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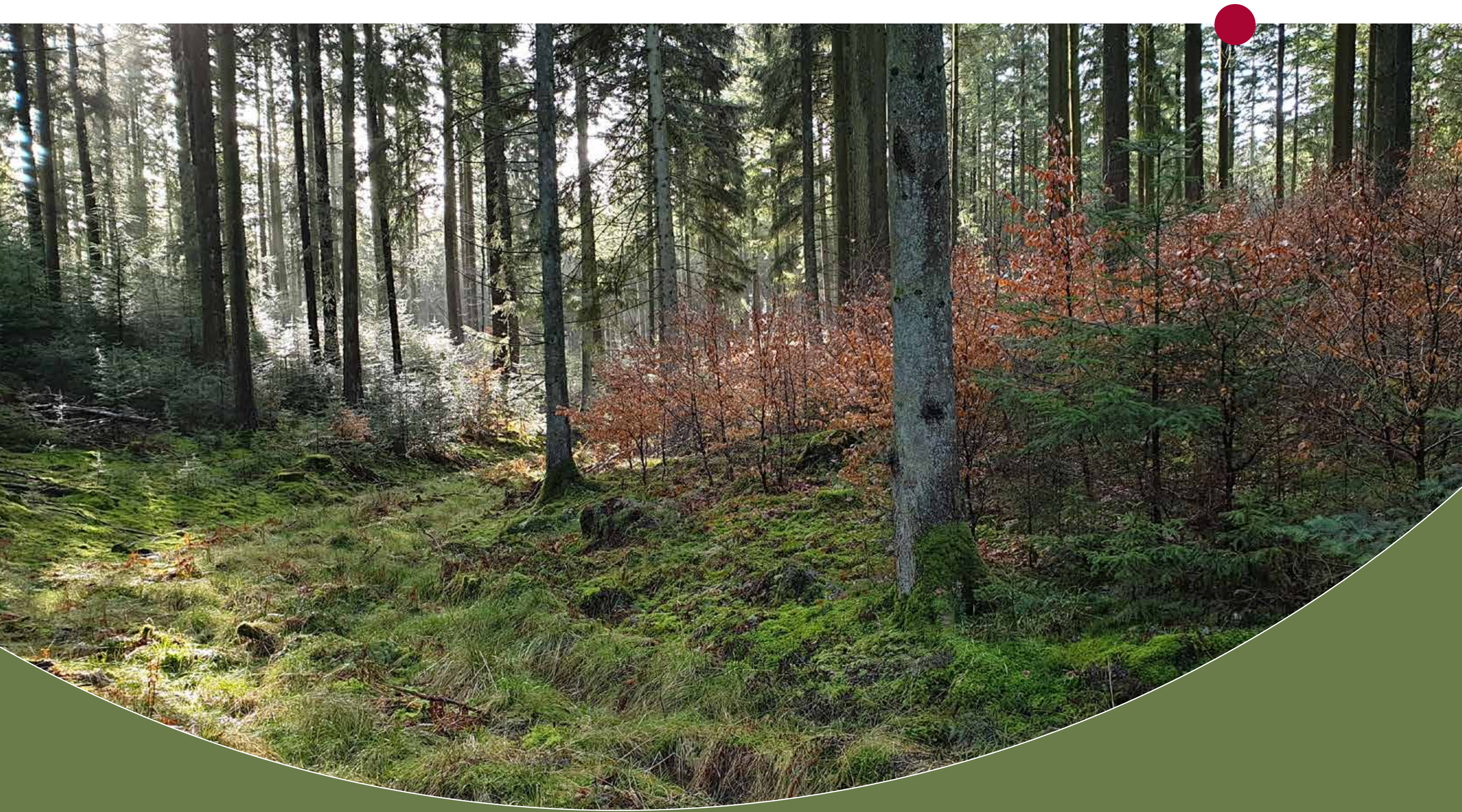

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Anders Tærø Nielsen, Niclas Scott Bentsen, and Thomas Nord-Larsen

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Contents

Preface

This report and the analysis behind were commissioned by the Danish Energy Agency in November 2021 to address questions about CO_2 emissions related to the current and future use of forest biomass for district heat and electricity production in Denmark. The analytical framework and approach build largely on previous work [1,2]. Details on assumptions and calculations can be found here. Major changes and new data are presented in this report. Confidential process and supply chain data for the initial analysis was partly updated and reused for this analysis in agreement with Danish Energy and Danish District Heating Association.

A preliminary version of this report was commented by the Danish Energy Agency by mid-January 2022.

The authors thank data providers from the Danish Energy Agency, Danish Energy, and the Danish District Heating Association for fruitful collaboration and contribution to the analysis.

We also thank Inge Stupak (Department of Geosciences and Natural Resource Management, University of Copenhagen) and Jette Bredahl Jacobsen (Department of Food and Resource Economics, University of Copenhagen for internal review and valuable comments.

The content and conclusions presented here is the sole responsibility of the authors.

April 2022.

Abstract

District heat and electricity production in Denmark has seen a significant transition over the last 30 years from fossil fuel to renewables in the form of biomass, wind, and solar energy. Forest biomass contribute considerably to the renewable energy consumption but the ability of forest bioenergy to mitigate global warming has been questioned due to concerns regarding the temporal difference in CO_2 emissions and re-sequestration from burning of forest biomass and the risk of overexploitation of the forest resource.

According to the Danish Climate Act of 2020, the Danish Energy Agency must annually report on Denmark's consumption-based greenhouse gas emissions. The aim of the present study was to provide scientific input on global CO_2 emissions attributable to Denmark's use of biomass for energy to the Global Assessment Report 2022 for the Danish Energy Agency.

The analysis is divided into three sub-sections:

1. analysis of a single year's emissions and recapture in forests of the biogenic part of the emissions. Results are reported as cumulative net CO_2 emissions to the atmosphere.

2. analysis of total net emissions of CO_2 to the atmosphere, separate for wood chips and wood pellets assuming a continuous biomass consumption over the coming 100 years. Results are reported as the cumulative net CO_2 emissions to the atmosphere.

3. analysis of the total net emissions of CO_2 to the atmosphere for the entire Danish consumption of wood pellets and wood chips for district heat and electricity assuming a continuous consumption over the coming 100 years. Results are reported as cumulative net CO_2 emissions to the atmosphere and as the Absolute Global Warming Potential (AGWP).

This report represents a further development of a model framework built with the aim of highlighting the historical climate effect of transitioning Danish heat and power plants from fossil fuel to biomass [1] as well as a series of subsequent analyses built on the same material [2]. The model calculations included the direct CO_2 emissions associated with the production of energy in the Danish transformation sector (production of electricity and district heat). These include emissions from the production of biomass (forest cultivation, transport, production of wood pellets, etc.) but not CO_2 emissions from the construction of the various transformation facilities.

The model includes forest carbon stocks as affected by the use of biomass and how this depends on how forests and wood would have been managed and treated absent the demand for bioenergy (counterfactuals and indirect emissions).

In relation to this project, additional data was collected from Danish heat and combined heat and power plants that use wood chips and wood pellets, so that data includes information updated to 2020. Several of the smaller utilities could not provide 2020 data within the given time frame of this project. Therefore, data for the smaller facilities come from the previous report. In total, 12 facilities

participated in the data collection, which covers 67% of the current Danish transformation sector consumption of wood chips and 96% of the consumption of wood pellets.

The first part of the analysis shows that, based on 2020 data, one year's consumption of wood chips and wood pellets emitted in total 7 Mt CO_2, roughly evenly distributed between wood chips and wood pellets. The biogenic part accounted for 93.5% of the total emissions. Net CO_2 emissions from the consumption decreased rapidly over time as a result of emissions being recaptured in new forest carbon stocks. After about 70-80 years, only emissions corresponding to the fossil emissions were left in the atmosphere as the forests had recaptured what corresponds to virtually all biogenic emissions. The sensitivity analysis showed that the rate at which net emissions decline depends on forest management affecting the recapture of CO_2 in the forest and the avoided emissions related to alternative fate of wood products absent a demand for bioenergy. This provides an interval for the recapture of CO_2 emissions in the forest between 5 and 100 years.

Assuming that the 2020 consumption of wood chips and pellets continue in the coming 100 years, cumulative net CO_2 emissions will reach 128 Mt, evenly distributed between wood pellets and wood chips. The majority of the change in cumulated net-emissions is attributed to the first 40 years after the transition to bioenergy. This is due to the fact that the cumulated annual emissions approach a fixed number as a result of the annual emissions declining towards zero when emitted CO_2 is recaptured in the forest (Figure 0.1). Oppositely, emissions from the fossil counterfactuals are not recaptured and hence results in principle in infinite cumulated net emissions. For comparison, a counterfactual energy supply corresponding to the 2020 consumption based on coal or natural gas would result in net CO_2 emissions of 689 and 421 Mt over a 100-year period.

Measuring the climate impact of the net CO_2 emissions (AGWP), the analysis shows that after about 20 years there is no further impact of the current consumption of biomass.

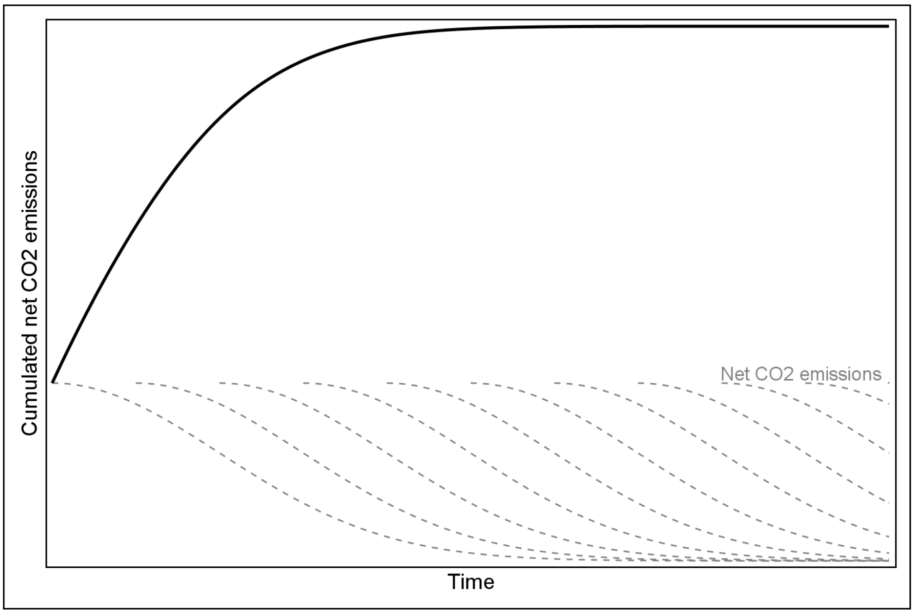


Figure 0.1. Illustration on how cumulated (full line) biogenic annual net emissions (individual hatched, grey lines) approach a fixed number. Annual net emissions are declining due to recapture of the emissions in renewed forest growth. The cumulated

biogenic emissions at steady state equals the total lowering of the forest carbon stock compared to setting the forest aside absent of bioenergy consumption.

The discussion emphasises a need for more research on decay rates of wood left in forests, indirect CO_2 emissions, and how the net-CO_2 emissions will be affected by the expected implementation of CO_2 capture and storage technologies (CCS) in Denmark.

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

Dansk resume

Dansk kraft-varmeproduktion har gennemgået en omfattende omstilling gennem de sidste 30 år. Fra fossile energikilder som kul og naturgas til fornybare ressourcer som biomasse, vind- og solenergi. Biomasse fra skovene bidrager med en stor andel af det samlede forbrug af vedvarende energikilder, men der er stillet videnskabeligt spørgsmålstegn ved skovbiomassens bidrag til imødegåelse af klimaforandringer som følge af den tidsmæssige forskel mellem udledningen og genoptaget af CO_2 når træbiomassen bruges til energi samt ved risikoen for skovødelæggelse som følge af brugen af bioenergi.

I henhold til Klimaloven fra 2020 er Energistyrelsen forpligtiget til årligt at rapportere Danmarks forbrugsbaserede udledninger af klimagasser. Formålet med denne rapport er at estimere nettoudledningerne af CO_2, der kan henføres til forbruget af biomasse fra skov til energiformål, til brug for Energistyrelsens Global Afrapportering 2022,

Analysen er opdelt i tre delanalyser.

1. analyser af et enkelt års udledning fra forbruget af biomasse fra skov til energiformål og af hvor hurtigt den biogene del af udledningerne genoptages i skoven
2. analyser af den samlede biogene nettoudledning CO_2 til atmosfæren fra forbruget af biomasse fra skov til energiformål opdelt på flis og træpiller med et kontinuerligt forbrug over 100 år.
3. analyser af den samlede biogene nettoudledning af CO_2 til atmosfæren fra forbruget af biomasse fra skov til energiformål for hele det danske forbrug af træpiller og træflis med et kontinuerligt forbrug over 100 år. Analysen omfatter omregning til effekten på jordens opvarmning - ”Absolute Global Warming Potential” (AGWP).

Rapporten bygger på videreudvikling af modeller og data præsenteret i et tidligere arbejde med formålet at belyse den historiske klimaeffekt ved konvertering af danske kraft- varmeværker til biomasse [1] samt en række analyser bygget på det samme materiale [2].

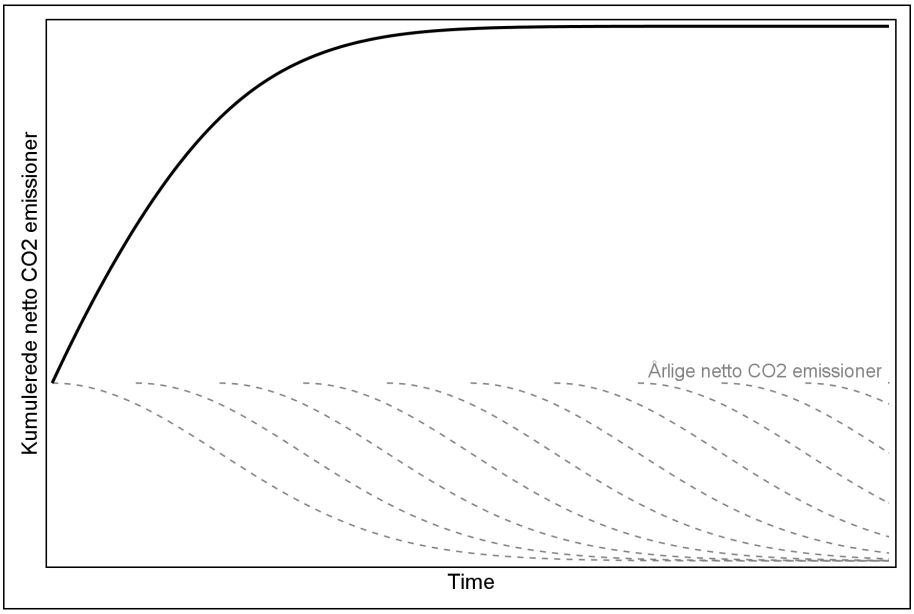
Modelberegningerne omfatter de direkte CO_2-udledninger, der er forbundet med fremstilling af energi ved afbrænding flis og træpiller i den danske konverteringssektor (produktion af elektricitet og fjernvarme) baseret på data fra værkerne. Disse omfatter udledninger, der følger af fremstillingen af biomasse (skovdyrkning, transport, fremstilling af træpiller mm), men ikke CO_2-udledninger fra konstruktion af de forskellige værker. Modelberegningerne omfatter endvidere hvordan skovenes kulstof lagre påvirkes af brug af biomasse samt hvordan dette afhænger af hvordan træet ellers ville være blevet behandlet, hvis det ikke havde været brugt til bioenergi (counterfactuals og indirekte udledninger), samt hvor hurtigt den udledte CO_2 genoptages i skovenes kulstoflagre.

Beregningerne er baseret på 2020 biomasse forbrugsdata. I forbindelse med dette projekt blev der udført en supplerende dataindsamling fra danske varme- og kraftvarmeværker, der bruger flis og træpiller, så analyserne omfatter opdaterede data frem til 2020. Flere af de mindre værker kunne ikke levere 2020-data inden for den givne tidsramme af nærværende projekt. Derfor stammer data for de mindre værker fra den tidligere rapport. I alt deltog 12 værker i dataindsamlingen, hvilket for flis dækker 67% af det samlede danske forbrug i konverteringssektoren og for træpiller 96%.

Den første del af analysen viste, at et enkelt års forbrug af flis og træpiller på basis af 2020 data udledte 7 mio., tons CO_2, rundt regnet ligeligt fordelt på forbruget af flis og træpiller. Den biogene del af disse udledninger står i afbrændingsåret for 93,5% af de samlede udledninger, hvor fossile procesudledninger forbundet med produktionen af bioenergi står for resten. Nettoudledningen, der resulterer af forbruget, falder hurtigt over tid, da de biogene udledninger genoptages i skovenes kulstoflagre. Efter ca. 70 år vil der kun være de fossile udledninger tilbage, da skovene her har optaget stort set samtlige biogene udledninger. Følsomhedsanalysen viser dog, at faldet i nettoudledningerne afhænger af skovforvaltningens effekt på CO_2-optaget, samt hvad træet bliver brugt til, havde det ikke været for afsætningen til bioenergi. Dette giver et udfaldsrum for genoptaget i skoven af de biogene udledninger på mellem 5 og 100 år.

