2025, from the transformation sector

For all the consumption of woody biomass in the transformation sector as well as in households, there was only results from GA24 and GA25 with a total consumption of 102.3 and 100.7 PJ respectively. This obviously resulted in a difference in the level of the CO_2 emissions, but the trajectory is not very different (figure 19).

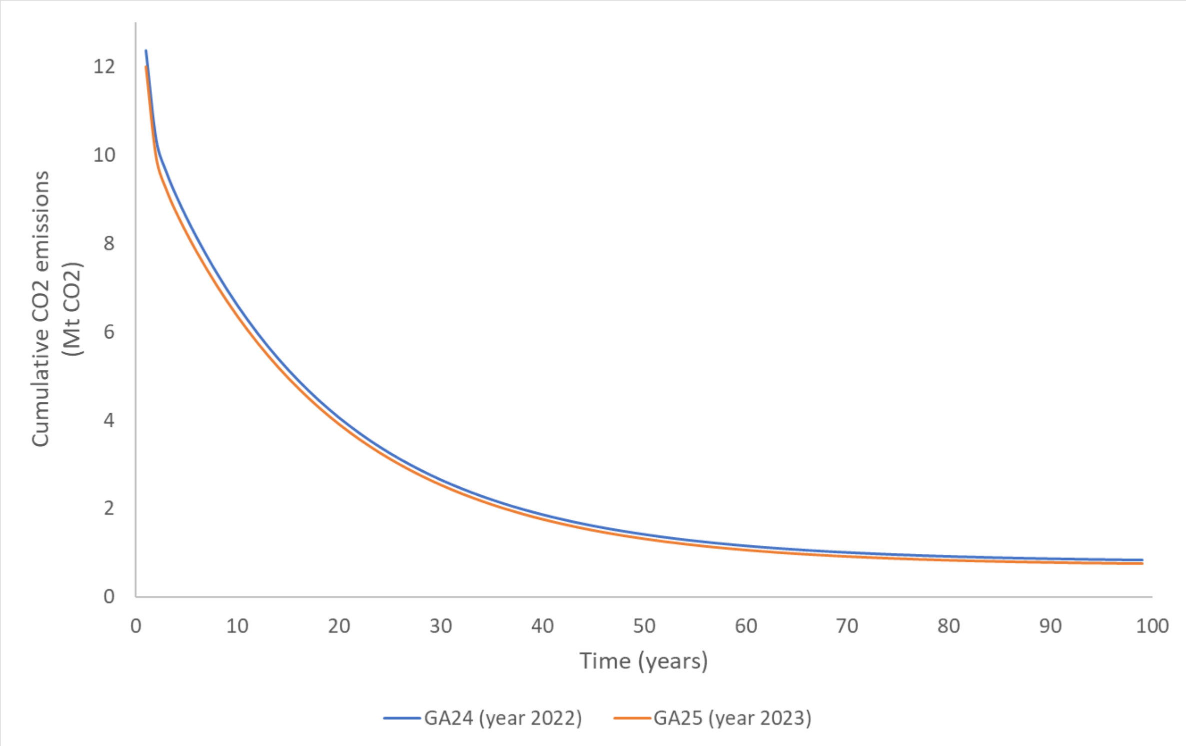

Figure 19: Comparison of emissions from total woody biomass use reported in [5] (blue) and total woody biomass use presented in this report.

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, and in Nielsen [4] the coverage for wood pellets and wood chips was only 75 and 53% of the total consumption of the wood chip and wood pellets used in in the transformation sector and 0% of the private consumption in households.

In Nielsen [5] the background data for wood pellet and wood chips covered 93% of the use for both fuels and in the present report the corresponding data coverage for the transformation sector was 89%. Thus, this report and Nielsen [5] has more certainty on the data side compared to [3] and [4]. Moreover, consumption in private households was included in [5] and this report which gives a much closer estimate of the true value of total emissions from consumption of woody biomass in 2022 and 2023 compared to 2020 and 2021. 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 [11].

