UNIVERSITY OF COPENHAGEN
DEPARTMENT OF GEOSCIENCES AND
NATURAL RESOURCE MANAGEMENT

CO_2 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

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

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Foreword

In the fall 2019, the Department of Geosciences and Natural Resource Management (IGN) was approached by Danish Energy, an association for Danish electricity producers and the Danish District Heating Association with questions regarding the climate benefit of the current use of biomass for heat and electricity production. As IGN did not have good answers to the questions at hand, a research project was developed to answer the questions on the climate benefit of the transitions from fossil to biomass fuels already completed on a number of Danish district heat and combined heat and power plants. The project was exclusively funded by Danish Energy and the Danish District Heating Association.

A project group at IGN was formed to conduct the research consisting of:

- Associate Professor Niclas Scott Bentsen, PI and analyst
- Researcher Anders Tærø Nielsen, main analyst
- Senior Scientist Thomas Nord-Larsen, analyst and co-PI

A reference group was associated to the project representing a range of stakeholders within the bioenergy community. Members of the reference group were:

- Bodil Harder, Centre for Global Cooperation, Danish Energy Agency
- Annika Lund Gade / Mads Jespersen, Green Transition Denmark
- Nora Skjernaa Hansen, Danish Society for Nature Conservation
- Torben Chrintz, Concito

Employees from Danish Energy and the Danish District Heating Association were not considered as members of the reference group and had no influence on the composition of the group. The reference group met three times during the project period and provided valuable comments and suggestions to methodology, data, assumptions and research communication.

The reference group was invited to collectively or individually provide a written assessment on the project, the report and analyses behind, and stakeholder involvement to be published with this report. The assessment is presented in appendix 1.

To ensure scientific rigor and integrity a peer review panel was associated the project. The task of the panel was to review the project report prior to publication. Members of the review panel were:

- Thomas Buchholz, Senior Scientist, University of Vermont, Gund Institute for the Environment, USA.
- Jette Bredahl Jacobsen, Professor, University of Copenhagen, Department of Food and Resource Economics, Denmark.

Review panel members were suggested and selected in collaboration between the project group and the reference group. Danish Energy and the Danish District Heating Association had no influence on the composition of the review panel.

The authors highly appreciate the constructive feedback and comments received from the reference group and the scientific reviewers.

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

Content

Abstract

The purpose of this study was to analyse how carbon dynamics and climate impacts were influenced by the transition from coal or natural gas to forest biomass on a number of district heat and combined heat and power plants in Denmark. The aim was to 1) retrospectively inform the scientific, public and policy debate on the potential CO2 emissions reductions of using forest biomass (harvest residues, stems, industrial residues or dedicated bioenergy) for heat and electricity production instead of fossil fuels (coal or natural gas), and 2) inform utility companies on their future fuel sourcing.

We calculated the cumulative net carbon emissions (CCE) for each of ten plants that delivered data to the analysis. From CCE we calculated the carbon parity time (CPT), a measure of the time it takes for a fuel transition to biomass to reduce the amount of carbon emitted to the atmosphere relative to a continuation of using fossil fuels. Subsequently, we derived the relative emissions (RE), as a measure of the carbon emission savings/costs induced by the fuel transition on Danish district heating and combined heat and power plants. We used RE 30 years after the fuel transition as a measure of the emission benefits a plant had achieved during a typical lifetime of a plant. Finally, we performed sensitivity analyses of key parameters, with special focus on emissions from indirect/market mediated effects.

For fuel transitions from coal to biomass, CPT ranged from 0-13 years indicating that carbon emission benefits were achieved at the latest after 13 years. Relative emissions after 30 years ranged from 0.29-0.85 demonstrating an emissions saving of 15-71% relative to a continuation of producing heat and electricity on coal. Mean CPT of coal to biomass transitions was 6 years and average relative emissions after 30 years was 0.69, indicating emission savings of 31%.

For fuel transitions from natural gas to biomass, CPT ranged from 9-37 and relative emissions after 30 years from 0.81-1.04. Our results demonstrated that transitions from natural gas to biomass achieved carbon emissions benefits after 9 to 37 years, and emissions savings/costs after 30 years ranged from -4 to 19%. Mean CPT for transitions from natural gas to biomass was 24 years and relative emissions after 30 years 0.93, demonstrating that natural gas transitions on average reached carbon benefits after 24 years and average emission savings of 7% after 30 years.

Sensitivity analyses showed that the use of truly residual biomass (harvest residues, or unusable industrial residues), biomass harvest from productive forests and short transport distances are beneficial in achieving a short carbon payback time, large emission savings and thus fast climate benefits. Whether using wood pellets or wood chips had little impact on payback times.

The quantification of indirect or market mediated GHG emissions is uncertain, also in this study. We analysed additional carbon emissions related to indirect land use change (iLUC), indirect wood use change (iWUC) and indirect fuel use change (iFUC). Including iLUC added 1-4 years, iWUC added 1-3 years and iFUC added 1 year to the mean CPT. We emphasize that more research is required to reach scientific consensus on the quantification of indirect emissions for different biomass types, supply chain configurations, and district heat/combined heat and power plant operational characteristics.

Sammendrag

Intentionen med dette studie var at analysere hvordan omstillingen fra kul eller naturgas til skovbiomasse på en række fjernvarme- og kraftvarmeværker i Danmark har påvirket kulstofdynamikken og CO2 udledninger. Formålet med studiet er 1) at retrospektivt informere den videnskabelige, offentlige og politiske debat om potentielle reduktioner af CO2 udledninger forårsaget af omstillingen til skovbiomasse, herunder grene, toppe, rester fra træindustri, udtyndningstræ og energiafgrøder i el- og varmeproduktionen, og 2) at informere forsyningssektoren om CO2 udledninger fra forskellige typer af biomasse til energi til støtte for fremtidige indkøbsstrategier for biomasse.

Vi beregner den kumulerede netto udledning af kulstof til atmosfæren (CCE) for ti fjernvarme- og kraftvarmeværker, der leverede produktionsdata til analysen. Ud fra den kumulerede nettoudledning beregner vi en kulstoftilbagebetalingstid (CPT), som er et mål for hvor lang tid det tager en brændselsomstilling at reducere mængden af kulstof udledt til atmosfæren sammenlignet med en fortsættelse af brugen af fossil energi. Sidst udleder vi de relative emissioner (RE(30)), som et mål for hvor meget kulstof atmosfæren er blevet sparet for eller har fået tilført ekstra i løbet af 30 år som følge af omstillingen fra kul eller naturgas til skovbiomasse.

For omstillinger fra kul til skovbiomasse fandt vi kulstoftilbagebetalingstider mellem 0 og 13 år forstået således, at efter senest 13 år har omstillingen bidraget til reduktion af mængden af drivhusgasser i atmosfæren. De relative emissioner efter 30 år var mellem 0.29 og 0.85 svarende til, at der efter 30 år er opnået en reduktion i drivhusgasudledninger mellem 15 og 71 % sammenlignet med en situation hvor kraftvarmeværkerne var fortsat med at bruge kul. Den gennemsnitlige kulstoftilbagebetalingstid var 6 år.

For omstillinger fra naturgas til skovbiomasse var kulstoftilbagebetalingstiderne mellem 9 og 37 år, med et gennemsnit på 24 år. De relative emissioner efter 30 år var mellem 1.04 og 0.81 svarende til, at efter 30 år er der opnået en reduktion i drivhusgasudledninger mellem -4 og 19 % sammenlignet med en situation hvor fjernvarme- eller kraftvarmeværkerne var fortsat med at bruge naturgas.

Følsomhedsanalyser viste, at for at reducere kulstoftilbagebetalingstiden bør forsyningsselskaberne fokusere på at anvende restbiomasse (grene og toppe fra hugst i skoven eller rester fra træindustrien, der ikke har andre anvendelser), biomasse fra produktive skove samt at reducere lange transporter. Det har lille betydning om der anvendes træpiller eller træflis.

I analysen inkluderede vi også indirekte effekter på drivhusgasudledningerne. Det er effekter, der kan opstå dels fordi der er konkurrence om forskellige træsortimenter, dels fordi der er konkurrence om forskellige anvendelser af landareal, og dels fordi elektricitet kan handles mellem landsdele og over grænser. Kvantificering af indirekte effekter er generelt usikkert og vanskeligt, og det har det også været i dette studie. Vi analyserede indirekte effekter på kulstoftilbagebetalingstider fra ændret areal anvendelse (iLUC), som lagde 1-4 år på tilbagebetalingstiden. Ændret brug af træressourcerne (iWUC) lagde 1-3 år på tilbagebetalingstiden, og ændret brug af brændsler (iFUC) lagde som gennemsnit 1 år på tilbagebetalingstiden. Der er behov for mere forskning for at udvikle alment anerkendte metoder til kvantificering af indirekte effekter på drivhusgasudledninger.

1. Introduction

The long-term goal of the Paris Agreement is to keep anthropogenic global warming well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C in recognition that this would substantially reduce the risks and impacts to society of climate change [1]. Denmark has ratified the Paris Agreement and through the European Union (EU) Nationally Determined Contributions (NDCs) committed itself to contribute to an economy wide reduction in greenhouse gas (GHG) emissions by at least 40% below 1990 levels by 2030 [1]. The current commitments are judged as insufficient to reach the goal of the Paris Agreement and points towards a 3°C temperature increase. It is expected that a revised and more ambitious NDC package is passed the EU sometime in 2020 (www.climateactiontracker.com).

In June 2020, a climate act was passed in the Danish Parliament, committing Denmark to reduce GHG emissions by 70% relative to 1990 by 2030 and to work actively to meet the Paris Agreement's 1.5°C target. Actions and targets for individual sectors are at the time of writing only partially determined.