Med et 100-årigt kontinuerligt forbrug som i 2020 går de totale biogene nettoudledninger mod en fast øvre størrelse på 128 mio. tons CO_2. Tallet svarer til den samlede, langsigtede reduktion i skovenes kulstoflager sammenholdt med et scenarium, hvor skovene ikke blev anvendt til høst af bioenergi. Den totale nettoudledning er nogenlunde ligeligt fordelt mellem udledninger fra træpiller og flis. Hovedparten af ændringen i den totale nettoudledning sker inden for de første 40 år efter konverteringen til bioenergi. Dette skyldes at summen af de enkelte års nettoemissioner går mod et fast tal, fordi nettoemissionerne fra de enkelte år over tid går mod 0, efterhånden som skovene optager det udledte CO2 (Figur 0.1). Når dette omregnes til AGWP (klimaeffekten) vil der efter ca. 20 år ikke vil være nogen yderligere klimapåvirkning af det nuværende forbrug af biomasse.

Modsætningsvis sker der ikke et sådant genoptag af udledningerne ved brug af fossile ressourcer, hvorfor de kumulerede udledninger principielt går mod uendelig. Eksempelvis vil de kumulerede nettoudledninger fra kul eller naturgas modsvarende et årligt energiforbrug som i 2020 over en 100 års periode være hhv. 689 og 421 millioner tons CO_2.



Figur 0.1. Illustration af hvordan summen af de biogene emissioner (sort fuldt optrukket linje) fra enkelte år (grå, stiplede linjer) går mod et fast tal. De årlige emissioner aftager som følge af skovens genoptag af CO_2 fra atmosfæren. Den samlede biogene emission ved steady-state modsvarer det samlede fald i skovens biomasse, der følger af hugst af træ til træprodukter og energi.

I diskussionen understreges det, at der behøves mere forskning inden for henfaldstider af træ efterladt i skovene, indirekte emissioner, samt hvordan resultaterne vil blive påvirket ved installation af CO_2-fangst og -lagring (CCS).

Resultater, der præsenteres her, kan og bør ikke sammenlignes med den nationale opgørelsesrapporter til UNFCCC eller med regnskab for reduktionsmål for drivhusgasudledninger. Denne analyse bygger på en forbrugsbaseret tilgang, mens de nationale opgørelser bygger på produktionsbaseret regnskabsmetode.

Description of terms and abbreviations

Abbreviation/term	English description	Dansk forklaring
DH	District heating plant	Varmeværk
CHP	Combined heat and power plant	Kraftvarmeværk
Process emissions	Biogene and fossil CO_2 emissions related to forest operations and production of wood pellets	Biogene og fossile CO_2-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
Biogenic 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 wood had it not been used for bioenergy e.g. a natural decay rate, described by a first-order exponential decay function. The half-life describes the time it will take before half of the carbon in the wood is emitted by decay or combustion of wood products	Udtryk der beskriver hvor hurtigt kulstof udledes fra træet, eksempelvis om følge af forrådnelse, beskrevet med en førsteordens eksponentiel henfaldsfuntion. Halveringstiden er den tid det tager før halvdelen af træpuljens kulstof er frigivet til atmosfæren som følge af forrådnelse eller afbrænding af træprodukter
Indirect emissions	Greenhouse gas emissions related to market pressure from bioenergy demand on land, raw materials, and fuels.	Drivhusgasudledninger der stammer fra markedspres på areal, råmaterialer og brændsler som følge af efterspørgsel på træ til bioenergi
iLUC	Indirect land use change relating to greenhouse gas emissions or uptake from the living forest biomass carbon pool as a consequence of demand for bioenergy	Indirekte Drivhusgasudledninger eller optag i skovenes levende kulstof pulje, der stammer fra øget pres fra bioenergiforbruget
iWUC	Indirect wood use change, greenhouse gas emissions related to change in price structure for bioenergy compared products, leading to consumers switching to other products, hereby creating emissions	Drivhusgasudledninger som følge af øget efterspørgsel efter bioenergi. En sådan øget efterspørgsel kan lede til ændrede forbrugsmønstre i andre sektorer og heraf følgende ændringer i CO_2-udledningen
Single pulse emissions:	All CO_2 emissions and forest carbon uptake related to a single year use of bioenergy	Alle CO_2-udledninger, samt optag i skoven som følge af et enkelt års bioenergi forbrug
Multi-pulse/cumulative emissions	The sum of single pulse emissions over time	Summen af single pulse udledninger over tid
Absolute biogenic emissions	The total biogenic emissions for current consumption level in an infinite time perspective	Totale biogene CO_2-udledninger som følge nuværende biomasse forbrug in uendeligt tidsperspektiv
AGWP	Absolute global warming potential, a metric that describes the climate effect of emissions expressed in watts per m^2	En metode til at beskrive klimaeffekten af udledninger der udregnes i watt pr. m^2

1 Introduction

The goal of the Paris Agreement is to keep anthropogenic global warming well below a 2ºC increase from pre-industrial levels and pursue efforts to limit the temperature increase to 1.5ºC above pre-industrial levels [3]. Meeting these goals require significant society wide transitions of the energy, agriculture, land use, industry, and transportation sectors. For the energy sector, the Intergovernmental Panel on Climate Change (IPCC) highlight four macro-level transformations required for decarbonization: 1) limits on the increase of the final energy demand, 2) reductions in the carbon intensity of electricity production, 3) increases in the share of final energy provided by electricity, and 4) reductions in the carbon intensity of other energy forms than electricity [4]. The use of biomass in the energy sector has been a favoured by political instruments since the mid-1990s in the transition of the Danish energy sector [5], targeting 2) and 4) listed above. Specifically, district heat and electricity production in Denmark has seen a significant transition over the last 30 years from fossil fuel to renewables in the form of biomass, wind, and solar energy [6]. In 2020, renewables made up 68% of both electricity and district heat production, with 19 PJ of electricity and 79 PJ of district heat being based on biomass (wood chips, wood pellets, straw, organic waste) corresponding to 22% of renewable electricity and 91% of renewable heat produced, respectively [6].

Wood in various forms makes up the lion's share of biomass used. In 2020, 38 PJ of wood was used for electricity production, corresponding to 70% of biomass used for electricity production. In 2020, the corresponding figures for district heat was 32 PJ and 63% [6].

The ability of forest bioenergy to mitigate global warming has been questioned due to concerns over the temporal difference in CO_2 emissions from burning of forest biomass and their subsequent sequestration in new biomass [7] and the risk of overexploitation of forests. Following IPCC guidelines, so-called production-based accounting, the use of biomass for energy is not allocated a CO_2 emission from the energy sector. Accounting for CO_2 emissions related to bioenergy are instead allocated to the land sector (LULUCF/AFOLU), where the harvest of e.g. wood in a forest is accounted for as an emission to the atmosphere. If wood from Danish forests was only used for energy generation in Denmark, the Danish climate account would represent the impact on the climate from bioenergy production. However, as a large proportion of the biomass used for energy in Denmark is imported, part of the emissions related to bioenergy are allocated to other countries' climate account. Biomass is not special in that respect as this is common to all goods and products traded over national borders.

Following the Danish Climate Act of 2020, the Danish Energy Agency must report annually on Denmark's impact on the global climate and assess its so-called consumption-based greenhouse gas emissions. While production-based accounting assesses GHG emissions from production within national borders, the consumption-based framework assesses emissions related to consumption within national borders including emissions from production for domestic use, emissions in other countries related to imported products and excluding emissions related to products exported to other countries.

1.1 Aims of study

The aim of this analysis was to provide scientific input to the global assessment report 2022 (Global afrapportering 2022, GA22) by the Danish Energy Agency. Specifically, this analysis contributes to GA22's appendix 6 on the use of biomass, with an analysis of the global CO_2 emissions attributable to Denmark's use of biomass for energy. The present study was tailored to the Energy Agency's reporting obligation and builds on an expansion of previous work by Nielsen, Bentsen and Nord-Larsen [1] to estimate impacts on net CO_2 emissions to the atmosphere aggregated in a 100 years projection and expressed as the absolute global warming potential (AGWP), from:

1. A single year use of the current amount and mix of biomass for energy production in CHP and district heating plants
2. A continued use of the current amount and mix of biomass for energy production in CHP and district heating plants
3. To calculate total net CO_2 emissions for the current level of production of bioenergy, at the equilibrium stage i.e. with an infinite time perspective and estimate the climate impact expressed as the absolute global warming potential (AGWP).

The findings presented here cannot and should not be compared to the national inventory report to the UNFCCC or to accounting against greenhouse gas emission reduction targets. This analysis builds on a consumption-based accounting 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

2.1 Model overview

For assessing cumulative CO_2 emissions, we set up a modelling framework that calculates carbon pools and fluxes linked to processes in the supply chain from forest management to heat and electricity production (Figure 2.1). Emissions from the construction of CHP/DH plants, machinery and infrastructure were disregarded in this analysis as we had no plant-specific data. Moreover, emissions from plant and infrastructure construction are typically negligible compared to the full life cycle emissions [8,9].

In the analysis we distinguish between direct and indirect emissions. Direct emissions are emissions from the supply chain of biomass e.g. from forest operations or transportation of biomass or combustion. Indirect emissions derive from market mediated consequences of the biomass use for energy, i.e. indirect land (iLUC), and wood (iWUC) use change. Contrary to the models in Nielsen, Bentsen and Nord-Larsen [1], there is no fossil fuel counterfactual in this analysis. Hence, the counterfactual elements in this study only focus on what would have happened to the wood biomass had it not been used for energy production e.g. left in the forest for natural decay or used for other forest/wood products. Counterfactuals are however introduced in the discussion of our results.

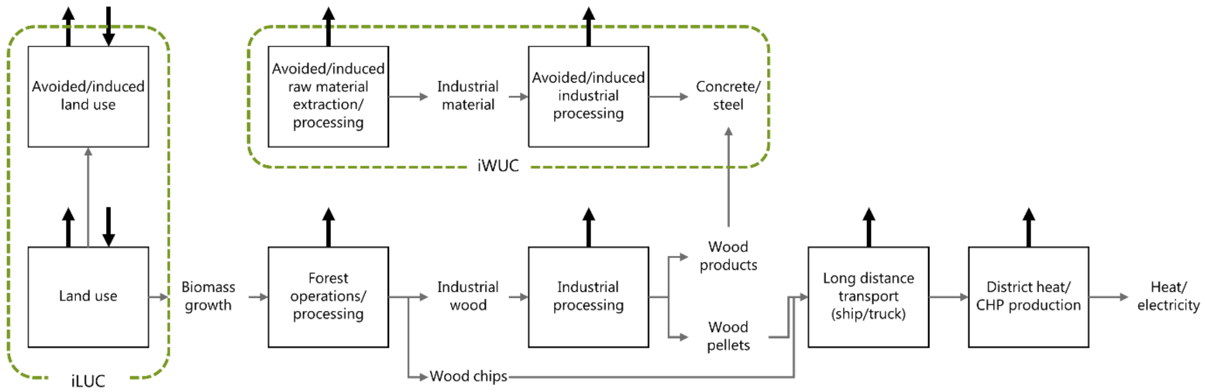


Figure 2.1. Overview of the model framework. Thin arrows represent material flows, while thick arrows represent material and energy flows.

Assumptions were made regarding e.g. counterfactual of the wood had it not been used for bioenergy, substitution factors and lifetime of forest products, forest growth etc. (Table 2.1). To test the robustness of the results to uncertain parametrization, we conducted sensitivity analyses with alternative parametrization on transportation distances, counterfactuals, and forest management, resulting in an outcome space for CO_2 emissions of current Danish biomass use in DH and CHP plants rather than a specific value.

Table 2.1. 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 for each biome: Boreal 80 (60-99) Mg C ha^{-1}, Temperate 177 (121-233) Mg C ha^{-1} and Tropical 159 (105-213) Mg C ha^{-1}	[10]
2	The soil carbon pools including forest floor in unmanaged forests are in a steady state over the whole projection period, and unchanged by use of bioenergy throughout the projection period.	[11,12]
3	We assume that establishment of forests and growth after intervention, follows existing yield tables and models of for the most common tree species in the region.	[13-15] See also section "forest carbon uptake"
4	Living root biomass of all forest management alternatives is assumed to be 20% of the aboveground living biomass.	[16]
5	90% of the aboveground living biomass harvest residues are extracted for use as wood fuel.	[17,18]
6	The half-life of all harvest residues left on the forest floor is 5 years in tropic regions, 10 years in temperate regions and 15 years in boreal for harvest residues and industrial residues left for decay. For stems, the half-lives are 10, 15 and 20 years for tropic, temperate and boreal regions, respectively.	[19-21]
7	For harvest residues, we assumed that 30% was burned and 70 % was piled giving and average half-life for harvest residues at 7.15 years. Moreover, we demonstrated the effect of crushing harvest residues, hereby making the half-life more comparable to industrial residues (5 years).	Assumptions
8	All biomass contains 50% carbon.	[22]
9	There are no significant emissions along the production chains of other greenhouse gasses than carbon dioxide.	Assumption
10	For forest site operations, we used 2.29 l diesel t^{-1}. For harvest, forwarding and chipping we used 2.31 and 0.87 kg C m^{-3} and finally for chipping we used 1.85 l diesel t^{-1}. For processing, we used emissions (fossil) equivalent to 15% of combustion emissions. 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	[23-25]
11	For grinding of wood and pressing to pellets, we assumed an energy use of 152 kWh $tons^{-1}$ (547 MJ $tons^{-1}$) pellets assuming natural gas-based electricity production.	[24]
12	The half-life of the wood product pool is 35 years for sawn timber, 25 years for boards and 2 years for paper.	[26,27]
13	The wood product substitution factor (SF) is set to 1.4 for timber, 1.2 for panels and boards and 1 for other products.	[28]

2.2 Data input

In collaboration with Danish Energy and the Danish District Heating Association, 12 utilities (CHP or DH) were selected to participate and provided data for the analysis. The data providers were selected to cover a broad range of supply chain configurations (e.g. using wood chips or wood pellets, sourcing biomass locally or from international markets, having biomass delivered by truck or ship). Data providers were asked to supply data as specified in Table 2.2 for the most recent years.

Table 2.2. Data specification for data providers.

No.	Requested information
1	Fuel use in energy units and mass units
2	Fuel type, all fuels included
3	Origin of the fuel, country, region, forest type, resource type (harvest residue, stems, bioenergy, industrial residue, non-forest)
4	Form of biomass as received at the CHP or district heating plant (pellets, chips, logs)
5	Transport form of fuel to the CHP or district heat plant (ship, truck, train)
6	Electricity and heat production
7	Electricity and heat production capacity
8	Energy use and fuel type in production of pellets

The type and detail of data requested was challenging for the data providers and the data received from the utilities exhibited large variation in the details provided (see [1]). However, within the last few years, where larger utilities have had to document sustainability compliance against the industry agreement [29], these data have been collected regularly [30]. The data received are characterised in Table 2.3.

Table 2.3. Data properties for the collected data.

Data type	Detail level
Fuel use in energy units and mass units	Yearly data for all included plants for biomass. Fossil data assumed for two plants, based on means from the other plants
Fuel type, all fuels included	Yearly data for all included plants for biomass. Fossil data assumed for two plants, based on means from the other plants
Origin of the fuel, country, region, forest type, resource type (harvest residue, stems, bioenergy, industrial residue, non-forest)	Typically, an educated guess by the manager at small plants. Detailed information from large plants after 2016
Fuel type as received at the CHP or district heating plant (pellets, chips, logs)	Some plants delivered detailed information, where others had a large proportion that was unknown
Transport form of fuel to the CHP or district heat plant (ship, truck, train)	Typically, an educated guess by the manager at small plants. Detailed information from large plants after 2016
Electricity and heat production	Detailed yearly information from all plants after conversion. Fossil data assumed for two plants, based on means from the other plants
Electricity and heat production capacity	Not informed
District heating grid to which the CHP or district heating plant delivers heat	Delivered

In the analysis, we aggregated the data, provided by utilities, to construct a 'weighted average wood chip consumption' and a 'weighted average wood pellet consumption' based on consumption-weighted averages for units using wood pellets or wood chips, respectively. The 'weighted average' subsequently represented wood chip and wood pellet use in an extrapolation from the wood use covered by data from utilities to a national coverage of wood used for district heating and combined heat and power production in the transformation sector. Data on national use of wood for energy and the production of heat and electricity in the transformation sector was acquired from the 'Grunddata' spreadsheet for the official energy statistics [6] (se data in section 3.1). In the calculation of cumulative net CO_2 emissions, 2020 data are projected 100 years into the future.

2.3 Forest operations, processing, and transport related emissions

2.3.1 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 forests are generally assumed to be grown with the aim of producing timber and these operations would have been performed, also if there was no market for bioenergy. In our study, we 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.