4.2 Origin of biomass

Contrary to Nielsen et al. [3] where the origin of biomass was based on data collection with an 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 sector and households comes from the mandatory reporting to the Danish Energy Agency [10]. Here all energy producing installations above 5 MW and importers/producers of more than 20.000 tonnes of wood pellets are mandated to declare the origin of biomass (countries) (In June 2023, this was changed to also include installations above 2.5 MW).

For wood pellets directly consumed in private households a very large proportion was sourced in USA (29%) and Canada (5%), consequently leading to large transport emissions. Contrary, the transport distances for firewood consumed in private households were very short as app. 90% was sourced locally. Moreover, assumptions on transport for wood pellets and firewood neglect that there may be additional 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 and previous reports.

4.3 Sourcing strategy and the single pulse curve

Data from the 2023 reporting showed that the lion's share of wood chips was sourced from harvest residues and also an increased share of industrial residues and with a smaller share sourced from stems compared to 2021 and 2022 [4, 5]. This explains the faster convergence of the single pulse curve observed for the 2023-consumption in this report compared to [4 and 5]. The level of convergence in year 100 did however not differ here compared to [4 and 5] (See also Figure 18).

For wood pellets used in the transformation sector the sourcing strategy differed in 2023 with a smaller amount of stems and a larger amount of harvest residues compared to 2021 and 2022 [4, 5]. These two effects (changed transport distances and different sourcing mix) show opposite effects on the convergence of the single pulse curve and thus only small overall differences were observed. The level of convergence (difference between factual and counterfactual in year 100) is slightly lower for 2023 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, Sweden and Germany, with shorter transport distances, leading to lower permanent emissions.

For wood pellets consumed directly in households in 2023, the sourcing was almost solely based on industrial or harvest 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. Contrary to 2022, the level of convergence is at the same level compared to the wood pellets used in the transformation sector. The reason for this is that Russia is no longer used as a source for wood pellets for households as it was in 2022. The decreased

Russian biomass was instead mainly sourced from USA and Cananda, where long transport distances are made by ship, instead of trucks and train in Russia, leading to lower 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. 79% stem wood in total. This leads 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 90% 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 a long half-life sourced mainly domestically (slow convergence to a low level). Comparison of results from [3], [4], should be handled with care as results in [3] and [4] do not contain specific data for wood pellets consumed in households and firewood was not included at all. This was, however, included in [5] and here results can be compared directly to the present results. Nonetheless, comparing the emission factors reveals that there are only limited differences from results from this year compared to all previous years. There is however a tendency to a faster convergence of time dependent emissions in year 2023 compared to earlier years, which is a consequence of the larger proportion of stems in the total mix in previous years and more harvest residues in 2023. The level of convergence is however similar, around 8 Kg CO_2/GJ in all years.

4.4 Data uncertainties and improvements

As mentioned in Nielsen [4], data on the origin of biomass was improved after 2021, by also containing origin of firewood and smaller importers of wood pellets.

As in the results presented in [3, 4 and 5], the counterfactuals in this report, natural or product decay rates (half-lives), are the main determinants of the speed of the convergence of the single pulse curve compared to the counterfactual situation. While data on this were limited to only a few scientific case studies covering this in [3, 4 and 5], the half-lives in this report were calculated on basis of the climatic conditions where the biomass origin, the diameter of the wood and there was differentiated between conifers and broadleaves, based on the model presented in [43]. The calculated half-lives by the model in [43], was however not substantially different from half-lives used in [3, 4 and 5], with the half-life for harvest residues being 12.4 years in this report and 10 in previous versions and for stems 14.2 years in this report compared to 15 in the previous reports. Although this is a significant improvement in the precision of the estimates of half-lives, additional improvements could still be made. First, data on the specific location of harvest and its climate can be improved. Moreover, data on the average diameter of the different types of wood (harvest residues and stems) could also be improved and finally, data on tree species could also enhance the precision of the half-lives estimates, as different species decompose at different rates (see

[43]). With these improvements, estimates of half-lives would be much more certain. The improvements already made did not make a substantial difference to the results (figure 18) and further effort may not do so either, however, the robustness of the results can still be improved. However, the results in this report can be considered relatively certain with regards to half-lives.

iLUC/iWUC emissions and fossil process and transport emissions determine the fraction of emissions not being offset over time by forest carbon sequestration and does not differ in this report compared to [3, 4 and 5]. These emissions, especially indirect emissions, may vary considerably and can have significant effect on the results and more research on the effect on the marked for other wood-based products from use of bioenergy would make results more precise.