Meeting the 1.5°C target requires significant society wide transitions. The IPCC report on the 1.5°C target [2] depicts four illustrative pathways to meet 1.5°C global warming by the end of the 21st century. In all pathways, the energy sector plays a leading role. The renewables share in electricity production must increase to 66-86% by 2050. Coal consumption must be reduced by 74-95% relative to 2010 by 2050, bioenergy production can increase by 123-261% relative to 2010 by 2050, other renewable energies must increase 576-1299% relative to 2010 by 2050, and carbon capture and storage combined with bioenergy (BECCS) must have immobilised 364-662 billion tons of atmospheric CO_2 by the end of the century.

In Denmark, energy supply and demand is responsible for a large contribution of the national GHG emissions. In 2018 more than 20% of the GHG emissions (9.4 out of 48 million tons CO_2) were attributable to heat and electricity production [3] [4].

1.1 Biomass in the energy sector

In a global perspective, according to the IPCC, substitution of fossil resources with bioenergy is seen as an important means to reduce CO_2 emissions and hence mitigate climate change [2] . The use of biomass in the energy sector in Denmark has been on the political agenda since the mid-1980s [5]. Since 1993, the Biomass Agreement [6] has been a major driver in the increasing use of straw and wood biomass in the energy supply. EU strategies and legislation also shaped the solid biomass use in the Danish energy sector. The 2001 Directive (2001/77/EC) [7] promoting electricity production from renewable resources recognised biomass as renewable, and the EU Biomass Action Plan from 2005 identified a number of initiatives to boost bioenergy [8].

Since 2005, the national commitments under the Kyoto Protocol of 1997 provided a policy incentive for countries to increase the amount of renewables in the energy system. Denmark committed itself to a GHG emissions reduction of 21% during the commitment period 2008–12 relative to 1990 [9]. In 2012, all political parties in the Danish parliament and the government agreed upon the energy policy for 2012-2020 [10] aiming at increased use of biomass for energy. In 2014, the policy framework for biomass fuelled CHPs were changed to favour increased use of biomass [11]. These favourable conditions will continue to 2030.

1.2 Development in forest bioenergy use

District heat and electricity production in Denmark has seen a significant transition in fuel use over the last 30 years (Figure 1), from predominantly coal in 1990's, over natural gas, and to the current dominance of biomass with wind power and coal as large contributors as well. The increase in biomass use has mostly been covered by increased wood use, and in the same period, wood has increased its share of the biomass used from 25% in 1990 to 67% in 2018.

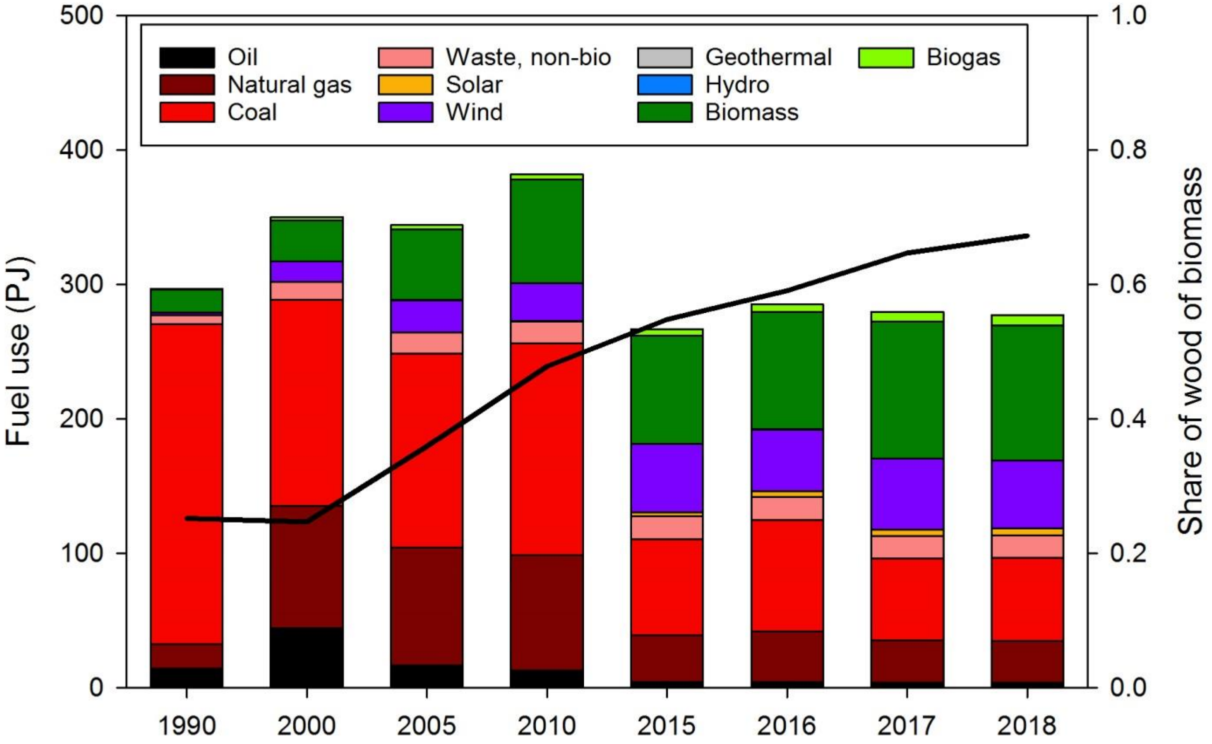

Figure 1. Fuel use for district heat and electricity production in Denmark 1990 to 2018. Biomass included straw, wood, bio oil and biological waste [3]. The use of biomass for private households and businesses is excluded.

The increased demand for wood for district heat and electricity production has brought about changes in production and trade of wood chips and wood pellets (Figure 2). In response to the increased demand for wood chips, domestic production has increased from 1.7 PJ in 1990 to 22.4 PJ in 2018, while import has increased from nothing in 1990 to 6.3 PJ in 2018 to constitute 22% of the current supply. For wood pellets, the picture is different. Domestic production has remained constant around 2.5 PJ annually, while import has increased from nothing in 1990 to 53 PJ in 2018. Import make up 95% of the current supply of wood pellets.

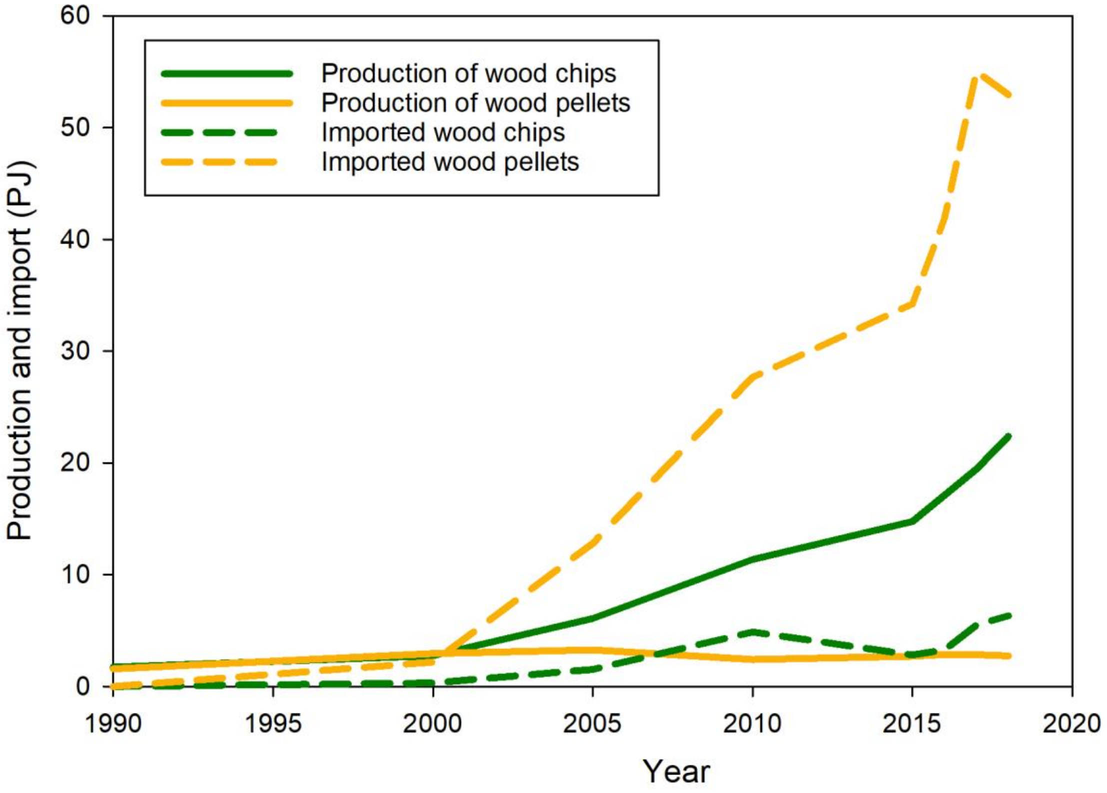

Figure 2. Production and import of wood chips and wood pellets for energy [3].

Not all wood chips and wood pellets are used for district heat and electricity production. In 2018, 7% of the wood chips supply and 34% of the wood pellet supply was used in the consumption sector to heat farmhouses, industries and family homes [12].

1.3 Sustainability of biomass for energy

The development in biomass use and trade not only in Denmark has spurred scientific, public and political concerns regarding the sustainability biomass for energy. Concerns have been expressed by several NGOs, researchers and other stakeholders and include sustainability and sustainability verification of wood use [12-14], Denmark's fair share of global wood resources [15], the climate benefit of using wood for energy production [16-18], GHG accounting of bioenergy as carbon neutral for the energy sector [19, 20], and policies and incentives in place to support and stimulate the energy sector's transition towards renewable energy production [21].