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 lumber production. Processes involved include grinding into smaller particles, drying, and pressing into pellets. For drying of wood pellets, the utility companies documented that in 2020, 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. 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 [31].

2.3.2 Transport of biomass

Transport emissions relates to emissions that occur due to transport by either truck, train, or ship. To determine the transport emissions, we made some simplifications, as these emissions are dependent on the exact location of biomass harvest, collection, and processing. Our data material did not contain such information but only the country of origin and if shipped by boat, the harbour from which it was shipped. The large utilities provided weighted average transport distances from each region (Table 2.4).

Table 2.4. 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

2.3.3 Combustion and conversion efficiency

Direct CO_2 emissions per produced unit of energy were calculated for each wood type (pellets or chips) building on standard emissions factors from IPCC [31] and were subsequently aggregated to total wood chip and wood pellet use. The efficiency in conversion of biomass to energy (heat and electricity) was based on weighted average of the efficiency data from the data providing utilities (see [1]).

2.4 Origin of wood for energy

In the present day market for wood, a large proportion of the wood produced from Danish forests (excluding industrial residues) is marketed as forest bioenergy, making up 57% of the total volume [32]. Importantly, higher qualities of wood can always be used for less valuable purposes, while the opposite is commonly not possible. For example, large logs suited for sawn timber can be used for pulp and bioenergy, but small trees of poor quality cannot be used for construction in the present day market. Hence, for industry to attract better qualities of wood, a premium is paid, making the higher qualities of wood more expensive. In an example based on Danish price statistics (Table 2.5), quality logs and timber attain prices more than five-fold that of bioenergy. As wood is an internationally marketed commodity, the international price structure is expected to be similar to the Danish example as also documented by international trade statistics [33].

In a practical context, the fate of a given piece of wood is not solely determined by its technical properties but depends also on e.g. the individual thinning operation in terms of terrain, machinery, the collective assortment distribution, and current and local price structure. Hence, the delineation between assortments is continuous in practice. However, in general, energy wood is poorly paid, expensive to extract, and rarely the real objective of forest production.

Table 2.5. Average prices for different assortments of wood. Based on annual statistics for 2020 reported by private forest owners in Denmark [34]. Prices on small logs of oak and sycamore maple and pulp wood of beech and sycamore maple are based on sold volumes at Frederiksdal Forest District in 2021. Net price at roadside for energy wood is calculated assuming a cost of 11.5 € m^{-3} for chipping and 9.6 € m^{-3} for land transport.

Deciduous wood				Coniferous wood		
Assortment	Beech	Oak	Sycamore maple	Assortment	Spruce	Larch, douglas fir
			€ m^{-3}			
Logs	111	294	124	Timber	52	65
Small logs	93	148	105	Packing	34	42
Flooring	68	79	62	Fibre board	29	29
Pulp	44	-	38	Pulp	26	28
Energy	26	26	26	Energy	9	9

Biomass for energy may come from all parts of the forest rotation but depends on the site conditions, tree species, forest management, tree size, tree quality, and price structure. Forest management, including the species choice, depends largely on growing conditions but also local tradition. In general, better growing conditions increases the economic incentive for investing in active forest management, while poorer growing conditions favours less intensive measures. Consequently, active forest management including plantings with high density, tending of the forest stand, thinning, and sometimes even corrective measures, such as pruning, is predominant in the temperate regions including Denmark and central Europe. Oppositely, in much of the boreal zone, management is commonly with low-density plantings or relying entirely on natural regeneration, less intensive tending of the forest stand, and rare or even no thinnings during the rotation [35]. Combined with the differences in biomass production between the different zones, this produces highly different profiles in terms of biomass production.

In managed forest stands established by natural seeding or planting, the plant number is typically much higher than the number of trees in the final crop. This allows selection of the best shaped individuals during thinnings and the mutual shading of the plants improves quality of the final crop. In early thinnings, excess competition is removed and is important for the future development of the stand. At this stage, the thinning trees are typically small and cannot in the present-day market be utilized as a timber (Figure 2.2). In addition, in these thinnings, undesired competing tree species commonly unsuited for timber production are removed. Thus, either the wood is left in the stand or used for bioenergy. The choice between utilizing the forest biomass from early thinnings or not depends on the local market for bioenergy, the size of the trees, since small trees may be too expensive to extract, and the accessibility of the site.

In the later thinnings, the wood achieves a size where it can be marketed and used for fibre products such as pulp for paper, in the chemical industry, and for packaging (pallets). As the trees grow larger, an increasing proportion of the coniferous wood is used for construction and for deciduous species for smaller elements in the furniture and flooring industry (Figure 2.2). The minimum diameter of the wood here is typically 15-20 cm. However, the smaller parts of the tree in the top and branches continues to be used as fibre and chemical products, and for bioenergy.

In the late thinnings and in the final harvest, where the trees become large, the proportion of timber assortments is large - for the coniferous species up to 90% and for hardwood species 50-70% (Figure 2.2). For the coniferous species, up to 70% become construction timber, while for the deciduous species 45-50% of the large trees become furniture or flooring wood. The remainder is used for fibre products and bioenergy. The proportion of wood for energy is usually higher for hardwoods than for conifers because branches and trunks are often less regular and therefore poorly fit industry requirements. As the trees grow even larger, an increasing part of the wood may be become damaged from insect attacks, root rot and windthrow, making the wood unsuitable for construction timber. In addition, the need to clear the ground prior to re-planting or seeding often creates an incentive to grind or extract tops and branches for bioenergy, increasing the share of bioenergy in the assortment distribution. In some Scandinavian countries, harvest residues also include roots and stumps [36,37]. Such biomass fractions are not included in the supply chains studied here.

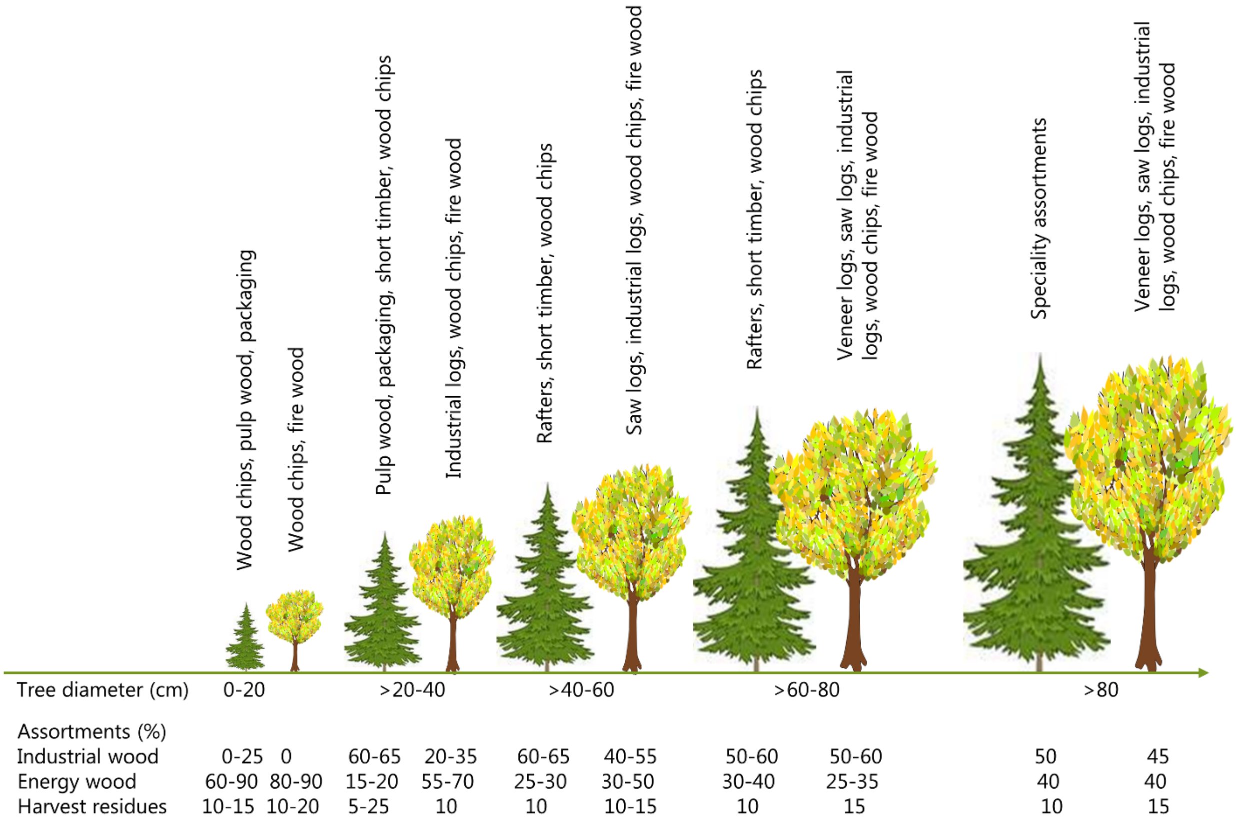


Figure 2.2. Example distribution of assortments at different tree diameters. The distribution is adopted from Graudal, *et al.* [38] based on experience from major Danish forest management companies.

2.4.1 Industrial residues

When the timber enters the sawmill, the round wood is first debarked. The bark is commonly used for bioenergy and has currently limited alternative use although methods are developed to extract tannins from softwood bark for use as a raw material in resins used in wood products and other material applications. The residual fibre fraction can be used to produce sugar for fermentation products. The bark fraction of the stem is typically 5-7%.

After debarking, the stems are cut into square or rectangular boards causing a production of residues in the form or slabs, sawdust, and shavings. Typically, the board yield is 45-50% of the total volume for both conifers and broadleaves. The residues are well suited for products such as particleboards and pulp and part of this is recirculated into other uses while some of it is used for bioenergy. The amount of residues being recycled is unknown. However, under Danish conditions the consumption of particleboards is much smaller than of sawn boards making a large part of this resource available for bioenergy in the current market situation.

The wood products are further processed in the building sector, furniture industry and elsewhere, leading to an additional production of residues. The fraction of the wood ending up in the final product is unknown and highly dependent on the processing industry. It is estimated that 10% of the volume is lost in the final processing. Hence as an example, if 70% of a final felling in Norway spruce is classified as timber and 50% of this volume is cut into boards and assuming a final 10% loss, 32% of the original volume ends up in the final product.

2.5 Forest resources and growth

Sustainably managed forests are characterized by a long-term uptake of CO_2 similar to or higher than that exported from the forest through natural decay and harvesting of wood for various purposes. In relation to the assessment of CO_2 emissions from bioenergy, this particular aspect is important because the recapturing of emitted CO_2 results in less impact on the global climate compared to the irreversible emissions resulting from energy production based on fossil resources.

2.5.1 Forest resources

The most commonly sourced biomass in our study comes from Denmark and the Baltic countries, making up almost 75% of the total volume. This region includes a total forest area of 8.7 million ha of which 91% is available for wood supply (Table 2.6) and roughly 50% is dominated by conifers. The third and fourth largest contributors to biomass sourcing are South-eastern USA and Belarus with both 7% of the total volume.

Table 2.6. Forest area, forest area available for wood supply (FAWS) and distribution of forest types for selected European countries in 2020 [39,40].

Country	Forest area	FAWS	Coniferous forest	Broadleaved forest	Mixed forest
	1,000 ha				
Belarus	8,768	6,575	3,932	3,507	1,329
Denmark	628	614	279	282	67
Estonia	2,438	2,106	896	959	583
Finland	22,409	19,719	17,631	1,689	3,089
Germany	11,419	9,942	3,118	2,506	5,795
Latvia	3,411	3,199	1,304	1,582	525
Lithuania	2,201	1,936	964	883	354
Norway	12,180	8,264	5,933	4,298	1,949
Poland	9,483	8,331	5,497	2,381	1,605
Portugal	3,312	2,199	-	-	-
Russian Federation	809,090	677,204	-	-	-
Spain	18,572	17,079	7,383	10,200	1,004
Sweden	27,980	19,556	20,672	2,468	4,840
South-eastern USA	53,050	51,429	21,849	24,831	5,810

The average biomass stock varies with a factor four across the European procurement area (Figure 2.3). The largest forest biomass stocks are observed in the temperate region, while much smaller average stocks are found in the boreal and Mediterranean regions. Generally, average biomass stocks are increasing throughout the European region despite substantial afforestation taking place in many countries.

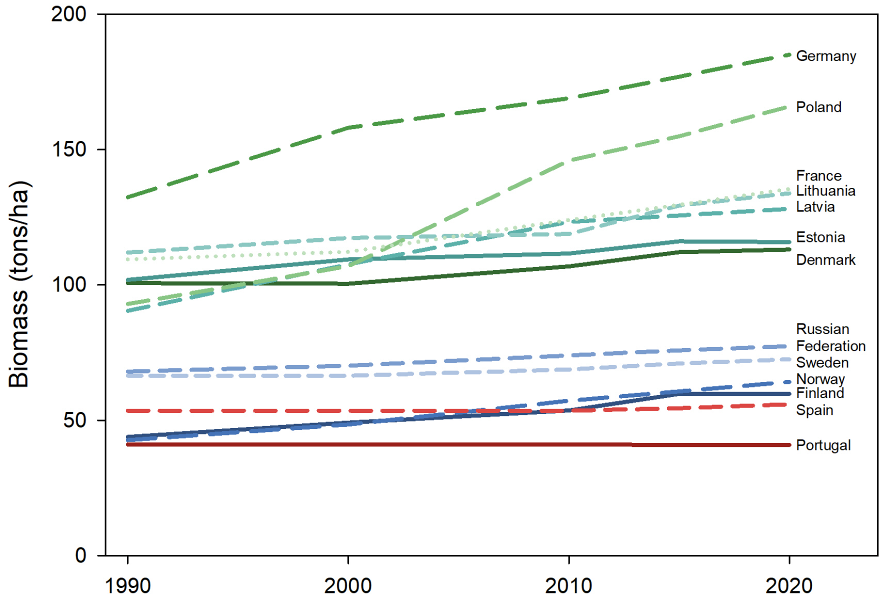


Figure 2.3. Development in average growing stock biomass of selected countries. Data obtained from the global forest resource assessment [41].

In most European countries within the procurement area of our study, the average as well as the total biomass resource has been increasing during the past 30 years (Figure 2.4). The only exception is Portugal, where drought and forest fires have reduced total growing stock. The increase in forest carbon stocks may origin from an uneven age class distribution and the general expansion of the forest area in most European countries. As the forests mature and are harvested as part of the normal forest rotation in forestry, the currently observed increase in forest carbon stocks may cease [42]. However, as part of normal forest management practices this would not give rise to iLUC emissions. It should however be noted, that management practices adapted to a market for bioenergy may impact – positively and negatively – forest carbon stocks resulting in direct and indirect emissions as described by Jacobsen [43]. In relation to the assumptions made in this study, it is generally observed that forest biomass is procured from countries where there is little evidence of substantial emissions from land use change associated with bioenergy resulting in iLUC emissions. This notion is substantiated by the requirements in the industry agreement in which sourcing of biomass locally cannot legally lead to deforestation [29].

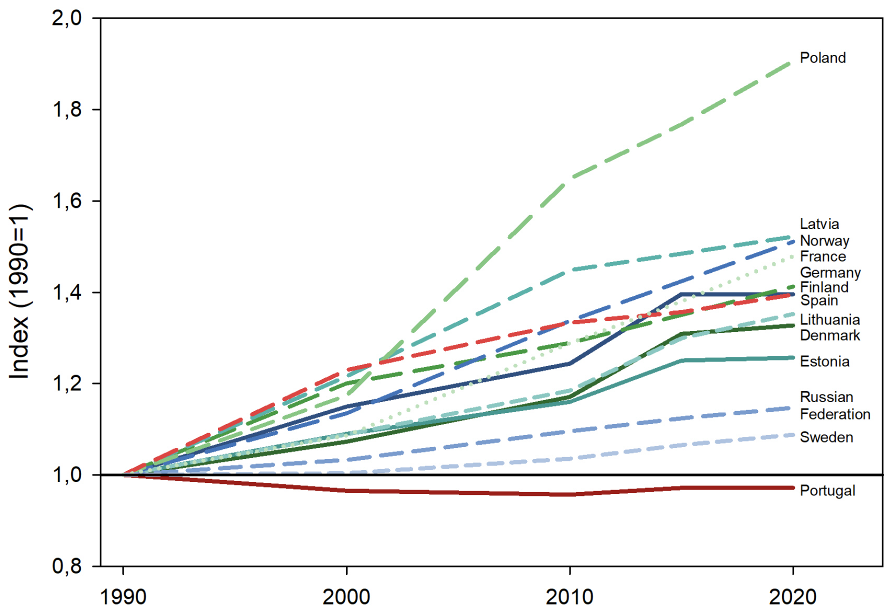


Figure 2.4. Relative total biomass accumulation in European forests. Reference year=1990.

2.5.2 Forest growth

Forest growth may vary considerably between species and sites even within a small distance. The data available on biomass consumption in Danish CHP and district heating plants did not include specific information on which species or where the biomass was harvested. Local growing conditions could therefore not be considered. Consequently, we collected national forest growth data to estimate forest growth and carbon sequestration (Table 2.7). Of the total procurement of biomass, 7% originated from Brazil but obtaining a representative annual growth rate from here was not possible within the frame of this project.