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 20). The foremost factor determining the results, is whether the biomass is a residue or has a counterfactual as another product (figure 20, green). 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 2023 [39] 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 [30], 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.

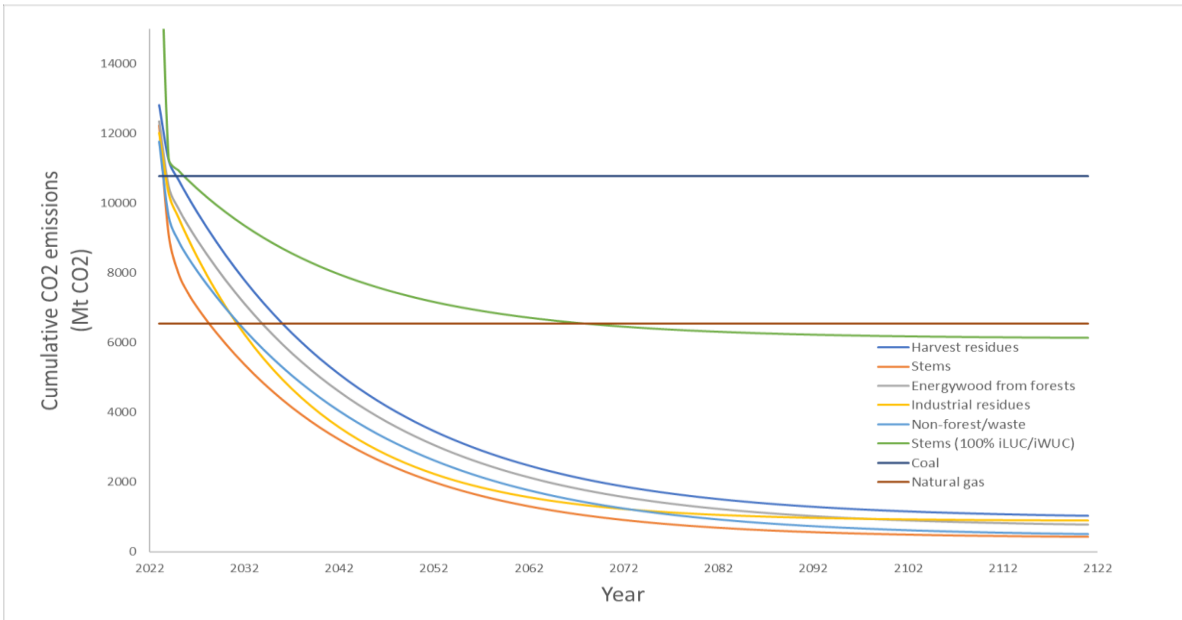

Figure 20: Conceptual figure demonstrating effects of different biomass categories and the entire outcome space for emissions from biomass for energy, based on total 2023 data.

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

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

In total, the emission for use of woody biomass for the Danish production of heating and electricity in 2023 was app. 12 mill. tons CO_2, which was reduced to 2.5 mill. tons 30 years after combustion and to 0.76 mill tons 100 years after combustion. Biomass used in the transformation sector accounted for 63% of the use, while consumption in private households accounted for 37% of the total.

All in all, the results presented here did not differ substantially from the results presented in [3, 4 and 5], except that direct consumption of wood pellets and firewood in private households was not included in [3 and 4]. 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 have 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 estimates of half-lives was in this report improved significantly compared to previous versions and should now be considered much more certain, although improvements can still be made.

The third largest factor was the transportation distances and finally other processing and forest operations. While transport distances have some effect especially in the long run, the emissions from forest operations are of minor importance and very small.

The foremost data improvements that in the future can be made are documentation that the wood used is truly a residue, that is not competing with other markets.

Comparisons of the emission factor results in the report to emissions factors presented in [3, 4 and 5], demonstrated that, despite changes in data end improvements in modelling and assumptions, the results were rather robust.

5 Literature

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