The concerns raised, has led to a demand for a set of sustainability criteria that ensures actual emission reductions and the protection of species and vulnerable habitats. As a consequence, in 2010 the EU issued recommendations which encouraged Member States to establish national sustainability criteria for solid and gaseous biomass [22]. Following these recommendations, the Danish government in 2012 suggested the establishment of an industry initiated, voluntary sustainability framework for wood chips and wood pellets. This resulted in the "Industry agreement to ensure sustainable biomass (wood pellets and wood chips)" that was approved by the government in 2014 [23]. Implementation of the framework was initiated on August 1st 2016 and it was fully implemented by the end of 2019. At EU level, the new Renewable Energy Directive (Directive (EU) 2018/2001, RED II) was adopted in 2018, becoming statutory from January 2021 [24]. The directive introduces risk-based sustainability criteria for solid and gaseous biomass used for heat and power in the EU. Some of the criteria are specific to solid biomass from forests, while others are specific to other types of biomass.

1.4 The contribution of forest bioenergy to mitigate global warming

An important aspect of biomass for energy is the potential to reduce total GHG emissions. In national carbon accounting reports to the UNFCCC, bioenergy is accounted for as carbon neutral. Biomass removals and changes in carbon stocks in the forest are accounted for under the LULUCF compartment. The potential of forest bioenergy to mitigate global warming arises when wood from sustainably managed forests (i.e. forests where harvests does not exceed growth and where carbon stocks are maintained or increased) substitutes fossil fuels that would otherwise lead to net emissions of CO_2 to the atmosphere.

The potential of forest bioenergy to mitigate global warming has been questioned [20] mainly because of the temporal displacement between 1) the CO_2 emission when forest biomass is used for energy and 2) the subsequent sequestration of carbon in new biomass. This displacement is summarized under the concept of carbon debt and its payback time [25]. The term 'carbon debt' is often attributed to a paper in Science in 2008 [17], however, the principles behind the carbon debt concept dates back to papers published in 1995-96 [26-28]. A number of recent narrative reviews discussed the implications of carbon dynamics and carbon debt of forest bioenergy with reference to climate impact and policy development [29-31]. The quantification of a carbon debt remains uncertain. The large differences in carbon debt and payback times among different studies focusing on forest bioenergy arise from differences in e.g. the fossil fuel baseline (coal, oil, natural gas), the energy system output (heat, electricity, liquid fuels), feedstock origin (primary, secondary or tertiary resources), forest management systems (untouched, managed, plantation, short or long rotation), alternative fate of forest products (natural decay, roadside burning, pulp production), assumptions in the modelling framework, and overall system boundaries.

1.5 Aim of the study

Numerous studies have analysed or modelled GHG emissions from the use of wood for energy [25]. Lamers and Junginger [30] demonstrated that the carbon payback time of apparently comparable forest bioenergy scenarios vary by up to 200 years allowing amble room for confusion and dispute about the potential climate benefit of forest bioenergy. Only a few studies have treated the carbon debt of using forest biomass for energy under Danish conditions. Taeroe, Mustapha [32] modelled carbon debt and payback times of three different hypothetical and generic forest management regimes with bioenergy displacing either coal or natural gas, and reported payback times for coal displacement between 0 and 59 years and for natural gas displacement between 0 and 156 years. Madsen and Bentsen [33] analysed a historic fuel transition on a specific combined heat and power plant shifting from coal to biomass. They reported carbon payback times round one year.

Rather than relying on model assumptions alone, more realistic estimates may arise building on a hybrid approach combining real data from actual systems with models and assumption. The purpose of this study is consequently to expand on the work by Madsen and Bentsen [33] and analyse how carbon dynamics were influenced by a number of historical heat and power plant transitions from coal or natural gas to wood pellets or wood chips.

By calculating carbon debts and payback times for the individual plants, and by synthesising findings across supply chains and operational configurations, the aim is to: 1) retrospectively inform the scientific, public and policy debate on the potential CO2 emissions savings of using forest biomass for heat and electricity production instead of fossil fuels (coal or natural gas), and 2) inform utility companies on their future fuel sourcing. In contrast to most studies, this analysis is based on data on actual supply chains and plant operations for time-periods before and after the fuel shift rather than relying on modelling. We believe that the restricted used of models and their in-build assumptions ensure a strong foundation for the analysis and may lead to more robust conclusions, where conclusion can be drawn.

2. Methods and data

2.1 Model overview

For modelling carbon debt and payback times, we set up a modelling framework that assesses carbon pools and fluxes linked to each central heat and power (CHP) or district heat (DH) plant and its supply chain (Figure 3). The framework is documented by Taeroe, Mustapha [32]. Using this framework, we calculated temporal changes in forest carbon pools, the wood product pool, and the fossil fuel pool that were affected directly and indirectly by the plant's transition from fossil fuel to biomass. We calculated the cumulative net carbon emissions (CCE), which is the sum of net emissions from all affected pools over a 40-year period. From CCE we derived the relative cumulative net carbon emissions (RE), which is the sum of emissions of the biomass life cycle relative to the sum of emissions of the replaced fossil fuel life cycle. To assess when a carbon debt is repaid and a fuel transition starts to contribute positively to climate change mitigation we calculated carbon parity time (CPT), which is the period, where the emissions from the biomass supply chain are higher than those of a hypothetical continuation of the fossil supply chain. CPT is reached when emissions from the biomass supply chain are permanently lower than the emissions from the fossil supply chain.

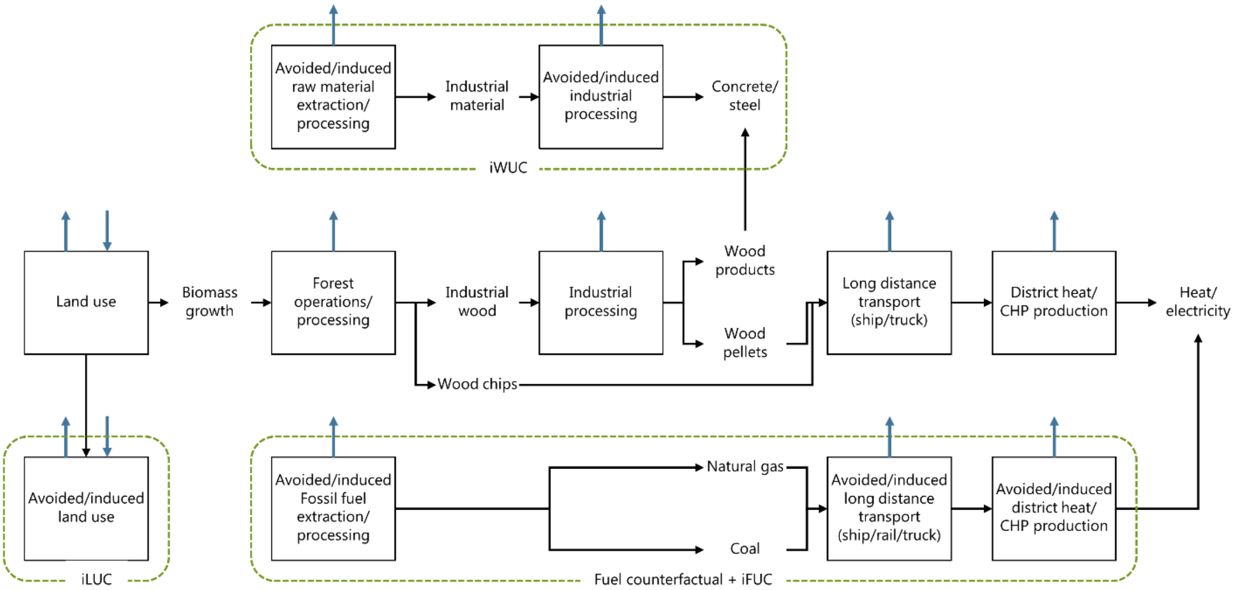

Figure 3. Modelling framework and processes included in the analysis. Black arrows indicate material and energy flows. Blue arrows indicate CO_2 flows included in the analysis.

To allow comparisons between CHP and district heat plants with different histories, the calculations of CCE and RE were made for a 40-year time series, departing 5 years before fuel transition for each power plant and using plant specific data.

The cumulative net carbon emissions to the atmosphere ($CCE_{i,t}$) for power plant *i* at a given point in time *t* during the 40-year time series, was calculated as:

$$CCE_{i,t} = \sum_{t=1}^{T} ED_{t,i} + \sum_{t=1}^{T} EB_{t,i} + \sum_{t=1}^{T} EF_{t,i} + \sum_{t=1}^{T} EP_{t,i,j} + \sum_{t=1}^{T} EiWUC_{t,i} + \sum_{t=1}^{T} EiLUC_{t,i} + \sum_{t=1}^{T} EiFUC_{t,i} + \sum_{t=1}^{T} EdLUC_{t,i} - \sum_{t=1}^{T} LC_{i,t}, \quad (1)$$

where

$\sum_{t=1}^{T} ED_{t,i}$ is the cumulative carbon emissions from decomposition of dead biomass,

$\sum_{t=1}^{T} EB_{t,i}$ is the cumulative carbon emissions from direct combustion of biomass,

$\sum_{i=1}^{T} EF_{t,i}$ is the cumulative carbon emission from combustion of fossil fuels (coal, oil or natural gas),

$\sum_{i=1}^{T} EP_{t,i,}$ is the cumulative production chain carbon emission from extraction, production, transportation and processing for biomass, or fossil fuels *(j)*, with *j* being wood fuel or fossil fuel,

$\sum_{i=1}^{T} EiWUC_{t,i}$ is the additional cumulative carbon emission along the whole supply chain from the amount of fossil fuel intensive products, such as steel, concrete or aluminium, that is needed to reach the same material output, as if wood products suited wood is used for energy,

$\sum_{i=1}^{T} EiLUC_{t,i}$ is the additional cumulative carbon emission along the whole supply chain from the amount of land that is indirectly intensified or converted as a consequence of increased use of biomass,

$\sum_{i=1}^{T} EiFUC_{t,i}$ is the additional emissions incurred when the use of bioenergy on a converted plant affect the fuel use on other plants in the same district heating area or in general,

$\sum_{i=1}^{T} EdLUC_{t,i}$ is the additional cumulative carbon emission along the whole supply chain from the amount land deforested and degraded or converted into other land use as a consequence of increased demand for biomass, and

$\sum_{t=1}^{T} LC_{i,t}$ is the cumulative net carbon uptake in both above- and belowground living biomass.