Forest volume growth was obtained from the 2020 global forest resource assessment [41]. To convert the volume growth into biomass, we furthermore obtained estimates of total above-ground biomass and growing stock from the same source. The ratio of the two constitute a biomass conversion and expansion factor (BCEF, [31]), subsequently used to expand volume growth to biomass increment. Obtained estimates of biomass growth were used to estimate carbon and CO_2 sequestration, using a carbon density of 0.5 and a conversion factor of carbon to CO_2 of 44/12, in line with the IPCC guidelines [31].

Table 2.7. Volume growth, expansion factor of volume to biomass and estimated biomass growth. Based on recalculations of figures from the 2020 global forest resource assessment [41]

Country	Volume growth	Biomass expansion	Biomass growth	CO_2-sequestration
	$m^3 ha^{-1} year^{-1}$		ton $ha^{-1} year^{-1}$	ton $ha^{-1} year^{-1}$
Belarus	4.1	0.76	3.1	5.8
Denmark	10.7	0.53	5.7	10.5
Estonia	5.8	0.57	3.3	6.1
Finland	4.9	0.55	2.7	4.9
France	5.1	0.76	3.9	7.1
Germany	10.3	0.55	5.7	10.4
Latvia	5.8	0.65	3.8	6.9
Lithuania	7.1	0.53	3.7	6.8
Norway	3.1	0.64	2.0	3.6
Poland	-	0.57	-	-
Portugal	-	0.79	-	-
Russian Federation	1.3	0.75	0.9	1.7
Spain	2.1	0.95	2.0	3.6
Sweden	4.8	0.57	2.8	5.0
South-eastern USA			7.3	12.7*

* Corresponding to the uptake of 3.45 tC $ha^{-1} year^{-1}$ reported by [1].

2.6 Biomass counterfactuals and biomass categories

2.6.1 Counterfactuals for harvest residues poor quality stems and wood processing "true residues"

Residue biomass is biomass that is not in use for other purposes than bioenergy or where there is no market for this biomass. In this study, residues can be harvest residues from forest operations, decayed stems or stems of low quality procured during forest harvest but unsuitable for other products, or non-commercial tree species. When timber is sawn and further processed, there is also a potential production of more residues, such as sawdust or shavings. The use of residues for energy purposes does not affect land or product markets as no other market exists for this biomass. Residual biomass with no other counterfactual than being burned or decaying over time was here denoted 'true residues'.

In modelling the alternative fate/counterfactual of biomass residues, we assumed two possible options: the residues may be burned on site or left to decay naturally. If residues are burned on site, we assumed a half-life of 0.5 year (almost all biomass is burned within the first 2 years after processing). If harvest residues are left to decay, we assumed half-lives for non-stem biomass (tops and branches) of 15, 10 and 5 years, respectively, for boreal, temperate, and tropical climates. For industrial residues left for natural decay in deposits, we assumed a half-life of 5 years as these are crushed into small pieces and piled e.g. behind the sawmill. The same assumption was made for crushed harvest residues. For stems left to decay, we assumed half-lives of 20, 15 and 10 years for boreal, temperate and tropical climates, respectively [21]. As such, the residue biomass represents a carbon pool that is released over time, had it not been used for energy, and the emissions from the residues are occurring both when they are used for energy (immediate release) and when left to decay in the forest (delayed release). The decay of forest biomass left on forest floors was assumed to follow a first order exponential decay function with the half-life determining the decay speed. The magnitude of the forest floor carbon storage thus relies on the specific decay rate (half-life) of the biomass and the input to this. Use of residues where the counterfactual is being left in forests will thus reduce the dead biomass carbon pool of utilized forests.

2.6.2 Emissions from indirect effects (iLUC and iWUC)

Biomass currently used for energy may have an alternative use, which may lead to a different pattern of emissions e.g. from decaying forest residues left on the forest floor or when products such as paper or panels are used and ultimately burned. If the biomass could have been used for something else, using it for bioenergy leads to market-mediated reactions linked to land use (iLUC) or the product market (iWUC). Such market-mediated reactions may lead to additional GHG emissions or savings.

Indirect emissions can affect forest carbon stocks and emissions in adjacent sectors in three different ways: management intensification of other existing forests to compensate products missing in the market (carbon stock increase or decrease), expansion of managed forest into previously unmanaged forests (carbon stock decrease), and a reduced supply (here treated as product shift - see iWUC section).

iLUC

The situation, where forest management expands into previously unmanaged forests was modelled according to the method developed by Schmidt*, et al.* [44]. In natural forest landscapes that are not affected by management, carbon stocks in living and dead biomass as well as in the soil are quite stable on a landscape level, but highly variable on stand level, as a result of an equilibrium between uptake with the photosynthesis and emissions from decaying biomass [19,20,45]. When such forests are taken into management, the carbon storage is affected on several parameters:

1. For a period after intervention, the carbon pool in living biomass is smaller in the managed forest compared to the unmanaged.

2. Input to the carbon pool in dead wood 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 decay of soil carbon.

For the carbon pool in unmanaged forest we used default carbon stocks given by Keith, Mackey and Lindenmayer [10] for the specific regions (boreal, temperate and tropic) as the reference carbon stocks (Table 2.1). For the living biomass carbon pool, we used the region-specific growth figures (Table 2.7) and a standard forest growth model, to determine both the living and dead biomass carbon stocks. As such, forest iLUC emissions were modelled as:

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

where $C_{unm,\,t}$ is the carbon stock of the unmanaged reference (living and dead biomass) at time t, and $C_{man,t}$ is the carbon stock of the managed forest (living and dead biomass) at time t.

Examples of iLUC

In the model, we operate with three different types of iLUC: Additional harvest, expansion of managed forest area and intensified management practices. Additional harvest occurs when trees that would not have been harvested are harvested for bioenergy use. An example of this could be a corner of the forest with poor quality trees not suitable for timber that is harvested together with a harvest operation in an adjacent forest stand. Here the counterfactual would be that this poor-quality forest compartment would be left and harvesting for bioenergy will thus reduce the living biomass carbon stock.

The second example of iLUC is if the price for energy wood exceeds that for e.g. pulpwood. The forest owner will likely sell the wood for energy instead of for pulp. When this happens, the supply of pulpwood will decrease. This may lead to expansion of the managed forest area into previously unmanaged forests from which biomass is harvested to meet the demand of pulpwood inducing a market mediated indirect land use change.

Both above-mentioned effects will lead to decreased living biomass carbon stocks in forests, which is considered a CO_2 emission attributed to the use of biomass for energy. Contrarily, increased demand for bioenergy can also lead to increased investments in forest management leading to intensified management practices, with two potential effects on forest carbon stocks and emissions. Forest managers may replant cleared forest stands with the use of nurse trees (fast growing trees mixed into main forest stand), with faster recovery of the forest carbon stock after felling compared to the counterfactual situation of regeneration with slower growing main tree species. Moreover, the economic incentive provided by bioenergy use makes particularly early thinnings profitable, which may incentivise forest managers to practice timely thinning and hereby increase the quality of the future forest stand, leading to a better assortment with higher construction/furniture timber shares. In the counterfactual situation, this kind of thinning is considered uncommercial, representing only costs for forest managers. While the specific long term effect on timber quality induced by e.g. timely thinning driven by bioenergy demand remains unknown, the use of nurse trees such as poplar and larch can increase the average carbon stock of up to 10-20% over the forest rotation under Danish conditions [46]. A 20% increase in forest carbon stock is modelled as an extreme case in the sensitivity analysis (Section 3.2.3).

As described above, indirect land use change can influence, negatively or positively, the forest carbon stocks and lead to higher levels of timber harvest with longer residence time (half-life 35 years), than other counterfactuals demonstrated here and also lead to positive substitution effects (see next section).

2.6.3 Product shift iWUC

When timber that could have been used for other wood products, due to increased bioenergy demand are used for energy, the supply of timber for wood products decreases. Consequently, the price of wood for products may increase, leading to decreasing wood consumption. In our model, and commonly in LCA, it is assumed that overall demand for goods and services e.g. buildings and furniture, at societal level is not affected by increased use of wood for energy [44]. Therefore, to supply an unchanged demand for buildings or furniture with decreased wood supply and hence increasing prices on wood, producers will shift to other products, such as concrete, steel, or plastic. Depending on price elasticities, a proportion of the demand for wood will shift to other products, with a lower price. Here we assumed that all demand not additionally supplied through iLUC (expansion of managed forest area) is shifted to other products such as steel, concrete or plastic i.e. full substitution. Such shifts, may lead to increased emissions as many of these products have higher supply chain emissions than wood [47]. The products that substitute wood can in some cases have emissions that are more than ten times higher than wood and in other cases the emissions are nearly the same or in few cases lower [48]. Commonly this is reported as a substitution factor (SF) that expresses the amount of fossil carbon savings as a factor of the amount of carbon in the wood product substitute:

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

where $C_{non\text{-}wood}$ and C_{wood} are the carbon emissions from the use of non-wood and wood alternatives and WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in wood and non-wood alternatives [47].

Leskinen, Cardellini, González-García, Hurmekoski, Sathre, Seppälä, Smyth, Stern and Verkerk [28] finds that the mean substitution factor for wood products is 1.3 for structural construction parts e.g. beams and wood frames, 1.6 for non-structural parts e.g. windows, floors, cladding and 1-1.5 for other products e.g. chemicals, packaging and furniture. Here we used a substitution factor of 1.4 for structural and non-structural parts, originating from sawn timber, 1.2 for panels and boards produced from industrial residues, and 1 for pulp and paper.

2.6.4 Biomass in different categories and counterfactuals

The biomass consumed by the Danish CHP and DH plants was categorized into five groups: harvest residues, non-forest, stems, industrial residues, and dedicated woody bioenergy crops. The counterfactual assumptions to bioenergy use are described below.

Harvest residues are biomass from tops and branches, which prior to the transition to renewables were left on site and burned or for decaying after a harvest or thinning operations. As the counterfactual for harvest residues, we assumed that 30% were burned directly on the forest floor with a half-life of 0.5 years and 70% was left in the forest for natural decay. All harvest residues are considered true residues in the current market situation and therefore we assumed that there were no indirect emissions for this type of biomass. With 30% being burned and 70% being left for decay, the mean half-life for harvest residues is 7.15 years. As a special case we demonstrated the situation where harvest residues are crushed after felling here leading to a decrease in the half-life to 5 years.

Non-forest biomass is a small category that includes municipal park waste, wood from removal of invasive species in nature areas, harvesting of shelterbelts etc. In the basic assumptions, we treated the biomass from this category as harvest residues piled in the forest for decay, with a mean half-life at 7.15 years.

Stems used for energy is a broader category which contains undersized stems, stems with rot, bend stems, and stems from non-merchantable tree species. For stems, we assumed that the alternative fate was to be felled and left on site during forest harvest (see assumptions on decay rates for stems in Table 2.1). For 90% of the stem biomass, we assumed that there was no commercial alternative use, i.e. resulting in no indirect emissions. However, the category can also contain stems that could have been used for pulp and paper or wood products, which leads to iLUC and/or iWUC emissions. We assumed that 10% of stem biomass leads to indirect emissions, with 5% attributed to iLUC emissions and 5% to iWUC emissions. This assumption is based on expert assessment building on the observed price structure of industrial round wood relative to wood for energy (Table 2.5).

In sensitivity analyses, we alternatively assumed stem biomass with no iLUC emissions and 5-20% negative and positive emissions from iLUC, i.e. changes in carbon stocks due to additional harvest and intensified forest management practices.

Industrial residues are mainly sawdust, bark, slabs, edgings, off-cuts, veneer clippings, sawmill and particleboard trimmings, planer shavings, and sander dust. Depending on the sawmill, and the type of residue, the alternative fate can be everything from burning or decaying on site to production of particleboards. We made the same assumptions on indirect emissions for industrial residues as for stem biomass: 5% leading to iLUC and 5% leading to iWUC.

Dedicated woody energy crops is biomass originating from dedicated bioenergy crops on agricultural land. The category was neglected as it represents less than 0.1% of the data material.

2.7 The temporal shift in carbon emissions

When forest bioenergy is produced, wood material is removed from the forest and combusted in an energy facility. In the absence of bioenergy production, the wood material would be left in the forest for natural decay, piled up and burned, used for other products, or not harvested at all. This results in a shift in timing of carbon emissions between bioenergy (instantaneous) and counterfactual situations (harvest residues left in the forest and forest products) (Figure 2.5). The difference in forest carbon stocks related to the shift in timing of carbon emissions between combustion in a CHP or DH facility and natural decay of wood in forests or as products is the principal determinant of the carbon emissions related to wood used for bioenergy.

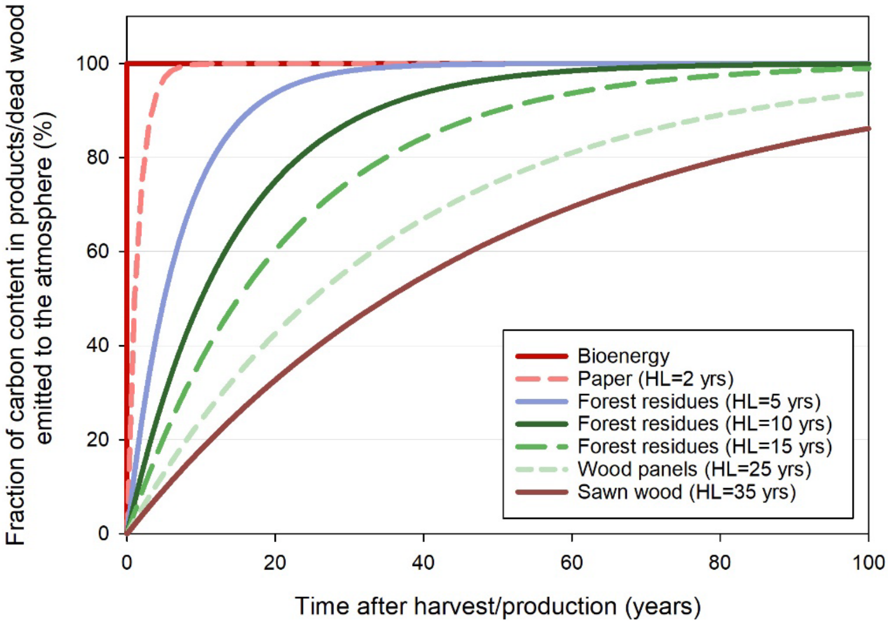


Figure 2.5. Time dependent carbon emissions from different counterfactual fates of wood resources compared to immediate carbon emissions through bioenergy. HL = half-life.

Estimating cumulative emissions for multi-pulse curves in a specific year requires detailed information of historical bioenergy use and historical counterfactuals to determine the net impact on the forest carbon stocks. In this study, all model runs were initiated in 2020, disregarding historical emissions from biomass use before 2020. As such, the cumulative emissions (multi-pulse) presented here are not representing a specific year but was merely used to calculate the level of cumulative biogenic emissions from a given level of production with given counterfactuals of the wood used and the timeframe from initiation to steady state.

2.8 Calculating Absolute Global Warming Potential

The model presented in the previous sections calculates the CO_2 emissions from use of bioenergy from the Danish DH and CHP plants and estimates the 2020 net CO_2 emissions. For the hypothetical scenario of future annual emissions being similar to the 2020 emissions, we calculated the cumulated net emissions. CO_2, however, will not last forever in the atmosphere, as the earth carbon cycle includes more factors that just emissions and forest carbon uptake. These factors are dominated by oceanic CO_2 absorption, while the remainder is absorbed by the land, including other processes (e.g. see Joos*, et al.* [49]). Such uptake is denoted atmospheric decay and can be described with an impulse response function (IRF), which determines the atmospheric decay of the cumulative net CO_2 emissions from our model. We used the parametrization of the IRF from [49] mean scenario. The IRF is hereafter multiplied with radiative efficiency R of CO2 here 0.925 W $m^{-2}kg^{-1}$ CO_2 also from [49] and integrated for t=0-100 to get the AGWP curve. The AGWP curve is thus expressed in m W m^{-2}.

2.9 Analysis of different types of biomass use

The analyses were conducted in four steps:

1. In the first part, we present the basic data forming the basis for constructing the weighted average wood chip and wood pellet data, based on the data provided by the utilities.
2. In the second part of the analyses, we estimate the CO_2 emissions and the net CO2 emission dynamics from a single year use of bioenergy, where we focus on emissions from the different fuel types (wood chips and wood pellets), different feedstocks (harvest residues, stems, industrial residues etc.), different transport distances, and extreme scenarios. The extreme scenarios include one where all wood is supplied with timber suited for lumber production and one where all biomass was stems from nurse trees leading to 20% increase in the forest carbon stock. Subsequently we calculated the time dependent CO_2 emission coefficients reported in kg CO_2 GJ^{-1}. Finally, we aggregate the single pulse emissions to include all emissions from wood chips and wood pellets used in DH and CHP in Denmark.
3. In part three, we calculate hypothetical cumulative net CO_2 emissions assuming a continuation of the current use of wood for energy over a 100-year period. As emissions from transport, processing etc. will change over time, we focus only on biogenic emissions and dynamics.
4. In the final part of the analyses, we estimated the total cumulative net CO_2 emissions of the current bioenergy consumption in the Danish transformation sector and calculated the climate effect, expressed as "Absolute global warming potential" in a 20 and 100 year time perspective (AGWP(20) and AGWP(100)).

3 Results

3.1 The data basis for the typical wood chip and wood pellet consumption

In 2020, the total primary energy supply (TPES) of solid biomass, excluding organic waste, was 125.3 PJ, out of which 38% was wood pellets and 29% wood chips (Table 3.1). Of the 125.3 PJ, 34.4 PJ was wood chips and 29.8 PJ of wood pellets used in the transformation sector to produce heat and electricity. These production data were used in the subsequent analyses.

Table 3.1. Consumption of biomass for energy from different types in 2020 [6].

	Wood pellets	Wood chips	Other solid biomass	Total
Total primary energy supply (PJ)	47.6	36.7	41.0	125.3
Share (%)	38	29	33	100
Supply for CHP and DH	29.8	34.4		

Feedstock for wood chips production is mostly stems, harvest residues, and a small fraction of industrial residues (probably shavings). Wood pellets are based primarily on industrial residues (sawdust etc.), but also on stems and a small amount of harvest residues (Table 3.2).

Table 3.2. Feedstock for wood chips and wood pellet production as reported by utility companies for 2020. The distribution observed is assumed representative of the total consumption of wood for producing district heat and electricity (64.3 PJ).

Fuel type	Stems	Harvest residues	Industrial residues
		%	
Wood chips	52	39	9
Wood pellets	44	2	53
Weighted average	47	15	37

Wood chips mostly come from Denmark and the Baltic States, where wood pellets were sourced more broadly within the Baltic countries followed by USA and Denmark being the prime sourcing countries (Table 3.3). Of the total Danish consumption in 2020, 51% of wood chips were domestically sourced compared to 4% of wood pellets [6].

Table 3.3. Origin of wood chips and wood pellets in the model data and for Denmark in total. Model data from utility companies. Totals are based on official trade statistics for 2020 (www.statistikbanken.dk) table KN8Y, CN numbers 44012100 and 44012200 for wood chips and 44013100 for wood pellets.

Country	Share wood chips (Our data)	Share wood pellets (Our data)	Wood chips (total 2020)	Wood pellets (total 2020)
	%			
Denmark	29	8	51	4
Baltic States	38	61	10	47
Belarus	0	3	0	<0.01
Russia	1	6	2	15
Norway	6	2	10	1
Germany	9	3	12	3
USA	4	11	<0.01	6
Portugal	1	2	0	8
France	3	1	<0.01	<0.01
Canada	1	2	0	2
Brazil	7	0		
Other	1		16	14
Total	100	100	100	100

3.2 CO_2 dynamics of a single year's biomass use

3.2.1 Wood chips

A single year use of wood chips with a yearly production of 34.4 PJ implies an emission of 3.3-3.5 Mt CO_2 in year one. However, depending on the counterfactual of the wood used for energy production, the CO_2 is recaptured in the forest carbon stocks, from where it was removed at different rates (5-100 years) (Figure 3.1). 100 years after combustion, CO_2 equivalent to all biomass sources, harvest residues and stems are recaptured in the forest carbon stock. CO_2 emissions do not converge towards zero, as there are fossil emissions related to forest operations, transport and iWUC.

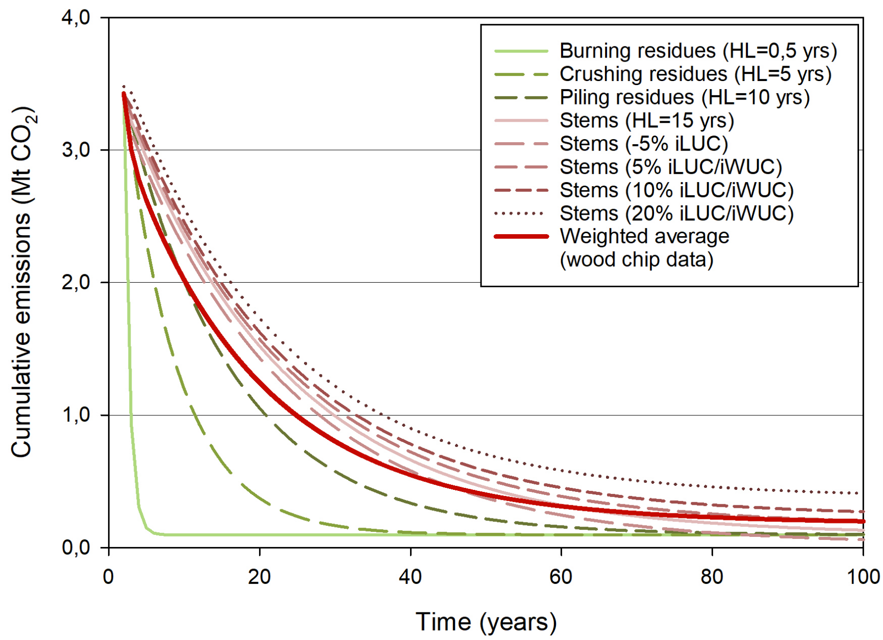


Figure 3.1. Cumulative emissions for one-year consumption of wood chips for energy production as in 2020 in Denmark. The number in the bracket is the half-life of the specific fuel source with a specific counterfactual for one year's production of 34.4 PJ and for the "weighted average wood chip data".

For wood chips, the initial emissions are higher than coal due to a higher energy density of the coal, but within few years, emissions are lower for the same energy production with coal due to the recapturing of CO_2 in forests (Table 3.4). After 30 years, the emissions are 3-39 kg CO_2/GJ, where after 100 years emissions are 3-14 kg CO_2/GJ. Comparable CO_2 emissions from coal and natural gas would be 107 and 65 kg CO_2/GJ, regardless of the time perspective.

Table 3.4. CO_2 emissions (kg GJ^{-1}) for different fuel sources used for wood chips and for the weighted average.

Years after consumption	1	10	20	30	50	70	100
				kg GJ^{-1}			
Burning stems or residues (HL=0.5 yrs)	115.0	3.2	3.2	3.2	3.2	3.2	3.2
Chrushed residues (HL=5 yrs)	115.0	35.4	11.3	5.2	3.3	3.2	3.2
Piled residues (HL=10 yrs)	115.0	63.1	33.1	18.2	7.0	4.1	3.3
Stems (-5% iLUC)	113.0	75.0	48.2	31.3	14.0	7.1	3.7
Stems (HL=15 yrs)	115.0	75.6	48.8	31.9	14.6	7.7	4.4
Stems (5% iLUC)	115.5	77.3	50.6	33.8	16.7	10.0	6.7
Stems (10% iLUC)	116.0	79.0	52.4	35.7	18.9	12.2	9.1
Stems (20% iLUC)	116.7	82.5	55.9	39.5	23.1	16.7	13.7
Weighted average	115.0	64.5	39.8	25.8	13.0	8.6	6.6
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

3.2.2 Sensitivity analysis on transport distances

Transport accounted for 1-7% of the total net CO_2 emission in year one and the location of sourcing influenced emissions. Assessment of the sensitivity on transport distances for the weighted average supply case found that with sourcing from Denmark, transport accounts for 1% of the emissions in the year of combustion. Correspondingly, with sourcing from the Baltic States or USA, transport accounted for 2 % and 7% respectively (Figure 3.2). Figures for the share of emissions attributed to transport also applies for wood pellets and for the 2020 mix of wood pellets and wood chips.

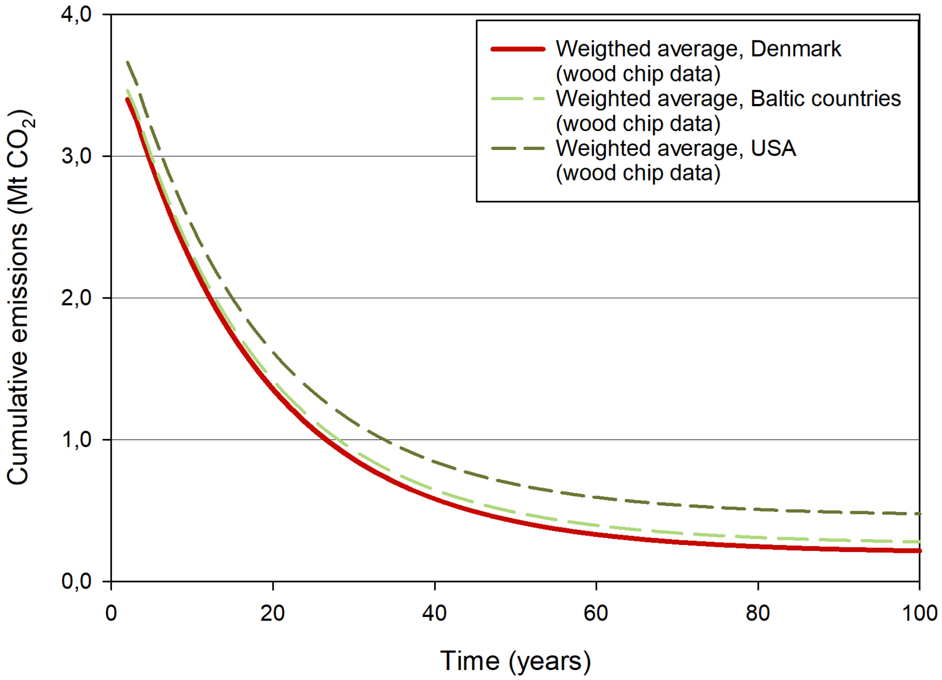


Figure 3.2. Single pulse CO_2 emissions for the weighted average wood chip data producing 34.4 PJ, with current biomass fuel mix sources in different locations. Emissions for transport are similar for wood pellets and 2020 fuel mix.

In year 100, emissions from biomass sourced in USA are twice the emissions than biomass sources in DK and Baltic States, as biogenic emissions at that point in time are recaptured in the forest carbon stock.

3.2.3 Sensitivity analysis with extreme scenarios

While our data and the current market situation indicated that nearly all biomass used in 2020 originates from low-grade stems, harvest residues or industrial residues, we included analyses of extreme scenarios. One in which saw logs are used for bioenergy and one where bioenergy demand incentivises forest managers to grow and harvest nurse crops as bioenergy feedstock.

Using saw logs for bioenergy will lead to much higher CO_2 emissions than any other scenario, both due to the longer half-life of lumber products (35 years) and due to the indirect market mediated fossil emissions from decreasing the supply of lumber that leads to a shift to other products (Figure 3.3, Table 3.5). On the other hand, if the bioenergy demand incentivises forest managers to grow and harvest nurse crops as bioenergy feedstock this would lead to an increased forest carbon stock (here 20%) compared to traditional forest management, which decreases net CO_2 emissions and after about 50 years lead to negative emissions.

The results demonstrated in Figure 3.3 and Table 3.5 are considered hypothetical extremes aimed to frame the outcome space of single pulse emission curves from Danish wood chips use.

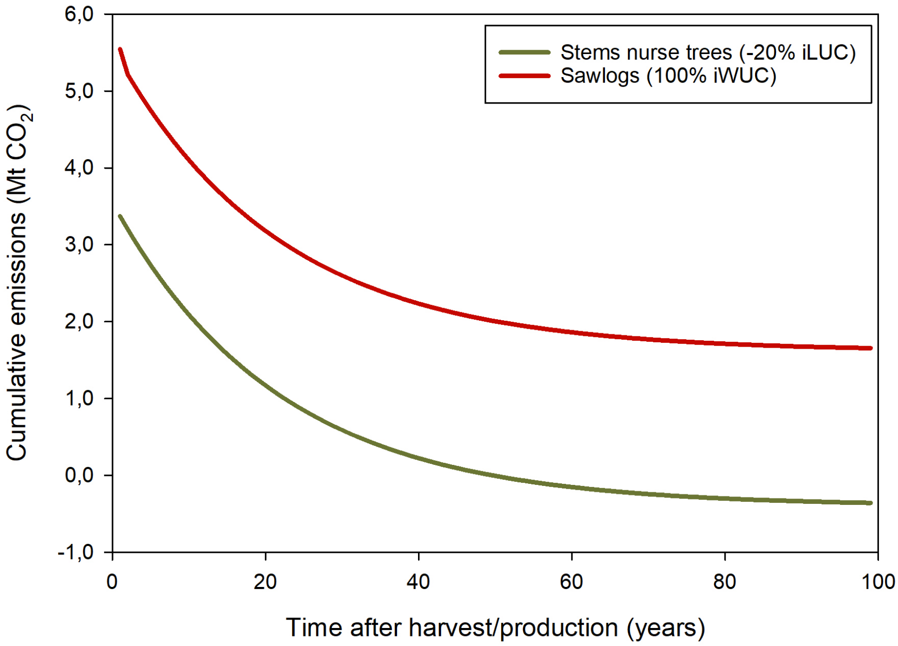


Figure 3.3. Extreme scenarios single pulse emissions, where either saw logs or stems from nurse trees are used for the entire wood chip production (34.4 PJ), respectively.

Table 3.5. CO_2 emissions for nurse tree stems that increase carbon stock on landscape level by 20% and sawlogs used for wood chips and for the typical wood chip plant. Negative emissions origin from a general increase in forest growing stock owing to the use of nurse trees.

Years after consumption	1	10	20	30	50	70	100
	kg GJ^{-1}						
Nurse tree stems: Forest carbon +20%	98.10	60.77	33.98	17.10	-0.22	-7.10	-10.44
Sawlogs 100% iWUC	161.3	119.3	92.5	75.7	58.3	51.5	48.1

3.2.4 Wood pellets

For wood pellets, the picture is similar to that of wood chips. As for wood chips, the emissions converge towards up-stream fossil process and transport emissions within 40 to 80 years (Figure 3.4).

CO_2 emissions per GJ from wood pellets are not much different from wood chips in year one although the use of fuel for drying, the longer transport distance, and the larger proportion of wood carrying iLUC/iWUC emissions, leads to slightly higher emissions (Table 3.6).

In a 100-year perspective, emissions from the current biomass use for wood chips and wood pellets, are approximately 6-10% and 9-16% of the emissions of coal and natural gas respectively.

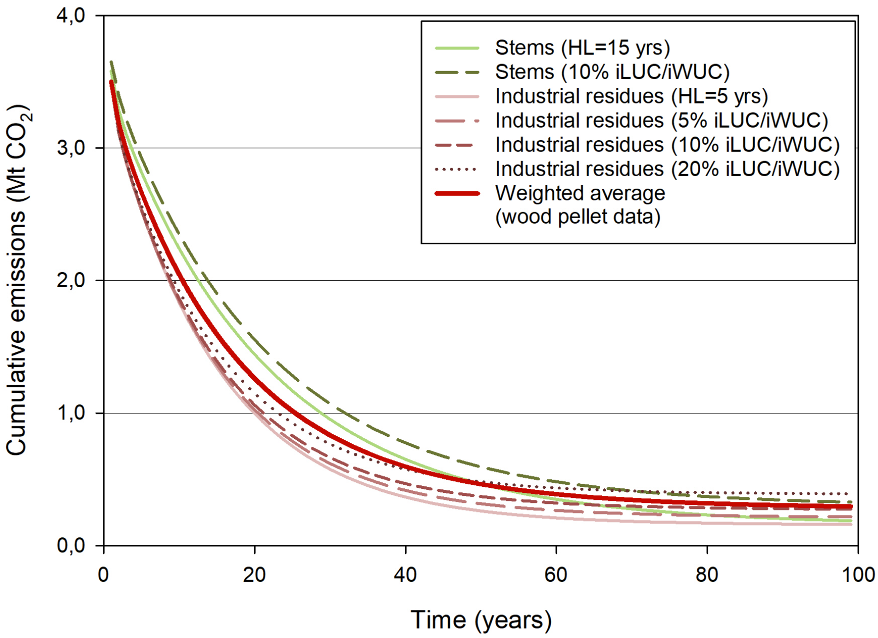


Figure 3.4. Cumulative net CO_2 emissions of a single year use of wood pellets, with a consumption of 29.9 PJ of wood pellets, for different biomass sources and for the current biomass sourcing as described for the "weighted average wood pellet data".

Table 3.6. CO_2 emissions coefficients (kg/GJ) for different fuel sources used for wood pellets and for the typical wood pellet plant based on best available data.

Years after consumption	1	10	20	30	50	70	100
				kg GJ^{-1}			
Stems (HL: 15)	120	75.3	48.4	32	15.6	9.3	6.3
Stems (10% iLUC)	123	78.9	52.1	35.9	19.9	13.8	11
Industrial residues (HL: 5)	119	61.5	33.4	19.3	8.8	6.1	5.4
Industrial residues 5% iLUC	120	61.9	34.4	20.7	10.6	8	7.3
Industrial residues 10% iLUC	121	62.5	35.6	22.3	12.4	9.9	9.2
Industrial residues 20% iLUC	122	64.4	38.5	25.7	16.1	13.8	13.1
Weighted average of wood pellet data	**122**	**68.1**	**42.3**	**28.1**	**15.7**	**11.6**	**10**
Coal	107.1	107.1	107.1	107.1	107.1	107.1	107.1
Natural gas	65.4	65.4	65.4	65.4	65.4	65.4	65.4

3.2.5 National wood chip and wood pellet consumption emissions

For the entire consumption of wood pellets and wood chips used in the Danish transformation sector in 2020, the emissions in year 1 are app. 7 million tons CO_2 (Figure 3.5). Net emissions, however, rapidly decline over the first 40 years after consumption and converge towards the fossil process emissions.