CPT was calculated as the time it takes CCE of fossil based energy production to permanently exceed CCE of biomass based energy production.

The relative cumulated net carbon emission of conversion to biomass relative to a continuation of fossil fuel use ($RE_{i,T}$), was calculated as:

$$RE_{biomass,t} = \frac{CCE_{biomass,t}}{CCE_{fossil,t}} \quad (2)$$

While we used CPT to indicate when carbon benefits from conversion occur, we used$RE_i(30)$, as an indicator of long term performance of the biomass conversion. 1-$RE_{biomass}$(t) are the actual emission savings from conversion to biomass achieved at time t,

During our study, the data collected was only related to the fuel use and related emissions before and after transition. Consequently, assumptions were made regarding e.g. substitution factors of forest products, emissions related to the alternative fate of wood, forest growth etc. (Table 1). To test the robustness of the results to uncertain assumptions, we repeated the calculations with several sets of alternative assumptions in sensitivity analyses.

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

No.	Assumption	Source
1	Living and deadwood carbon pools in unmanaged forest are set as the default IPCC values	[34]
2	The soil carbon pools in unmanaged forests are in steady state during the whole projection period, and unchanged by use of bioenergy throughout the projection period.	[35, 36]
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.	[37-39] 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.	[40]
5	90% of the aboveground living biomass harvest residues are extracted for use as wood fuel.	[41, 42]
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.	[43-45]
7	All biomass contains 50% carbon.	[46]
8	There are no significant emissions along the production chains of other greenhouse gasses than carbon dioxide.	Assumption for simplicity
9	For forest site operations, we used 2.29 l diesel t^{-1}. For harvest, forwarding and chipping we used 2.31 and 0.87 Kg C $m3^{-1}$ 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	[47-49]
10	Mining emissions for coal was set to 5% of combustion. Production chain and transport emissions for oil and natural gas were assumed to be 10% and 14%, respectively, of the emissions from their combustion.	[50] [51]
11	The half-life of the wood product pool is 35 years for sawn timber, 25 for boards and 2 for paper.	[52, 53]
12	The wood product substitution factor (SF) is set to 1.4 for timber, 1.2 for panels and boards and 1 for other products.	[54]
13	Indirect emissions related to a changes in electricity production in conversion to biomass were based on calculations and projection by the Danish Energy Agency	[55]

2.2 Data types and variation in time and space

2.2.1 Data from utilities

Ten utilities (CHP or district heating plants) were selected to participate and provide data for the analysis in collaboration with Danish Energy and the Danish District Heating Association (Table 2). 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; with fuel transition from natural gas or coal to biomass; having biomass delivered by truck or ship).

Table 2. Overview of district heating and combined heat and power plants contributing data to the analysis.

Plant	Type	Biofuel capacity (MW)	District heating network
Grenaa kraftvarmeværk	CHP	83	Grenaa fjernvarme
Ebeltoft fjernvarmeværk	DH	23	Ebeltoft fjernvarme
Amagerværket, blok 1	CHP	362	Storkøbenhavns fjernvarme
Skanderborg-Hørning fjernvarme	DH	30	Århus fjernvarme
Hillerød biokraftvarmeværk	CHP	29	Hillerød-Farum-Værløse
Hillerød Varmecentral	DH	18	Hillerød-Farum-Værløse
Køge kraftvarmeværk	CHP	103	Storkøbenhavns fjernvarme
Herningværket	CHP	299	Herning-Ikast fjernvarme
Avedøreværket, blok 1	CHP	595	Storkøbenhavns fjernvarme
Skærbækværket	CHP	280	TVIS
Studstrupværket	CHP	852	Århus fjernvarme

DH = district heating plant
CHP = combined heat and power plant

Data providers were asked to supply data as specified in Table 3 for a time series beginning five years prior to the fuel transition and ending five years after the fuel transition.

Table 3. 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	Shape 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	District heating grid to which the CHP or district heating plant delivers heat

Data received from the utilities exhibited large variation in the details provided, length of time series, and in resolution. The type and detail of data requested was clearly challenging for the data providers to supply. Only within the last few years, where utilities have had to document sustainability compliance against the industry agreement, these data have been collected regularly [56]. Some utilities delivered data for a long time series (up to 21 years) but at a low spatial resolution regarding the supply chain e.g. sourcing from eastern Jutland; mainly thinning and harvest residues from Norway spruce plantations. Other utilities delivered data where biomass or fossil fuel delivery could be traced back to the specific delivery with detailed information on the type of biomass. The conversions started back in 1985 and continued till 2017, where the last plant was converted. The data received is characterised in Table 4.

Table 4. Data properties for the collected data.

Data type	Detail level	Length of time series
Fuel use in energy units and mass units	Yearly data for all included plants for biomass. Fossil data assumed for two plant, based on means from the other plants	2-21
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	2-21
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	1-4
Fuel type as received at the CHP or district heating plant (pellets, chips, logs)	Some plants delivered detailed information, where other 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	1-3
Electricity and heat production	Detailed yearly information from all plants after conversion. Fossil data assumed for two plant, based on means from the other plants	2-21
Electricity and heat production capacity	Not informed, achieved from other sources.	n.a.
District heating grid to which the CHP or district heating plant delivers heat	Delivered	n.a.

To make a time series long enough to calculate CCE for a 40-year projection period and to estimate CPT, we used the first point in time on the data from the specific CHP or district heat plant to extrapolate back in time. Likewise, we used the last point in the time series to extrapolate forth in time, hereby, constructing a 40-year time series for each plant. For the utilities that did not deliver data of the fossil system before conversion, we used average data based on data from similar plants in the data; coal or natural gas fuelled.

2.2.2 Carbon fluxes in the biomass based energy system

The biomass system refers to all exchanges of carbon between carbon pools that emerge as a consequence of converting a fossil based CHP or DH plant to a biomass based, both directly and indirectly.

Direct emissions are emissions that come directly from the supply chain of biomass e.g. forest operations or transportation of biomass or combustion. Indirect emissions derive from market mediated consequences of the same fuel transition.

2.2.3 Forest operations, harvest and processing of biomass

For forest operations, we used 2.29 l diesel Mg^{-1} harvested biomass. For harvest, forwarding and chipping we used 2.31 and 0.87 Kg C m^{-3} harvested biomass and finally for chipping we used 1.85 l diesel Mg^{-1} biomass [48]. All values were recalculated into Mg C Mg^{-1} biomass, using standard emission factors from the IPCC [57]. Our data material included mainly two types of biomass, wood chips and wood pellets. Wood chips are wood that is chopped directly from the harvested biomass and combusted without further processing. Production of wood pellets includes more processing than chips, depending on the fuel type used e.g. sawdust, stems, or other residues from lumber production. Processes involved include grinding into smaller particles, drying, and pressing into pellets. For production and drying of wood pellets we assumed fossil emissions equivalent to 15% of combustion emissions from the wood pellets as in [48].

2.2.4 Transport of biomass

Transport emissions relates to emissions that occur due to transport either by truck, train or ship. To determine the transport emissions, we had to make some simplifications, as these emissions are dependent on where exactly the biomass was harvested and collected. Our data material did not contain such information; only the country of origin and if shipped, the harbour from which it was shipped. Within each country, we estimated transport distances for each specific country or region, before shipping to Denmark, by assuming that the biomass was harvested uniformly over the whole region and used google maps to determine the distance from the central part of the region to the harbour. For example, biomass from Latvia was assumed to be transported 250 km by truck to the harbour, equivalent to truck transport from central Latvia to Riga Harbour. Thereafter, we assumed that it was shipped directly to Denmark to the plant harbour or the harbour nearest to the plant (Table 5). The shipping distance was measured on Garmin nautical charts. Distances were rounded to the nearest 100, to indicate that these are approximations and not precise data.

Table 5. Standard transport distance for biomass from different regions

Country	Truck	Train	Ship
	Transport distance (km)		
Denmark	150	0	0
Baltic States	250	0	1,000
Belarus	400	0	1,000
Russia	500	0	1,300
Norway	300	0	600
Sweden	300	0	200
Germany	500	0	0
Ghana	200	0	5,000
USA/Canada	500	0	5,000
Unspecified	344	0	1,567
Europe	500	0	1,000

For transport of biomass and coal we used fuel consumption of 1.3, 0.68 and 0.22 MJ $Mg^{-1}km^{-1}$ for truck, train and ship, respectively [49]. We chose an older source of transport emissions, as the data material contains conversions and coal consumption reaching back to 1981.

2.2.5 Combustion and conversion efficiency

Each utility delivered data on the amount of fuel used and the amount of heat and/or electricity produced. Carbon emissions per produced energy unit were calculated for each plant for each year directly from the data by using standard emissions factors from [58].

2.3 Carbon emissions in the fossil fuel supply chain

As for the biomass system, there are also emissions related to extraction and use of fossil fuels. Fossil fuels are only used for energy production and do not have an alternative fate than being burned in power plants, except staying in the ground, which leads to no emissions. Therefore, there are no indirect emissions in the fossil fuel energy system and only the direct emissions were modelled.

2.3.1 Mining and transporting fossil resources

Mining emissions for coal were assumed to 5% of combustion emissions as in Yu, Ge [51]. Transport emissions relate emissions that occur due to any transport by truck, train, or ship. To determine the emissions related we had to make simplifications, as these emissions are dependent on the exact fuel origin. To simplify we used the same transport distances value for each specific country or region from which the coal was imported, as it was done for biomass (Table 6). For other regions, we used the same method to approximate distances as for biomass (see 2.2.4).

Table 6. Standard transport distance for coal from different regions

Country	Truck	Train	Ship
	Transport distance (km)		
Australia	500	100	24,000
Russia	500	100	1,200
South Africa	500	100	12,000
Norway	300	100	600
Kazakhstan	700	100	9,000
Poland	500	100	300
Colombia	500	100	9,000
USA/Canada	500	100	5,000
Unspecified	500	100	6,933

For transport fuel consumption of 1.3, 0.70 and 0.23 MJ $Mg^{-1}km^{-1}$ for truck, train and ship, respectively [49], to calculate the emissions from transportation of coal. As no detailed information was available in data for oil and natural gas, we used emissions factors given by Wihersaari [59], to model upstream emissions for these fuels. Process and transport emissions for oil and natural gas were thus set to 10% and 14% of combustion emissions.

2.3.2 Combustion of fossil fuels

Each power plant delivered data on the amount of biomass that they used and the amount of heat and/or electricity that was produced from this. As such, carbon emissions per produced energy unit were calculated for each plant for each year directly from the data using standard emissions factors for coal oil or natural gas given by the [52].

2.4 Forest carbon uptake

An important feature of energy from forest biomass is the ability of managed forests to sequester carbon from the atmosphere. The rate at which carbon is sequestered is dependent on the growth rate of the forests, from which the biomass is harvested. The utilities providing data to this study sourced its biomass from different parts of the world.

Forest growth may vary considerably between species and sites even within a small distance. The data available did not include specific information on where the biomass was harvested and local growing conditions could therefore not be considered. Consequently, we applied national and regional forest growth models for the most common tree species in individual countries to estimate forest growth and carbon sequestration.

The most commonly sourced biomass in our study comes from Denmark, Baltic countries, making up almost 75% of the total volume. This region includes a total forest area of 8.4 million ha of which 91% is available for wood supply (

Table 7) and roughly 50% is dominated by conifers. The third and fourth largest contributors to biomass sourcing are South-eastern US and Belarus with both 7% of the total volume.

The data available differed between the different regions and consequently calculations of annual forest carbon sequestration differed between regions according to the data available.

Table 7. Distribution of forest types by 2015 [60, 61].

	Unit	Denmark	Estonia	Latvia	Lithuania	Belarus	SE US
Forest area	1,000 ha	625	2,232	3,356	2,180	8,634	53,050
… available for wood supply	1,000 ha	585	1,994	3,151	1,924	6,478	51,429
… predominantly coniferous	1,000 ha	272	765	1,282	949	3,883	21,849
… predominantly broadleaved	1,000 ha	259	862	1,556	849	3,452	24,831
… mixed forest	1,000 ha	68	607	516	372	1,295	5,810

2.4.1 Denmark

The most common tree species in Denmark are Norway spruce (14%), beech (13%), and oak (11%) [62]. According to the National Forest Inventory increment varies substantially between species from 20.8 $m^3ha^{-1}year^{-1}$ for Norway spruce to 5.5 $m^3ha^{-1}year^{-1}$ for oak [62].

Although the NFI provides estimates of carbon sequestration, these are uncertain for less common species and affected by the current age class distribution. Consequently, we made an assessment of a tree species trial covering major growth regions of Denmark [63] and found that the majority of Norway spruce grown in Denmark had a site index of 24 m (index age 50, site class I according to the common yield table by [39]) and only two plots on very sandy soils to the very west of Denmark had a site index of 18 m (index age 50, site class III). We consequently opted for an average site index of 21 m, corresponding to site class II in the calculations as a conservative estimate (Appendix 1, Table 13). For a rotation age of 70 years, this corresponds to a mean annual increment of 15.8 m^3/ha/year, which is somewhat lower than measured with the Danish National forest Inventory reflecting a skewed age class distribution with much of the forest area in the most productive age classes [62].

In a similar assessment for beech, the majority of sites in eastern Denmark had site index of 32 m (site class I, index age 100) or better. The range of site classes was however larger, and at very sandy soils in eastern Denmark the site class was as low as 20 m (site class IV, index age 100). However, given the geographical distribution of beech, the vast majority of the beech forest will be at site class I. We consequently used an average site index of 32 m, corresponding to site class I according to [39] in the calculations (Appendix 1, Table 14). For a rotation age of 120 years, this corresponds to mean annual increment of 12.9 m^3/ha/year, which is somewhat larger than measured with the Danish National forest Inventory and the consequence of a larger proportion of old and less productive age-classes [62].

In the calculations, we used the growth of Norway spruce as a proxy for the growth of conifers and beech as a proxy for the growth of broadleaves.

2.4.2 Baltic countries and Belarus

For the Baltic countries, we used the area distribution of site classes together with a standard growth model to assess the likely growth of the main species in each country. Subsequently, since we have no specific knowledge on the when during the rotation biomass is harvested and assuming that biomass may be harvested during all parts of the rotation, we used the country specific mean annual increment for the main species in the calculation of CO_2 sequestration.

In the former USSR, site productivity is classified into six different site classes (Table 8). According to Anonymous [64], the site classes (SC) may be transformed into site index (SI, stand height attained at an index age of 100 years) using the general equation: $\mathrm{SI} = 33.5 - 4 \times \mathrm{SC}$ and may further be transformed to the site index at alternative base-ages (i.e. 50 years) using species specific base-age invariant height growth models.

For Estonia and Lithuania, country and species specific site class distributions were obtained from the establishment of the National Reference Level [65] and a report on Lithuanian Forestry [66], respectively. For Latvia and Belarus, no such distribution was available and we used the distribution provided in Table 8.

Table 8. Area distribution in percent to different site classes for countries in the former USSR [67].

Site class	Site index (base age=100 years)	Belarus	Estonia	Lithuania	Latvia
		Percent			
Ia	33.5	5.6	0.9	6.9	11.4
I	29.5	35.3	12	24.5	29.6
II	25.5	42.4	26.2	37.8	31.9
III	21.5	11.9	29.9	23.5	16.5
IV	17.5	3.1	21.3	5.8	8.5
V	13.5	1.7	9.7	1.5	2.1

Although local growth models and yield tables are available specifically for the Baltic countries e.g. [68, 69], these growth models are in Russian or Estonian and proved difficult to get access to. However, the Baltic countries to a large extent share growing conditions with southern Finland for which suitable yield tables are available for the far most important tree species in the region: Norway spruce, Scots pine and birch [70, 71]. We consequently calculated the area weighted average site class for each country and species, converted the site class to site index and used the corresponding growth model to estimate mean annual increment for each species. We thereby assumed that the growth rate of other conifers and broadleaves had similar growth rates to Norway spruce/Scots pine and birch. Specifically for the conifers, we used the average area weighted growth of Norway spruce and Scots pine as an estimate of conifer forest growth using the data compiled in (Table 9).

Table 9. Species specific estimates of growth for the Baltic countries and Belarus.

Country	Area			Site class			MAI		
	Norway spruce	Scots pine	Birch	Norway spruce	Scots pine	Birch	Norway spruce	Scots pine	Birch
	1,000 ha			m			$m^3 ha^{-1} year^{-1}$		
Estonia	371	775	669	27	27	28	6.6	6.0	5.9
Latvia	606	851	888	24	24	28	5.5	4.4	5.9
Lithuania	377	678	431	24	24	28	5.5	4.4	5.9
Belarus	3,994	747	1,819	24	24	28	5.5	4.4	5.9

2.4.3 South-eastern USA

The main part of biomass sourced from outside Europe comes from the South-eastern USA, spanning from Virginia in the north to Florida, Mississippi and Alabama in the south. The seven states span more than 50 million ha of forest land (Table 10). The most common forest types are Loblolly/shortleaf pine (31%), Exotic conifers (11%), Oak/pine (30%), and Oak/hickory (12%).

Table 10. Total forest area distribution to species groups [61].