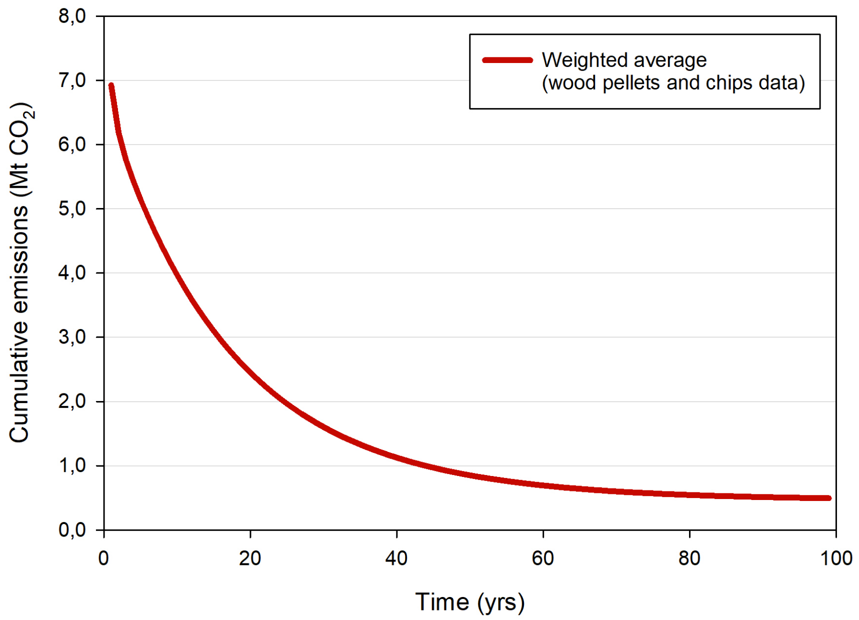


Figure 3.5. Weighted average consumption of wood pellets and wood chips in Danish DH and CHP.

The recapturing of CO_2 is reflected in the change in emission profile over time. Emissions are lower than coal already few years after combustion, while for natural gas the emissions are higher for about 10 years but lower hereafter (Figure 3.6).

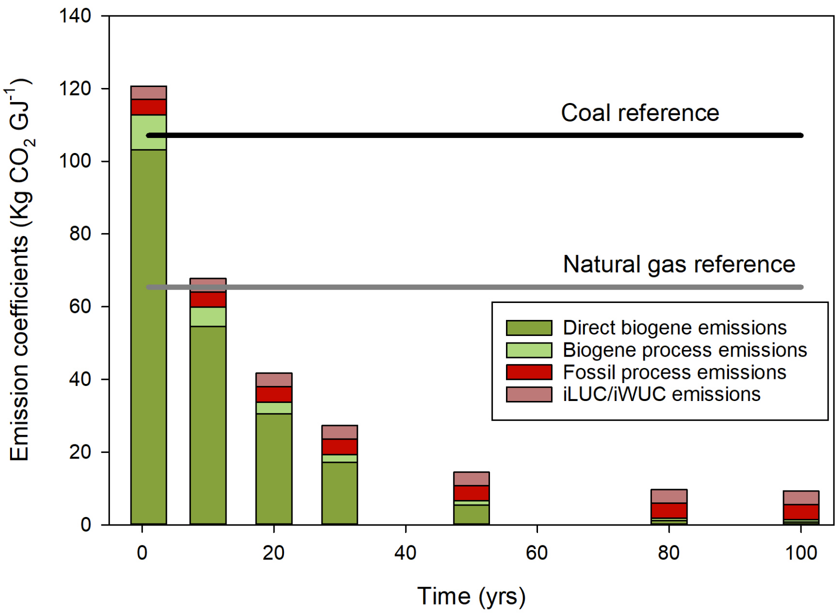


Figure 3.6. Emission coefficients for the Danish wood chips and wood pellet consumption for district heat and electricity and for fossil energy sources (coal and natural gas) over time. Importantly, the biogenic emissions are reduced over time due to recapture of the emitted CO_2.

3.3 Cumulative biogenic CO_2 emissions with a continuous production in 100 years

3.3.1 Wood chips

Assuming a 100-year continuation of the current use of wood chips at 34.4 PJ, the cumulative biogenic CO_2 emissions increase sharply in the first years and level out over time. For residues, where the counterfactual is burning in the forest, emissions level out after a few years, while it takes longer time for stems and other slow decaying sources (Figure 3.7). For the fuel sources with iLUC/iWUC, the emissions continue to increase even after 100 years.

The outcome space after 100 years of continued use of wood chips range between 8 and 100 million tons CO_2, depending on the counterfactual assumptions. The emission profile of the weighted average wood chip consumption finds itself in the center of the outcome space of the different scenarios at app. 66 million tons CO_2 after 100 years. The increase in cumulative emissions for the weighted average wood chip data level out after 60 years (Figure 3.7). For comparison, a similar energy production with coal would have emitted 340 million tons CO_2 over a 100-year period.

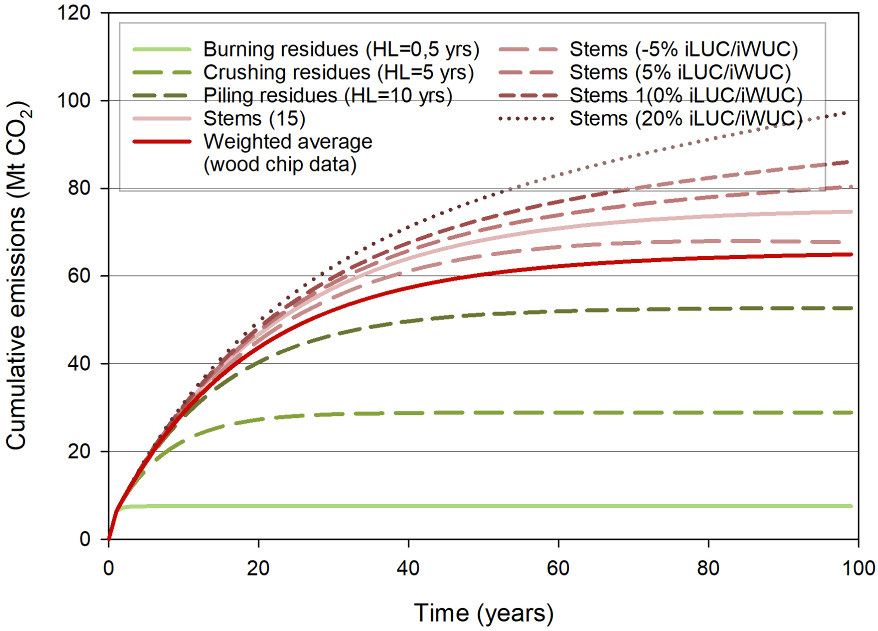


Figure 3.7. Cumulative CO_2 emissions for wood chips over 100 years for different biomass sources and the basic data, with a continued production of 34.4 PJ.

3.3.2 Wood pellets

As for the wood chips, the cumulative biogenic CO_2 emissions are lower for the fast-decaying biomass sources (industrial residues) with a half-life of 5 years and no iLUC/iWUC than for slow decaying sources (stems) with large amounts of iLUC/iWUC burdened biomass feedstock (Figure 3.8).

The outcome after 100 years consumption range between 50 and 85 million tons CO_2. The cumulative emissions for the weighted wood pellet data, ends in the center of the outcome space of the different scenarios and after 100 years the emissions are app. 70 million tons CO_2 (Figure 3.8).

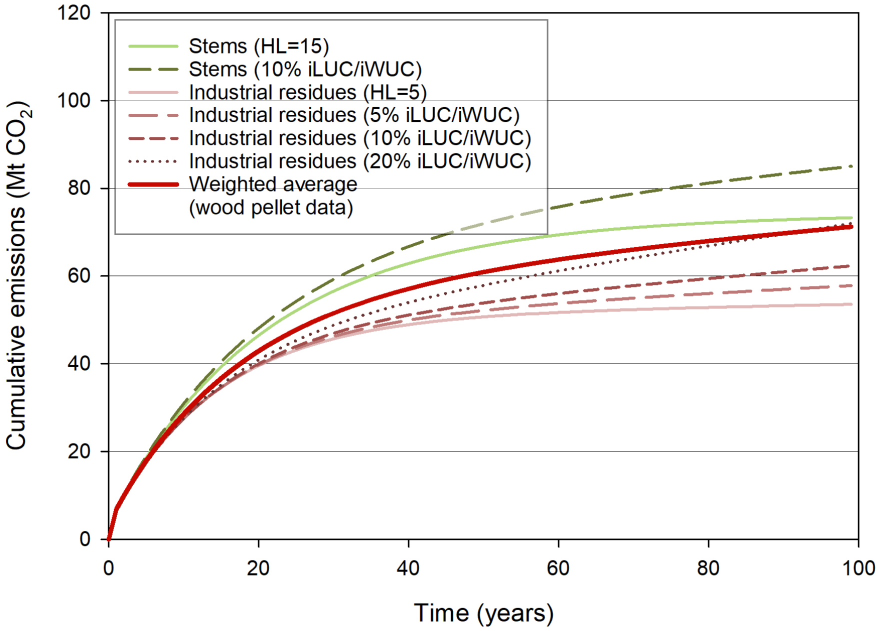


Figure 3.8. Cumulative CO_2 emissions for wood pellets with a continued use over 100 years for different biomass sources and the basic data with a production of 29.9. PJ.

3.4 Time independent biogenic CO_2 emissions of current biomass use

The biogenic carbon emissions for a temporary use of biomass for energy decrease to zero in an infinite time perspective unless the biomass demand leads to permanent (also in an infinite time perspective) degradation of forest carbon stocks. Obviously, there will be fossil emissions related to forest operations, transport, plant construction, process, and iWUC, but these will change/decrease as society moves towards a fossil free future.

With continued use of biomass for energy there will be a permanent increased level of CO_2 in the atmosphere, which converges asymptotically towards a steady state that depends on the counterfactual of the biomass source (Figure 3.9). With the 2020 consumption in the Danish transformation sector of 64.3 PJ, where wood biomass is sourced from true residues with a half-life of 5 years, biogenic CO_2 emissions stabilize round 62 million tons. Correspondingly, for stem biomass with a half-life of 15 years, biogenic CO_2 emissions reach 160 million tons after 100 years. Continuation of the current sourcing pattern of biomass lead to a total cumulative biogenic emission of app. 128 million tons CO_2. Total biogenic emissions can be expressed as an absolute biogenic emission factor that is a fraction of yearly production (64.3 PJ), which here is ranging from 0.94 tons CO_2/GJ for residues to 2.48 tons CO_2/GJ biomass for stems (Table 3.7).

For comparison, the absolute cumulative CO_2 emissions from coal and natural gas, and any other fossil resource would be infinite.

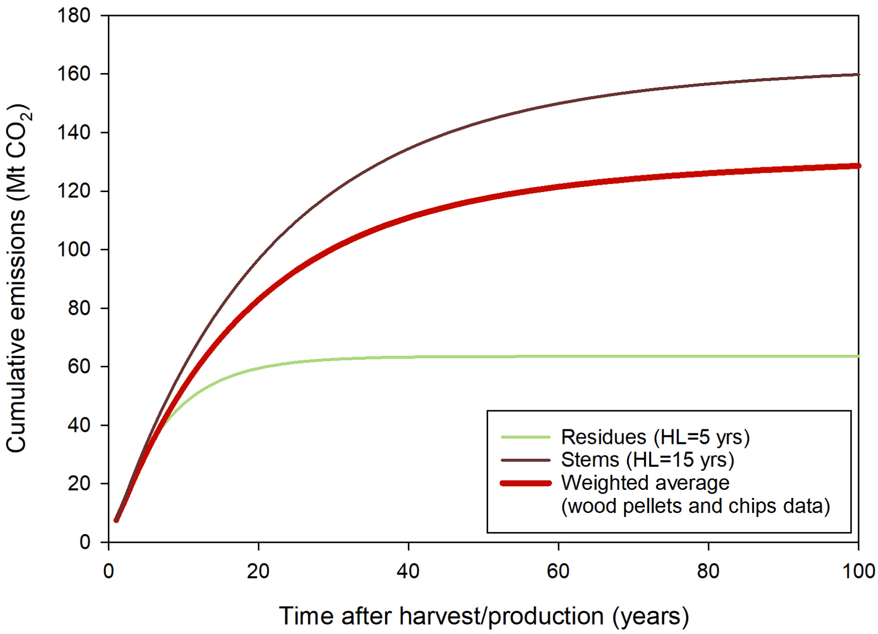


Figure 3.9. Total biogenic CO_2 emissions for an infinitely continued annual consumption of 34.4 PJ of wood chips and 29.9 PJ of wood pellets for heat and electricity production.

Table 3.7. Total cumulative biogenic CO_2 emissions from an infinite continuation of a yearly biomass consumption of 64.4 PJ.

	Stems (HL=15 yrs)	Residues (HL=5 yrs)	Weighted average
Total biogenic emissions (million tons CO^2)	160	62	128
Total biogenic emissions factor (Tons CO^2/GJ)	2.48	0.94	1.98

3.4.1 Climate impact from biogenic emissions from Danish biomass use in DH and CHP

The absolute global warming potential rises rapidly the first 15 years after initiation for both biomass, coal, and natural gas. For all energy sources, the increase in AGWP regresses due to the atmospheric decay of the emitted CO_2 (Figure 3.10). While AGWP keeps increasing at different speeds for coal and natural gas, the increase in biomass the AGWP regresses even more due to uptake of CO_2 in the forests. After year 20, there are no additional net climate effects from the bioenergy scenario and AGWP is stable although a slight decrease can be spotted. AGWP(20) is 50, 80 and 60 mW/m^2 for biomass, coal and natural gas respectively and AGWP(100) is 45, 320 and 230 mW/m^2 for biomass, coal and natural gas.

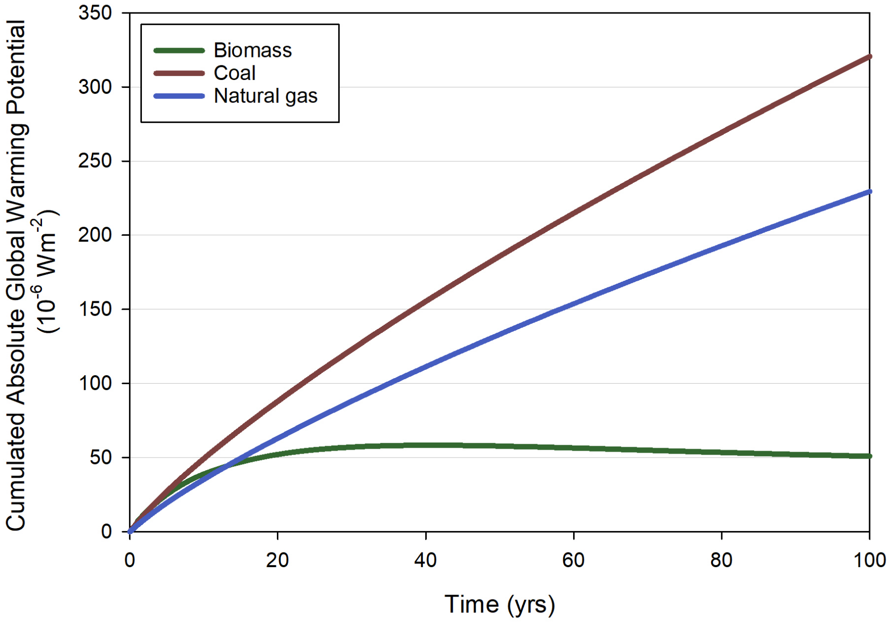


Figure 3.10. Potential absolute global warming for a continued use of coal, natural gas, or biomass at the level of the 2020 consumption derived from the model presented here. The impulse response function and radiative efficiency follows the mean scenario in [49].

4 Discussion

In summary, the single pulse emission analyses demonstrated that regardless of the biomass feedstock used for energy, initial biogenic emissions were offset 2-80 years after combustion. The counterfactual, natural or product decay rates are the main determinants of the speed of the offset. iLUC/iWUC and other fossil process emissions determine the fraction of emissions not being offset by forest carbon sequestration. Moreover, we demonstrated that transport accounts for 1-7% of total emissions in year one and that these emissions, with the current use of fossil fuels, are not offset. In the extreme cases, i.e. if saw logs were used were used for energy or feedstock was solely sourced from nurse trees, cumulative single pulse emissions stabilized on a higher (saw logs) or lower negative level (nurse trees) compared to the weighted average. Wood chips and wood pellets did not differ significantly in emissions. Apparent differences are attributable to sourcing strategies and transport distances.

For the cumulative biogenic emissions, which should be interpreted as the impact on the forest carbon stock of bioenergy harvest, we demonstrated that the emissions stabilized within a few years if the counterfactual was burning the biomass feedstock on site to app. 80 years if counterfactual was stems. Common for all bioenergy sources was, however, that a stabilization occurred in this time span only if there was no iLUC (continued reduction in forest carbon stock) or iWUC (fossil emissions from production of other products). In the cases with iLUC/iWUC cumulative emissions kept rising after 100 years.

In absolute terms the biogenic emissions stabilized at app. 128 million tons CO_2 for a continuation of the current wood biomass use with a range between 62 and 160 million tons CO_2. These emissions lead to an AGWP(20) at 50, 80 and 60 mW/m^2 for biomass, coal, and natural gas respectively and AGWP(100) is 45, 320 and 230 mW/m^2 for biomass, coal, and natural gas. The total biogenic emissions correspond to the total decrease in forest carbon stocks resulting from the harvesting of wood for materials and energy and may consequently be recaptured by the forests in the event of other materials and energy forms being available in the future.

4.1 Data

The data provided by the utilities covered 96% of the wood pellet and 69% of wood chip use for district heat and combined heat and power in Denmark in 2020 and illustrated a wide range of different sourcing strategies. For wood chips, the mass not covered by utility data, is used on smaller district heating plants, which are numerous, but only a few provided data for the analysis. This might explain why our data material differs from the national consumption provided in Table 3.3, especially regarding our data material having a smaller part of data from Denmark than the common data.

Our analysis did not include emissions associated with the construction of processing plants and infrastructure. This was based on a lack of plant specific data but also on a notion that the emissions associated with building of the plants included in the analysis as a “sunk cost” and that comparisons with emission profiles for coal and gas (e.g. Figure 3.6) similarly excluded the much similar construction emission. Not including the emissions associated with processing facilities in principle renders the analyses unsuitable for comparison with energy forms with deviating emission profiles, such as wind energy. However, previous studies have shown that construction and infrastructure emissions are a negligible part of the full life cycle emissions of a power plant [8,9].

4.2 Counterfactuals

Roughly, counterfactuals can be divided into two categories. One where the wood has no other use, where the counterfactual assumption is burning on site or natural decay, only affecting the dead wood forest carbon pool (true residues). The second category is where the bioenergy use directly or indirectly drives the living forest carbon pool up or down (iLUC) or affects adjacent market emissions (iWUC) (denoted indirect emissions).

4.2.1 Residue decay rates

While the decay rate of burning wood is relatively simple and certain to determine i.e. most of the carbon is released few years after felling, natural decay rates are more uncertain. In the present study we based our assumptions on natural decay rates from scientific literature covering a wide geographical range [19-21]. However, decay rates of wood depend on many factors and literature on the topic is relatively scarce. Factors determining decay rates of wood left for natural decay includes temperature, precipitation, soil type and moisture regime, particle size and soil contact. Temperature differences are reflected in the literature used but several other factors affects decay rates. For example decay rates are faster in alkaline, well-drained soils and slower in acidic wet soils or where the wood has little soil contact and a small surface area relative to volume. We had no data on decay rates at specific sourcing locations, but we assess that the span presented here likely cover most of the situations experienced for the Danish utilities. However, we emphasize that more research efforts are put to this topic as estimates on CO_2 emissions from use of biomass will be significantly improved by this.

4.2.2 Indirect emissions

Biomass is a scarce resource and the transition from fossil fuels to bioenergy is implicitly associated with a reduction of biomass available for alternative uses. Often indirect effects contribute substantially to the bioenergy supply chain GHG emissions [50-53]. At the same time, quantification of indirect effects builds on a weak scientific foundation [54,55]. While there is scientific consensus on the existence of indirect GHG emissions related to bioenergy production, the quantification of indirect GHG emissions remains controversial and calls for further research.

Additionally, there is little empirical evidence to build assumptions on what fraction of a specific biomass assortment or a specific supply chain generates indirect emissions. The 10% of stems generating indirect effects as assumed in this study represents quality timber, with a product half-life of 35 years [27] and a substitution factor of 1.4 [28].

Historical wood prices have been shown to fluctuate and although prices of different assortments are highly correlated, the ranking between lower grade assortments are commonly observed to shift [56]. For example, the net prices of pulp, paper, and wood fuel assortments can overlap and may with increased pressure on the bioenergy market, favour the sale of wood in pulp and paper quality for fuel purposes. However, the half-life of paper and cardboard is 2 years [27], 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. The net price difference between wood fuel assortment and timber assortments remains large and hence there is little risk that changed bioenergy demand will affect the market for sawn timber severely.

Our analysis largely rests on the assumption that forestry practices are based on an incentive to produce higher value timber rather than energy. This assumption is based on both the current price structure and the costs associated with procuring bioenergy from typically small trees or heterogeneous materials such as large tree crowns. The consequence of this assumption is that emissions are not burdened with an additional iLUC owing to a changed forest biomass carbon stock. With changes in the price structure such as increasing prices for bioenergy, this assumption may no longer be valid. Similarly, with increasing use of biomass for various products through innovative use of forest resources, the proportion of true residues that may be burdened with iLUC or iWUC will likely grow along with increased market pressure. Such, yet not realized, development, may in the future change the conclusions regarding climate effects of bioenergy reached in this study.

Greater demand and increasing prices for bioenergy may make it profitable to harvest of biomass in forests with poor timber quality in remote sites, especially in countries where forests are managed extensively, relying on natural regeneration with no tending after final harvest. Such forestry practices reduce post-felling costs and may make it profitable to harvest low quality/price assortments, which will increase the risk of iLUC through additional harvest. Conversely, in intensively managed forests with higher costs (planting, nurse trees and tending) after interventions, the low price of bioenergy compared with other assortments may make it less profitable to harvest low quality compartments and reduce the risk of iLUC. In our data, most of the biomass originates from northern European countries e.g., Scandinavia, the Baltic countries, and Germany, where most forests are intensively managed. Moreover, the carbon stock in most European forests has been increasing over several decades or centuries, but also over the latest decades, where the demand for bioenergy has increased [57,58], indicating that overutilization of the forest resource is limited. Therefore, we believe that the risk of iLUC from additional harvest has been limited in most of Europe for the period in scope, and that our assumption that 10% (5-20%) of the stems and industrial residues are associated with iLUC emissions is reasonable. In other countries, with large extensively managed forest areas, where regulation is poor or absent, with high levels of corruption and poorly developed forest sectors, there is a much larger risk of iLUC, especially in the form of additional harvest. We recommend that the issues of iWUC and iLUC for bioenergy receive much more scientific attention in the future.

4.3 Methodological issues

4.3.1 Metrics

The outcome and conclusions of analyses as the one presented here are dependent on the choice of performance metric [59]. Climate impact studies of wood for energy usually account for CO_2 emissions and removals and identify the so-called carbon debt through a comparison with a counterfactual reference system [60,61]. This approach is based on a simple sum of fluxes and does not consider any direct physical impact or climate system response. Other metrics, global warming potential (GWP) and global temperature change potential (GTP) link the sum of carbon fluxes with the fate of greenhouse gases in the atmosphere or the response of the climate system to changes in the atmospheric energy balance caused by changes in the atmospheric concentration of greenhouse gases. Generally, moving down the cause-effect chain of carbon fluxes to the atmosphere increase the policy and societal relevance of performance metrics, but at the same time scientific certainty is sacrificed [59].

Assessments of a carbon debt of transitions from fossil to wood fuel in Denmark have been published in later years [1,2,62]. This analysis does not estimate a carbon debt of wood bioenergy but calculate a carbon footprint based on a simple sum of carbon fluxes between the forest bioenergy system and its surroundings. It further applies a GWP based metric in terms of the absolute global warming potential (AGWP) linking the annual net carbon emissions from the bioenergy system to the decay of CO_2 in the atmosphere through its impulse response function (IRF). Recent papers also use the AGWP metric [63-69]

4.4 Household and industry use of wood pellets, wood chips and firewood

The period 1985 to 2020 has seen an increased use of solid wood biomass for energy also outside the transformation sector. In the consumption sector, including manufacturing industry, public and private service, and family housing, 10 PJ of firewood was used in 1985 increasing to 35 PJ of firewood, wood chips and wood pellets in 2020 (Figure 4.1). Albeit wood chips are mainly used in manufacturing industries; firewood exclusively and wood pellets mainly in family houses, the period has also seen a shift in composition of solid wood used for energy in the consumption sector. Where firewood was dominant in 1985, wood pellets now make up 51% of the consumption and firewood 43%.

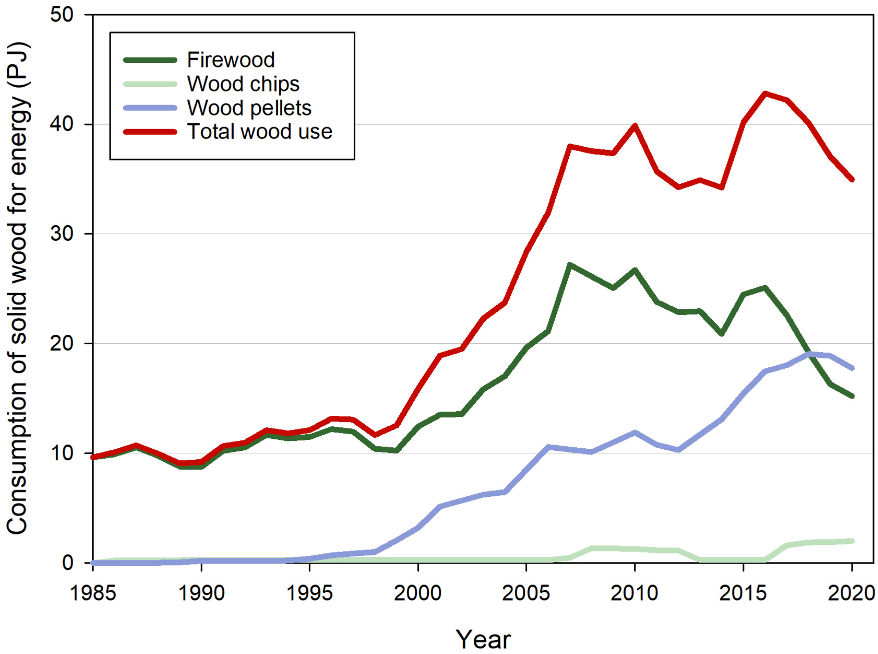


Figure 4.1. Use of solid wood for energy 1985-2020 in the consumption sector (agriculture, forestry, manufacturing, private and public service, and households). Based on data from [6]

The use of solid wood biomass in the consumption sector has not been included quantitatively in this analysis due to lack of data. Only with the entry into force 30 June 2021 of the so-called handbook executive order (Bekendtgørelse om Håndbog om opfyldelse af bæredygtighedskrav og krav til besparelse af drivhusgasemissioner for biomassebrændsler til energiformål) [70], which also include Danish producers and importers of firewood and wood pellets, data on origin can be expected in the future.

For firewood, 90% of the supply in 2020 was of Danish origin. An assessment from 2016 found that 14% of the firewood used in 2015 came directly from the forest, 48% came from private gardens, hedgerows and windbreaks, 18% from outlets other than forests. As such, there is little information available on the supply chain of firewood and on the forest and other land management behind the supply of firewood.

For wood pellets, 37% of the supply in 2020 was used in the consumption sector. It is assumed that the consumption sector to some extent is supplied through un-accounted import and trade across the German-Danish border [71]. It is not known to what extent and how origins and supply chains of wood pellets to the consumption sector differ from those supplying the transformation sector.

In 2020, 5% of the total supply of wood chips was used in the consumption sector, and 6% of solid wood biomass used in that sector was wood chips [6]. Over the period 1985-2020, wood chips has made up a minor part of the use of solid wood biomass in the consumption sector, on average 2%. As wood chips are primarily used in manufacturing industries and in public service, we assume they are sourced locally. There is, however, no information is available on the underlying resources (harvest or industrial residues, or stems) for this resource.

The emissions from firewood cannot be derived from the figures presented in this report as conversion efficiencies are variable and data availability is scarce. For wood chips and wood pellets in private consumption, however, the emissions coefficients will be similar to what we derived here as conversion efficiencies are only slightly lower than in DH and CHP plants. As such, emissions coefficients for wood pellets and chips in the consumption sector may be slightly higher than for DH and CHP. As for the pellets and chips analyzed here the counterfactual, transport distances and indirect emissions will affect the actual net emissions.

4.5 Perspectives

In this study, we demonstrated the outcome space of CO_2 emissions and climate impact from the current biomass use in DH and CHP plants in Denmark and in a hypothetical *ceteris paribus* projection of the current bioenergy production. In the future, however, there are several routes the use of bioenergy can take, which will have substantial effects on CO_2 emissions.

Conceptually there are four pathways to go (Figure 4.2). The first is to go back to fossil energy source. The second is to continue with business as usual (BAU). Contrary, the Danish society can end bioenergy use in 2030 and reduce consumption accordingly. Finally, the society can invest in carbon capture and storage (CCS) facilities on bioenergy plants.

The four different pathways show widely different patterns of CO_2 emissions to the atmosphere. Not surprisingly, a shift back to fossil resources results in long-term elevated emissions compared to the current energy system and likely to further climate change. Oppositely, abandoning bioenergy entirely in combination with widespread reductions in consumption or conversion to other emission friendly technologies (e.g. solar and wind power) reduce emissions compared to the current energy system resulting in near-zero emissions. Finally, maintaining current bioenergy consumption but in combination with CCS technologies leads to large negative emissions. The latter scenario corresponds well with the recommendations of the IPCC on pathways to reach the target of keeping global warming below 1.5° relative to pre-industrial levels [72].

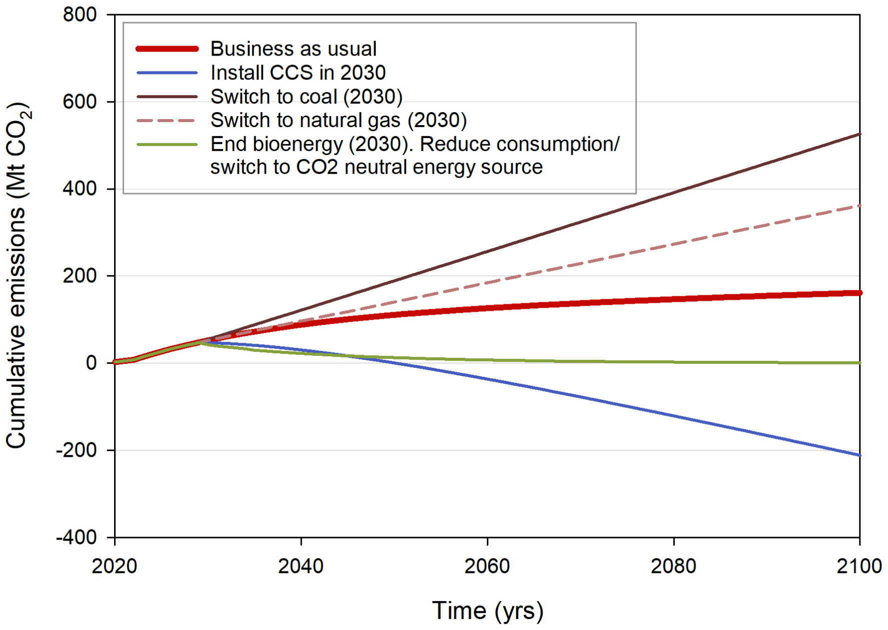


Figure 4.2. Conceptual demonstration of pathways for future bioenergy use in DN and CHP plants in Denmark. Figures for coal, natural gas business as usual and end of bioenergy are derived directly from the model and the CCS scenario is the same as the business as usual with 80% capture of the emitted carbon and 10% additional fossil process emissions.

5 Conclusions

Our analysis showed that based on 2020 data, one year's consumption of wood chips and wood pellets emitted 7 million tonnes of CO_2, roughly evenly distributed between wood chips and wood pellet consumption. The biogenic part of these emissions accounted for 93.5% of total emissions, with fossil emissions associated with the processing, transport of feedstock for bioenergy and iWUC being responsible for the remainder.

Net CO_2 emissions from the consumption of wood chips and pellets decreased rapidly over time as emissions are recaptured in new forest carbon stocks. After about 70 years, what corresponds to the fossil emissions were left in the atmosphere as the forests had sequestered what corresponds to virtually all biogenic emissions.

A sensitivity analysis showed that the rate at which CO_2 was recaptured in the forest depends on counterfactual assumptions, i.e. what would have happened in the forests and with wood products absent bioenergy demand, and provides an interval for the recapture of what corresponds to biogenic emissions in the forest between 5 and 80 years.

Assuming that the 2020 consumption of wood chips and wood pellets continue in the coming 100 years, cumulative net-emissions will reach 128 million tons of CO_2 evenly distributed between wood pellets and wood chips. The majority of these net-emissions were emitted within 40 after the transition to bioenergy. Measuring the climate impact of net CO_2 emissions as the absolute global warming potential (AGWP), shows that after about 20 years there is no further climate impact on the current consumption of wood biomass for district heat and electricity.