Forest type	Total	Alabama	Mississippi	Georgia	Florida	South Carolina	North Carolina	Virginia
	Forest area (1,000 ha)							
Total	53,200	9,350	7,788	9,900	6,868	5,203	7,588	6,502
White/red/jack pine	163	7	-	34	-	7	46	68
Spruce/fir	10	-	-	-	-	-	7	3
Longleaf/slash pine	4,912	458	339	1,435	2,266	232	177	4
Loblolly/shortleaf pine	16,649	3,787	3,241	3,012	727	2,236	2,402	1,243
Other eastern softwoods	114	27	22	4	6	14	10	31
Exotic softwoods	2	-	-	-	-	-	-	2
Oak/pine	5,810	1,110	744	1,124	623	609	917	683
Oak/hickory	16,052	2,740	1,772	2,598	1,074	1,077	2,860	3,932
Oak/gum/cypress	6,425	887	1,028	1,320	1,517	785	740	147
Elm/ash/cottonwood	1,581	251	481	191	81	174	228	176
Maple/beech/birch	187	-	-	-	-	1	44	142
Aspen/birch	3	-	-	-	-	-	2	1
Other hardwoods	135	3	7	12	10	2	75	26
Tropical hardwoods	307	-	-	2	305	-	-	-
Exotic hardwoods	141	23	27	32	28	11	9	10
Non-stocked	709	56	128	136	231	55	69	34

A number of scientific studies have focused on the productivity of the forests in Southeastern US with particular emphasis on loblolly pine forests [72, 73] but also including other forest types in the southeast [74]. In much of the available literature, focus is on the advances in high productive stands through intense forest management and improved genetic material. However, in our study focus was on the productivity of forest from which biomass was harvested, which is not likely only from such highly productive stands. Consequently, we opted for using data on carbon sequestration extracted from the US National forest Inventory database (Table 11).

The majority of wood sourced from southeast USA originate from pine forests (mainly loblolly/shortleaf pine) and oak/pine forests. We consequently used the overall average for Loblolly/shortleaf pine as an estimate for mean annual C-sequestration in conifer forests and the overall average for oak/pine as an estimate for C-sequestration in broadleaved forests in the further calculations of carbon sequestration.

Table 11. Mean annual C-sequestration in above and below ground biomass across different states and tree species [61]. For converting above ground biomass C to total tree C, we used a root to shoot ratio of 0.2 [75].

Forest type	All states	Alabama	Florida	Georgia	Mississippi	North Carolina	South Carolina	Virginia
	Mean annual C-sequestration (tC $ha^{-1}year^{-1}$)							
All	3.45	3.61	2.44	3.32	3.94	3.59	3.67	3.45
White/red/jack pine	3.76	2.99		3.74		4.15	4.79	3.47
Spruce/fir	2.34					2.47		2.13
Longleaf/slash pine	3.10	3.04	2.82	3.71	3.13	2.16	2.83	1.15
Loblolly/shortleaf pine	4.81	4.72	3.28	4.41	5.28	4.87	4.80	5.55
Other eastern softwoods	1.57	1.04	2.83	1.22	2.16	1.22	1.24	1.78
Exotic softwoods	1.36							1.36
Oak/pine	3.02	3.10	2.21	2.84	3.25	3.35	3.05	3.16
Oak/hickory	2.74	2.71	1.90	2.47	2.95	3.02	2.44	2.94
Oak/gum/cypress	2.85	3.02	2.35	2.78	3.19	2.70	3.28	2.55
Elm/ash/cottonwood	2.63	2.77	2.05	2.48	2.65	2.86	2.52	2.47
Maple/beech/birch	2.58					2.06	1.54	2.68

2.4.4 Carbon sequestration

The yield tables used in the above assessment for the European countries provide estimates of above ground stem volumes growth. To convert this into carbon uptake in the forest, we used the default biomass conversion and expansion factors (BCEF from the IPCC [75]) to produce above ground biomass. For broadleaves in Denmark, yield tables provide the total above ground tree volumes, and hence the BCEF corresponded only to the basic density of hardwoods set to 0.57. Subsequently, we used the default root to shoot ratio’s from [75] to expand above ground biomass to total tree biomass and finally we used the default carbon to biomass ratio (0.5) to convert biomass to carbon.

Table 12. Average annual carbon sequestration used in the project.

	Denmark	Estonia	Lithuania	Latvia	Belarus	SE USA
	tC $ha^{-1}year^{-1}$					
Broadleaves	4.6	1.9	1.9	1.9	1.9	3.0
Conifers	5.7	1.8	1.4	1.4	1.3	4.8

2.4.5 Estimating landscape forest carbon stock and stock changes

The mean annual carbon sequestration for conifers and broad leaves from the different regions formed the basis for estimating forest growth and dynamics in the forest carbon stocks, as these were used to calibrate a standard growth model for conifer and broad-leaved forests (Figure 4). The model includes four thinnings throughout the life of the stand, where 35-50% of the biomass is removed and a final harvest after 70 years for conifers and 120 for broad-leaved stands.

The model was then aggregated into a landscape model, with a uniform age class distribution representing the above ground forest carbon stock in the living trees. Biomass expansion factors were then used to estimate the amount roots, hereby giving the full picture of the landscape carbon level for each of the growth regions described above. During harvest the model, also via biomass expansion factors, estimated the amounts of stems and harvest residues that is produced during forest thinning or harvest.

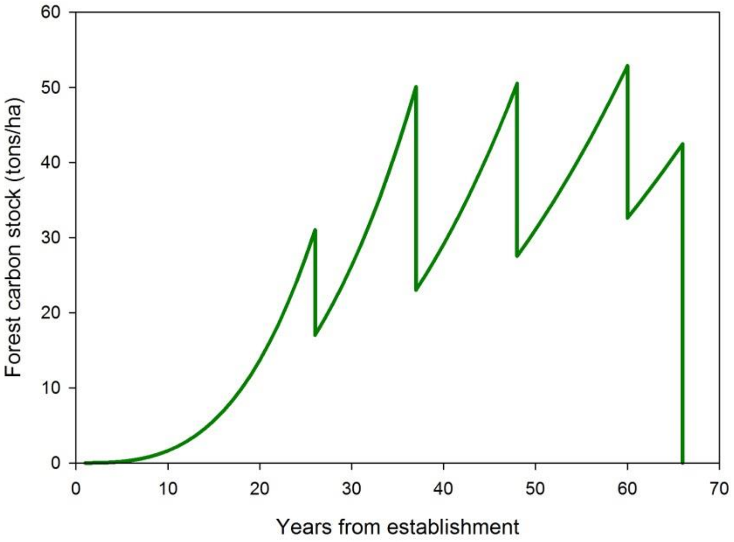

Figure 4. Dynamics in the living forest carbon in a forest with mean annual increment as estimated for a managed Baltic conifer stand.

As we here model a period where demand for biomass has been increasing, the forest carbon model assumes that all biomass that was used in the period is additional demand, hereby affecting the forest carbon pools (dead or alive). There is however a distinction between use of what is denoted true residues (see 2.5.1) and additional harvesting (see 2.5.2).

True residues affects the dead wood carbon pool, as the input to this pool is diminished when harvest residues are not left in the forest, but used for bioenergy. Therefore this pool moved from a no bioenergy equilibrium into a bioenergy equilibrium.

Additional harvest, can be all from harvesting corners that in the absence of bioenergy would not have been removed to doing harder thinning's or earlier final harvests. Common for these responses to increased demand for bioenergy, is that it drives the living forest carbon stock from a no bioenergy equilibrium into a bioenergy equilibrium, which is lower. The model estimates this lowering of the forest carbon stocks and this lowering is denoted the "carbon debt."

2.5 Biomass counterfactuals

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 reactions within the land use market (iLUC) or the product market (iWUC). Such market reactions may lead to additional GHG emissions or savings.

2.5.1 Alternative fate of residues from forestry and wood processing 'true residues'

Residues are biomass that is not in use for other purposes. In this study, residues can be harvest residues from forest operations, rotten stems or stems of low quality, not suitable for other products. 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 it is in surplus. Biomass with no other counterfactual than being burned or decaying over time was here denoted "true residues".

In modelling the alternative fate of biomass residues (either harvest residues in the forest or processing residues from the wood processing industry), 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 year after processing). If residues were left to decay, we assumed half-lifes for non-stem biomass (tops and branches) of 15, 10 and 5 years, respectively, for boreal, temperate and tropical climates. For stems left to decay, we assumed half-lives of 20, 15 and 10 years for boreal, temperate and tropical climates, respectively [43-45]. As such, the biomass represent 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. The forest floor carbon storage thus relies on the specific decay rate (half-life) of the biomass and the input to the. Use of residues where the counterfactual is being left in forests will thus reduce the dead biomass carbon pool of utilized forests.

2.5.2 Emissions from indirect effects (iLUC, iWUC and iFUC)

When the demand for biomass for energy exceeds the supply of residues, the prices may increase and influence GHG emissions from adjacent sectors. For example if the price for energy wood exceeds the price for pulp wood, the forest owner will likely sell the wood to the energy company instead of the pulp and paper mill. When this happens, the supply of pulp and paper wood will decrease. This may lead to expansion of the forest area from which biomass is harvested to meet the demand of pulp and paper inducing *indirect land use change* (here denoted forest iLUC). Moreover, forest iLUC can occur with increased demand for biomass that makes forest owners harvest forest compartments with poor quality trees that in the absence of biomass demand would have been left unharvested.

Increased demand for energy wood and the increasing price may also make farmers convert from agricultural crops into dedicated bioenergy crops, hereby diminishing agricultural production, which may push agricultural production to land that was not in use or to intensification causing iLUC [76]. Here denoted *agricultural iLUC.*

Finally, an increase in price for paper, due to the diminished supply, may make consumers shift to other products, causing and *indirect wood use change* (here denoted iWUC). Common for such land use and product shift is that it affects GHG emissions to the atmosphere.

Forest iLUC

Forest iLUC can affect forest land in three different ways, intensification of management in existing managed forests, expansion of managed forest into previously unmanaged forests, and a reduced supply (here treated as product shift - see iWUC section).

In our study, the case of intensification is only covered by additional harvesting, as the knowledge on the consequences of other intensification schemes in terms of forest carbon stocks is poor [77] and forest iLUC is thus treated as expansion of extensively or intensively managed forest into primary or secondary forests and additional harvest (which to some degree covers intensification). The situation, where forest management expands into previously unmanaged forests was modelled according to the method developed by [76]. In natural forests that are not affected by forest management, carbon stocks in living and dead biomass as well as in the soil are quite stable, as a result of an equilibrium between uptake with the photosynthesis and emissions from decaying biomass [78]. When such forests are taken into management, the carbon storage is affected on several parameters:

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

Input to the carbon pool in dead wood is reduced, as part of the biomass is extracted for products or energy.