Finally, we emphasise a need for continued research on decay rates (half-lives) of wood left in forests, on indirect emissions and the expected life time of wood products, and on how net CO_2 emissions from bioenergy will be affected by the expected deployment of CO_2 capture and storage (CCS).

6 References

1. Nielsen, A.T.; Bentsen, N.S.; Nord-Larsen, T. *CO2 emission mitigation through fuel transition on Danish CHP and district heat plants – Carbon debt and payback time of CHP and district heating plant's transition from fossil to biofuel*; Department of Geosciences and Natural Resource Management, University of Copenhagen: Frederiksberg, DK, 2020; p. 83.
2. Nielsen, A.T.; Nord-Larsen, T.; Bentsen, N.S. CO2 emission mitigation through fuel transition on Danish CHP and district heating plants. *Gcb Bioenergy* **2021**, *13*, 1162-1178, doi:10.1111/gcbb.12836.
3. UNFCCC. Paris Agreement. **2015**.
4. Rogelj, J.; Shindell, D.; Jiang, K.; Fifita, S.; Forster, P.; Ginzburg, V.; Handa, C.; Kheshgi, H.; Kobayashi, S.; Kriegler, E.; et al. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; In Press, 2018.
5. Bentsen, N.S.; Nilsson, D.; Larsen, S. Agricultural residues for energy - A case study on the influence of resource availability, economy and policy on the use of straw for energy in Denmark and Sweden. *Biomass and Bioenergy* **2018**, *108*, 278-288, doi:https://doi.org/10.1016/j.biombioe.2017.11.015.
6. Energistyrelsen. *Energistatistik 2020*; Energistyrelsen: København, 2021.
7. Mather-Gratton, Z.J.; Larsen, S.; Bentsen, N.S. Understanding the sustainability debate on forest biomass for energy in Europe: A discourse analysis. *PLoS ONE* **2021**, *16*, doi:10.1371/journal.pone.0246873.
8. Weisser, D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* **2007**, *32*, 1543-1559, doi:https://doi.org/10.1016/j.energy.2007.01.008.
9. Sebastián, F.; Royo, J.; Gómez, M. Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology. *Energy* **2011**, *36*, 2029-2037, doi:https://doi.org/10.1016/j.energy.2010.06.003.
10. Keith, H.; Mackey, B.G.; Lindenmayer, D.B. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proceedings of the National Academy of Sciences* **2009**, *106*, 11635-11640, doi:10.1073/pnas.0901970106.
11. Callesen, I.; Stupak, I.; Georgiadis, P.; Johansen, V.; Østergaard, H.; Vesterdal, L. Soil carbon stock change in the forests of Denmark between 1990 and 2008. *Geoderma Regional* **2015**, *5*, 169-180.
12. Vesterdal, L.; Christensen, M. The carbon pools in a Danish semi-natural forest. *Ecological Bulletins* **2007**, *52*, 113-121.
13. Taeroe, A., Stupak, I., Raulund-Rasmussen, K. Growth and management of the OP42 poplar clone in southern Scandinavia. *Unpublished* **2016**.
14. Nord-Larsen, T.; Johannsen, V.K. A state-space approach to stand growth modelling of European beech. *Annals of Forest Science* **2007**, *64*, 365-374.
15. Møller, C.M.M. Bonitetstabeller og Bonitetsvise Tilvækstoversigter for Bøg, Eg og Rødgran i Danmark. *Dansk Skovforenings Tidsskrift* **1933**, *18*, 537-623.
16. Nord-Larsen, T.; Meilby, H.; Skovsgaard, J.P. Simultaneous estimation of biomass models for 13 tree species: effects of compatible additivity requirements. *Canadian Journal of Forest Research* **2017**, *47*, 765-776, doi:10.1139/cjfr-2016-0430.
17. Nord-Larsen, T.; VK., J.; Riis-Nielsen, T.; IM., T.; Schou, E.; Suadicani, K.; Jørgensen, B. *Skove og Plantager 2014*; 2014 2014.

18. Johannsen, V.K.; Nord-Larsen, T.; Scott Bentsen, N.; Suadicani, K.; Hansen, J.K.; Braüner, U.; Graudal, L. *Scenarieberegning for biomasseproduktion i skov – virkemidler og forudsætninger. Baggrundsnotat til Perspektiver for skovenes bidrag til grøn omstilling mod en biobaseret økonomi. Muligheder for bæredygtig udvidelse af dansk produceret vedmasse 2010-2110.*; 2012 2012.

19. Hérault, B.; Beauchêne, J.; Muller, F.; Wagner, F.; Baraloto, C.; Blanc, L.; Martin, J.-M. Modeling decay rates of dead wood in a neotropical forest. *Oecologia* **2010**, *164*, 243-251.

20. Krankina, O.N.; Harmon, M.E. Dynamics of the Dead Wood Carbon Pool in Northwestern Russian Boreal Forests. *Water Air Soil Poll* **1995**, *82*, 227-238, doi:Doi 10.1007/Bf01182836.

21. Russell, M.B.; Woodall, C.W.; Fraver, S.; D'Amato, A.W.; Domke, G.M.; Skog, K.E. Residence Times and Decay Rates of Downed Woody Debris Biomass/Carbon in Eastern US Forests. *Ecosystems* **2014**, *17*, 765-777, doi:DOI: 10.1007/s10021-014-9757-5.

22. Huntington, T.G. Carbon Sequestration in An Aggrading Forest Ecosystem in the Southeastern Usa. *Soil Science Society of America Journal* **1995**, *59*, 1459-1467.

23. Spinelli, R.; De Arruda Moura, A.C. Decreasing the Fuel Consumption and CO2 Emissions of Excavator-Based Harvesters with a Machine Control System. *Forests* **2019**, *10*, 43.

24. Röder, M.; Whittaker, C.; Thornley, P. How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass and Bioenergy* **2015**, *79*, 50-63.

25. Börjesson, P.I.I. Energy analysis of biomass production and transportation. *Biomass and Bioenergy* **1996**, *11*, 305-318, doi:https://doi.org/10.1016/0961-9534(96)00024-4.

26. Schou, E.; Suadicani, K.; Johannsen, V.K. Carbon Sequestration in Harvested Wood Products (HWP). Available online: (accessed on

27. IPCC. Harvested wood products, Chapter 12 IPCC Guidelines for National Greenhouse Gas Inventories. Available online: (accessed on

28. Leskinen, P.; Cardellini, G.; González-García, S.; Hurmekoski, E.; Sathre, R.; Seppälä, J.; Smyth, C.; Stern, T.; Verkerk, J.P. *Substitution effects of wood-based products in climate change mitigation*; European Forest Institute: 2018; p. 27 p.

29. Dansk Energi; Dansk Fjernvarme. *Brancheaftale om sikring af bæredygtig biomasse (træpiller og træflis)*; København, 2016; p. 7 pp.

30. Larsen, S.; Bentsen, N.S.; Stupak, I. Implementation of voluntary verification of sustainability for solid biomass—a case study from Denmark. *Energy, Sustainability and Society* **2019**, *9*, 33, doi:10.1186/s13705-019-0209-0.

31. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 2 Stationary Combustion*; 2006.

32. Nord-Larsen, T.; Johannsen, V.K.; Riis-Nielsen, T.; Thomsen, I.M.; Jørgensen, B.B. *Skovstatistik 2020*; Department of Geosciences and Natural Resource Management, University of Copenhagen: Frederiksberg, 2021; p. 61 pp.

33. BALTPOOL. Prices of timber products. Available online: https://www.baltpool.eu/en/prices-of-timber-products/ (accessed on 31-03-2022).

34. The Danish Forest Association. Årsstatistik for Danmark. Available online: (accessed on 12-21).

35. Högberg, P.; Ceder, L.A.; Astrup, R.; Binkley, D.; Dalsgaard, L.; Egnell, G.; Filipchuk, A.; Genet, H.; et al. *Sustainable boreal forest management challenges and opportunities for climate change mitigation*; 2021; p. 60 pp.

36. Kangas, H.-L.; Lyytimäki, J.; Saarela, S.-R.; Primmer, E. Burning roots: Stakeholder arguments and media representations on the sustainability of tree stump extraction in Finland. *Biomass and Bioenergy* **2018**, *118*, 65-73, doi:https://doi.org/10.1016/j.biombioe.2018.08.006.

37. Lindholm, E.L.; Berg, S.; Hansson, P.A. Energy efficiency and the environmental impact of harvesting stumps and logging residues. *European Journal of Forest Research* **2010**, *129*, 1223-1235, doi:10.1007/s10342-010-0412-1.

38. Graudal, L.; Nielsen, U.B.; Schou, E.; Thorsen, B.J.; Hansen, J.K.; Bentsen, N.S.; Johannsen, V.K. *Dansk skovbrugs mulige bidrag til øget træproduktion og imødegåelse af klimaforandringer 2010-2100: Perspektiver for skovenes bidrag til grøn omstilling mod en biobaseret økonomi*; 978-87-7903-640-6; Institut for Geovidenskab og Naturforvaltning, Københavns Universitet: 2014.

39. FAO. *The Global Forest Resources Assessment 2015*; Food and Agriculture Organisation of the United Nations: Rome, IT, 2016.

40. USDA. Forest Inventory EVALIDator web-application Version 1.8.0.01. . Available online: (accessed on Fri Apr 17 14:42:51 GMT).

41. FAO. Global Forest Resources Assessment. Available online: https://fra-data.fao.org/FE/panEuropean/home/ (accessed on 25-01).

42. Johannsen, V.K.; Nord-Larsen, T.; Bentsen, N.S. *Opdatering af skovfremskrivning: Forventet drivhusgasregnskab for de danske skove 2020-2050*; Institut for Geovidenskab og Naturforvaltning, Københavns Universitet: Frederiksberg, 2022.

43. Jacobsen, J.B. Hvorfor brug af træ til bioenergi ikke altid er en god idé [Why the use of wood for bioenergy may not always be a good idea]. *Skoven* **2019**, *51*, 34-36.

44. Schmidt, J.H.; Weidema, B.P.; Brandão, M. A framework for modelling indirect land use changes in Life Cycle Assessment. *Journal of Cleaner Production* **2015**, *99*, 230-238, doi:10.1016/j.jclepro.2015.03.013.

45. Nord-Larsen, T.; Vesterdal, L.; Bentsen, N.S.; Larsen, J.B. Ecosystem carbon stocks and their temporal resilience in a semi-natural beech-dominated forest. *Forest Ecology and Management* **2019**, *447*, 67-76, doi:https://doi.org/10.1016/j.foreco.2019.05.038.

46. Nielsen, A.T. Forest Biomass for Climate Change Mitigation. University of Copenhagen, 2016.

47. Sathre, R.; O'Connor, J. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy* **2010**, *13*, 104-114, doi:http://dx.doi.org/10.1016/j.envsci.2009.12.005.

48. Oliver, C.D.; Nassar, N.T.; Lippke, B.R.; McCarter, J.B. Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests. *Journal of Sustainable Forestry* **2014**, *33*, 248-275, doi:10.1080/10549811.2013.839386.

49. Joos, F.; Roth, R.; Fuglestvedt, J.S.; Peters, G.P.; Enting, I.G.; von Bloh, W.; Brovkin, V.; Burke, E.J.; Eby, M.; Edwards, N.R.; et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmos Chem Phys* **2013**, *13*, 2793-2825, doi:DOI 10.5194/acp-13-2793-2013.

50. Lapola, D.M.; Schaldach, R.; Alcamo, J.; Bondeau, A.; Koch, J.; Koelking, C.; Priess, J.A. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences* **2010**, *107*, 3388-3393, doi:10.1073/pnas.0907318107.

51. Repo, A.; Tuomi, M.; Liski, J. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *Gcb Bioenergy* **2011**, *3*, 107-115, doi:10.1111/j.1757-1707.2010.01065.x.

52. Plevin, R.J.; O'Hare, M.; Jones, A.D.; Torn, M.S.; Gibbs, H.K. Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated. *Environmental Science & Technology* **2010**, *44*, 8015-8021, doi:10.1021/es101946t.

53. Djuric Ilic, D.; Dotzauer, E.; Trygg, L.; Broman, G. Introduction of large-scale biofuel production in a district heating system – an opportunity for reduction of global greenhouse gas emissions. *Journal of Cleaner Production* **2014**, *64*, 552-561, doi:https://doi.org/10.1016/j.jclepro.2013.08.029.

54. Wicke, B.; Verweij, P.; van Meijl, H.; van Vuuren, D.P.; Faaij, A.P.C. Indirect land use change: review of existing models and strategies for mitigation. *Biofuels* **2012**, *3*, 87-100, doi:10.4155/bfs.11.154.

55. Kim, S.; Dale, B.E. Indirect land use change for biofuels: Testing predictions and improving analytical methodologies. *Biomass and Bioenergy* **2011**, *35*, 3235-3240, doi:10.1016/j.biombioe.2011.04.039.

56. Jacobsen, J.B.; Helles, F. Adaptive and nonadaptive harvesting in uneven-aged beech forest with stochastic prices. *Forest Policy and Economics* **2006**, *8*, 223-238, doi:https://doi.org/10.1016/j.forpol.2004.06.004.

57. Nabuurs, G.-J.; Lindner, M.; Verkerk, P.J.; Gunia, K.; Deda, P.; Michalak, R.; Grassi, G. First signs of carbon sink saturation in European forest biomass. *Nature Clim. Change* **2013**, *3*, 792-796, doi:10.1038/nclimate1853.

58. Forest Europe. *State of Europe's forests 2020*; Liaison Unit Bratislava: Bratislava, 2020.

59. Cherubini, F.; Bright, R.M.; Strømman, A.H. Global climate impacts of forest bioenergy: what, when and how to measure? *Environmental Research Letters* **2013**, *8*, 014049.

60. Bentsen, N.S. Carbon debt and payback time – Lost in the forest? *Renewable and Sustainable Energy Reviews* **2017**, *73*, 1211-1217, doi:http://dx.doi.org/10.1016/j.rser.2017.02.004.

61. Cowie, A.L.; Berndes, G.; Bentsen, N.S.; Brandao, M.; Cherubini, F.; Egnell, G.; George, B.; Gustavsson, L.; Hanewinkel, M.; Harris, Z.M.; et al. Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *Gcb Bioenergy* **2021**, *13*, 1210-1231, doi:10.1111/gcbb.12844.

62. Madsen, K.; Bentsen, N.S. Carbon Debt Payback Time for a Biomass Fired CHP Plant—A Case Study from Northern Europe. *Energies* **2018**, *11*, doi:10.3390/en11040807.

63. Saez de Bikuña, K.; Garcia, R.; Dias, A.C.; Freire, F. Global warming implications from increased forest biomass utilization for bioenergy in a supply-constrained context. *Journal of Environmental Management* **2020**, *263*, 110292, doi:https://doi.org/10.1016/j.jenvman.2020.110292.

64. Cherubini, F.; Huijbregts, M.; Kindermann, G.; Van Zelm, R.; Van Der Velde, M.; Stadler, K.; Strømman, A.H. Global spatially explicit CO2 emission metrics for forest bioenergy. *Scientific Reports* **2016**, *6*, 20186, doi:10.1038/srep20186.

65. Withey, P.; Johnston, C.; Guo, J. Quantifying the global warming potential of carbon dioxide emissions from bioenergy with carbon capture and storage. *Renewable and Sustainable Energy Reviews* **2019**, *115*, 109408, doi:https://doi.org/10.1016/j.rser.2019.109408.

66. Iordan, C.M.; Verones, F.; Cherubini, F. Integrating impacts on climate change and biodiversity from forest harvest in Norway. *Ecological Indicators* **2018**, *89*, 411-421, doi:https://doi.org/10.1016/j.ecolind.2018.02.034.

67. Liu, W.; Zhang, Z.; Xie, X.; Yu, Z.; von Gadow, K.; Xu, J.; Zhao, S.; Yang, Y. Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. *Scientific Reports* **2017**, *7*, 39857, doi:10.1038/srep39857.

68. Hao, H.; Dai, L.; Wang, K.; Xu, J.; Liu, W. An updated framework for climate change impact assessment of bioenergy and an application in poplar biomass. *Applied Energy* **2021**, *299*, 117323, doi:https://doi.org/10.1016/j.apenergy.2021.117323.

69. Cooper, S.J.G.; Green, R.; Hattam, L.; Röder, M.; Welfle, A.; McManus, M. Exploring temporal aspects of climate-change effects due to bioenergy. *Biomass and Bioenergy* **2020**, *142*, 105778, doi:https://doi.org/10.1016/j.biombioe.2020.105778.

70. Klima- Energi- og Forsyningsministeriet. Bekendtgørelse om Håndbog om opfyldelse af bæredygtighedskrav og krav til besparelse af drivhusgasemissioner for biomassebrændsler til energiformål (HB 2021). *1352* **2021**, *1352*.

71. Ea Energianalyse. *Det danske træpillemarked 2020*; 2021; p. 29.

72. IPCC. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; IPCC: Geneva, CH, 2018.

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