In some cases the soil carbon pool is also affected due to lower input, induced by increased extraction.

For the carbon pool in unmanaged forest we used default carbon stocks given by Keith, Mackey [34] for the specific regions (boreal, temperate and tropic) as the reference carbon stocks. For the living forest carbon pool we used the region specific yield tables and the standard forest growth model, to determine both the living and dead forest carbon stocks. As such, the forest iLUC emissions were modelled as:

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

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.'

The situation of additional harvest is more diverse as it covers all other forest harvests in managed forests, which can be attributed to bioenergy demand. The dynamics are however similar to what is demonstrated above i.e. forest carbon stock moves to a lower equilibrium, than without bioenergy, and is describes in 2.4.5.

Agricultural iLUC

Increased demand for bioenergy may cause farmers to start producing dedicated energy crops on agricultural land. When such crops are taking up space, the amount of agricultural land that is available for food production is reduced, and may cause either intensification of existing agricultural land or expansion of agricultural land into undeveloped land, to sustain the level of food production.

Emissions from iLUC through expansion are modelled based on land net primary production (NPP), meaning that the potential NPP of food lost to dedicated bioenergy crops must be compensated by occupation of an area of land with an equivalent NPP. Agricultural expansion can have very different emissions, depending on the type of land that is occupied. For example, expansion in forest areas heavily reduces the carbon stock in living biomass on the land and iLUC emissions here are large. Oppositely, expansion into degraded land may cause an increase in the land carbon stock. Here we assumed that iLUC emissions occurred from deforestation of forested areas.

As the proportion of bioenergy crops was very limited (0.17% of the data material), we modelled agricultural iLUC only by a factor (0.5 times the emissions of processing and combustion), similar to the iLUC emissions presented in [77] for wood pellets from loblolly pine, grown in Georgia, USA.

Market pressure leading to land use change (dLUC)

Increasing prices on biomass may create an incentive for landowners to cut forest that would otherwise not have been cut and hereafter either leave the land degraded or to change the land use from forest to another form of land use e.g. agriculture.

The classic deforestation/degradation/land use change cases were modelled as a permanent removal of the above ground biomass i.e. immediate release of the carbon to the atmosphere with no recapture and a delayed release of the below ground biomass as decay. Here we used the same half-lives as described in 0.

Product shift iWUC

When the supply of timber for wood products is decreasing or demand is increasing, the price of wood 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 [76]. Therefore, to supply an unchanged demand for buildings or furniture with decreased wood supply inducing increasing prices on wood, producers will shift to other products, such as concrete, steel or plastic. As such, depending on the price elasticity, a proportion of the demand for wood will shift to other products, with a lower price. Here we assumed that all demand not supplied by iLUC (expansion of managed forest area or additional harvest) is shifted to other products such as steel, concrete or plastic i.e. full substitution. Such shift, may lead to increased emissions as many of these products have higher production chain emissions than wood [79]. The products that substitute wood can in some cases have emissions that are more than 10 times higher than wood and in other cases the emissions are nearly the same or in few cases lower [80]. Commonly this is expressed as a substitution factor (SF) that gives the carbon saving as a factor of the carbon in the wood used to 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 [79].

A newly published paper [54], finds that the mean substitution factor for other products replacing wood 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 1.4 for structural and non-structural parts, origin from sawn timber and 1.2 for panels and boards produced from industrial residues and 1 for pulp and paper.

Indirect fuel use change (iFUC)

The direct fuel displacement on the converted CHP or district heating plants was quantified directly from the data supplied by the data providers. The production on an individual CHP or district heating plant is potentially linked to other plants through connection to the same district heating network or the electricity grid. If the fuel switch on the plants included here led to a change in the production of heat and electricity this may have led to compensatory actions on other plants supplying the same district heating network or the electricity grid, which again may have changed the fuel use on these compensating plants, and in turn changed GHG emissions. These market mediated ripple effects in the heat and electricity market are considered as indirect fuel use change (iFUC), and the GHG emissions attributable to iFUC are added the bioenergy supply chain. Emissions related to iFUC can be positive as well as negative.

Indirect fuel use change related to the production of district heat was explored through a statistical approach, based on production data from the Danish Energy Agency (Energiproducenttællingen, confidential data).

The statistical model is:

$$Y_{ij} = \mu_{ij} + W_j + C_j + H_j + E_j + \varepsilon_{ij},$$

where Y_{ij} is the use of fuel (i) in year (j) at all contributors to the district heating network ex the converted plant, μ_{ij} is the overall mean, W_j is the use of wood biomass on the plant that was converted, C_j is the fuel capacity of the district heating network ex the converted plant, H_j is the heat production from all contributors to the district heating network ex the converted plant, E_j is the electricity production from all contributors ex the converted plant, and ε_{ij} is the random error. The statistical analysis was conducted as longitudinal data analysis taking into consideration auto correlation within model parameters.

The statistical analysis revealed that fuel changes at suppliers to a district heating network other than the fuel switched plant could not be attributed to the introduction of wood on the fuel switched plant. Consequently, in this analysis it is assumed that there are no iFUC GHG emissions with reference to district heat production. Further details on the analysis can be found in appendix 2.

GHG emissions from indirect fuel use change related to the production of electricity could not be quantified in a similar way as for district heat production. Here we assume that if electricity delivery to the grid changes following the fuel switch on a CHPt, then electricity production will be supplied elsewhere in the grid leading to changes in emissions. We used current and projected average GHG emissions related to electricity production obtained from the Danish Energy Agency to substitute for changes electricity production [55].

2.5.3 Biomass in different categories and counterfactuals

The biomass that was used by the CHP and DH plants was categorized into six categories: harvest residues, stems, bioenergy, Industrial residues, non-forest, and unknown. The counterfactuals to being used in heat and electricity production are described below.

Harvest residues are biomass from tops and branches, which are normally left on site and burned or for decaying after a harvest or thinning operation. As the counterfactual for harvest residues, we assumed that 30% were burned directly on the forest floor with a half-life on 0.5 and 70% was left in the forest for decay with the median decay rate at 10 years for the boreal, temperate and tropic regions. All harvest residues are considered true residues and therefore we assumed that there were no indirect emissions for this type of biomass.

Stems is a more broad category which contains undersized stems, stems with rot, bended stems or 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. For this part (90%) we assumed that there were no market mediated indirect emissions. However, the stem category can also hold 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 the stem biomass category leads to indirect emissions, with 5% attributed to iLUC emissions and 5% to iWUC emissions. The amounts of stems bearing iLUC/iWUC were varied in the sensitivity analyses**.**

Bioenergy is biomass originating from dedicated bioenergy crops on agricultural land. Here we assumed that 100% of the dedicated bioenergy leads to agricultural iLUC.

Industrial residues are mainly sawdust, bark, slabs, edgings, off-cuts, veneer clippings, sawmill and particleboard trim, when reduced in size, planer shavings and sander dust. Depending on the sawmill and the type of residue, the alternative fate can be all from burning or decaying on site to types from which indirect emissions occur. We made the same assumptions in indirect emissions for industrial residues as stems with 5% leading to iLUC and 5% leading to iWUC.

Non-forest 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 stems that were left for decay, with a half-life at 15 years.

Unknown biomass origin was treated as 50% for the stem category and 50% for the industrial residue category as these two categories were the largest**.**

The choice of 10% of the biomass with indirect emissions is arbitrary, as no data is available to describe this. Indirect emissions rely on three basic elements, product prices, price-demand elasticities and the cost of forest management after harvest. In the context of this analysis, market pressure occurs when prices for wood for energy exceeds the prices of one of the other products. In Danish forestry, the current net price for sawn timber, pulpwood are higher and fuel wood averages [81]. As such, there is currently little risk that forest owners will sell timber suited for sawn wood or pulp as energy wood and hereby put pressure on these markets under Danish conditions. Boards and panels are often made from sawmill residues, leading to risks that energy demand of these residues may put pressure on this market. However, on sawmills, approximately half of the stems that are sawn ends as sawn timber, where the remaining ends as residues. Compared with the current consumption of boards and panels relative to sawn timber, which is only 10% [82], much of the sawmill residues is historically and currently believed to be available for other use, making the risk of large scale iLUC and iWUC low.

Increased demand for bioenergy may also lead to harvest of biomass in forest compartments of poor quality for timber, that in the absence of bioenergy demand would be left unharvested or harder thinning’s. However, in most of Europe the forests are either intensively managed or protected by law, which is leaving only little parts of forests available for such additional harvest. Thus, only leaving the option of doing harder thinning’s to increase bioenergy output from such forests. As such, we believe that data on biomass origin presented in this study (77% from northern Europe) bears a relatively low risk of iWUC or iLUC emissions, but not that these emissions should be omitted (See sensitivity analyses and discussion for further elaboration).

2.6 Basic analyses

In the basic analyses, we used the assumptions listed in Table 1 and described above to calculate CPT and relative emissions 30 years after conversion (RE(30)), for each CHP and DH plant. We used the plant specific CPT and RE(30) to calculate a mean and median CPT and RE(30) for coal and natural gas plants, respectively.

Subsequently, we developed a “typical” plant, which is a plant of average size, with a weighted average conversion efficiency, and a weighted average fuel mix and sourcing strategy (see figures section 3.1). As such, the typical plant represents the full data set and can be interpreted as a proxy for the Danish transition from fossil to biomass fuels in CHP and DH plants, in the period 2002-2018, as the majority of data origins from this period. The typical plant was analysed for transition to biomass from both coal and natural gas and was used to conduct sensitivity analyses. For the typical plant, we also assumed 10% indirect emissions on stems and industrial residues, with equal proportions of iWUC and iLUC.

2.6.1 Analyses of key variables and sensitivity analysis

Where a large part of the model input described above is based on data, there are still several assumptions that are based on literature or a qualified guess and thus are subject to substantial uncertainty, potentially affecting the results significantly. To gain insight on the robustness of the calculated carbon emissions, expressed by CCE and CPT, we changed several assumptions one at a time and recalculated CCE, and CPT under the new assumptions.

First, we analysed how variations in assumptions related to transport distance affected the result by letting the “typical” plant first source all biomass from Denmark and thereafter from USA. Secondly, we analysed the effect of using either only wood chips or only wood pellets in the “typical” plant. Subsequently we analysed parameters related to the fuel category (residues, stems etc.). Here we analysed the sensitivity of the results to changes in decay rates (halt-lives) of biomass left in the forest (harvest residues).

We further analysed the effect of doubling and halving of stem biomass that had indirect emissions (5% and 20%). Here we used iWUC for all indirect emissions, to illustrate iWUC separately from iLUC.

For industrial residues, we also doubled and halved the amount of biomass bearing indirect emissions (5 and 20%). Here we used iLUC for all indirect emissions, to illustrate iLUC separately. In the analyses of iLUC we also tested the effect of intensification of forest management on the iLUC emissions.

There are no specific data on what sources of electricity that are replacing or are being replaced (wind mills, other biomass plants, or fossil fuel fired plants) by the changes in electricity production when fossil fuel fired CHP’s are converted to biomass fired CHP’s. Therefore, we demonstrated this effect in the sensitivity analyses, first by excluding iFUC and subsequently by using a natural gas fired plant as the substitute.

3. Results

3.1 Data presentation

The data material contained data from 10 district heat and CHP plants, where one of the plants had a CHP unit and a DH unit. Seven out of the ten plants had shifted from coal to biomass and two had shifted from natural gas. The last plant had first shifted from coal to natural gas and shortly after to biomass.

The fossil fuel origin were in many cases unknown, however, those who delivered data on this, had been sourcing mainly from Russia, Poland, South Africa, Colombia, and Norway and to a minor extend from Kazakhstan, Australia, and USA. The origin of the natural gas was not reported but was assumed Danish.

Approximately 32% of the biomass originated from Denmark and 41% from the Baltic countries, 7% from Russia and Belarus and 7% from USA. A part of the remaining biomass originated mainly from Norway, Sweden, Germany and southern Europe, with a few cases from Canada and Ghana. For the last part (6.5%), the origin was unknown (Figure 5).

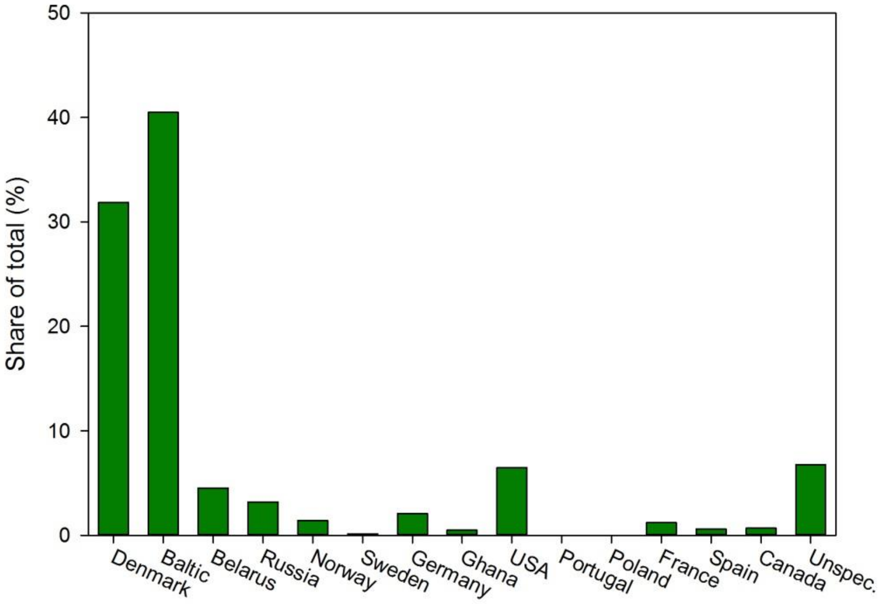

Figure 5. Origin of biomass sourced by the 10 heat and power plants included in the study.

Of all the biomass included in the analysis, 24% were residues from forestry, 34% were stems, 36% were industrial residues, 2.8% came from non-forests sources, and 0.17% came from dedicated bioenergy plantations.

3.2 Overall results for the cases included in the study

The conversion of the included power plants from fossil resources to bioenergy started in the mid 80ies, where two plants converted. One converted in the early 00'es and the remaining converted from 2009 to 2017. At the end of the studied period, biomass consumption for the converted heat and power plants totalled approximately 2.8 tons wood chips (30%) and wood pellets (70%), equivalent to an annual displacement of 2.85 million tons fossil CO_2 emissions in 2017. However, the displacement for individual years varies according to climate and other factors affecting the production, which the data extrapolation is unable to express.

The CPT for conversion of the coal plants to biomass ranged from 0 to 13 years (Figure 6a, thin lines). The relative emissions 30 years after conversion, RE(30), ranged from 0.29 to 0.85, corresponding to an emission saving of 15-71%, compared to continuation of the coal plants that were converted, 30 years after conversion. The plants with the short CPT and low RE(30) were the plants that had low or negative iFUC emissions and low iWUC/iLUC emissions i.e. plants with a high electricity production after conversion and a higher than average proportion of true residues in the fuel mix. Plants with reduced electricity production and a large proportion of stems and industrial residues leading to large iFUC and iWUC/iLUC emissions had longer CPT and larger RE(30).

For the natural gas (NG) plants the CPT ranged from 9-37 years (Figure 6b, thin lines). The relative emissions 30 years after conversion ranged from 0.81 to 1.05. The plant with the longest CPT and highest relative emissions 30 years after conversion, had very high iFUC emissions, but also iLUC and iWUC emissions.

There was no clear indication that other factors than the type of biomass (residues, stems, industrial residues etc.) and hence the indirect emissions (iFUC, iWUC and iLUC) were determining if heat and power plants had low or high CPT and RE(30), although some of the plants with large CPT had long transport distances for the biomass.

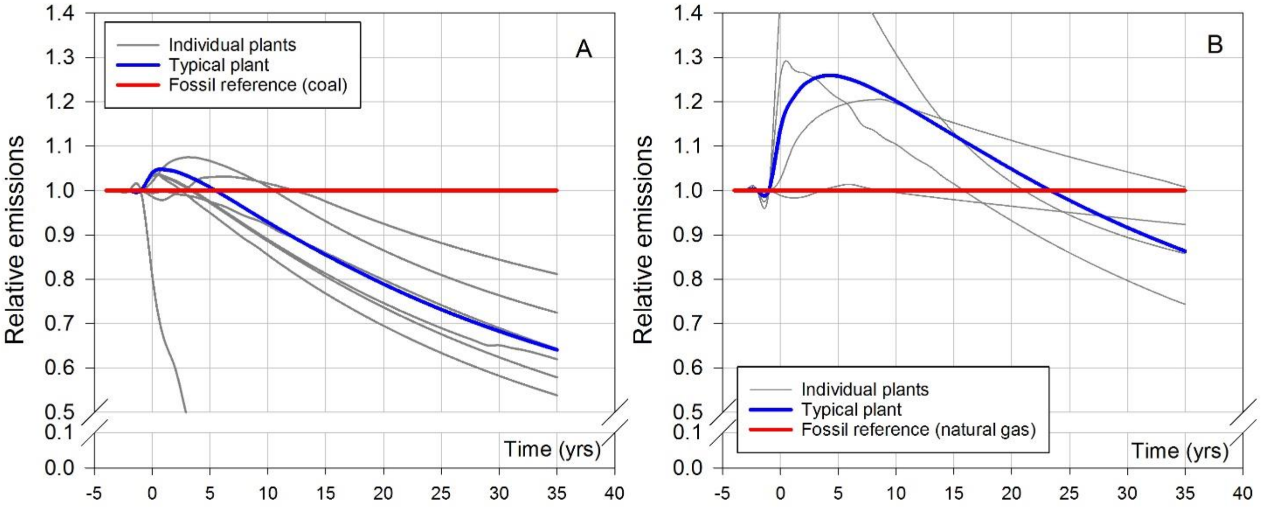

Figure 6. Relative emissions of the different heat and power plants part of the study divided according to the fuel source shifted from coal (A) or natural gas (B).

3.2.1 Emissions of the 'typical' case

The average biomass, coal and natural gas heat and power plant with an output on 2.6 PJ ('typical case') had direct emissions at 83, 74 and 52 kilo tonnes C, respectively, corresponding to a substitution factor for biomass replacing coal at 0.89 and for natural gas at 0.63, including process emissions. The corresponding substitution factors without process emissions are 0.94 and 0.64.

The 'typical' heat and power plant, representing the mean value of the data input variables lends itself for studying general patterns in the emissions. The 'typical' coal or natural gas fired heat and power plant had a CPT of 6 years for the coal plant conversion and a relative emissions after 30 years (RE(30)) at 0.69. For the natural gas conversion the CPT was 24 years and the relative emissions 30 years after conversion was 0.93 (Figure 7).

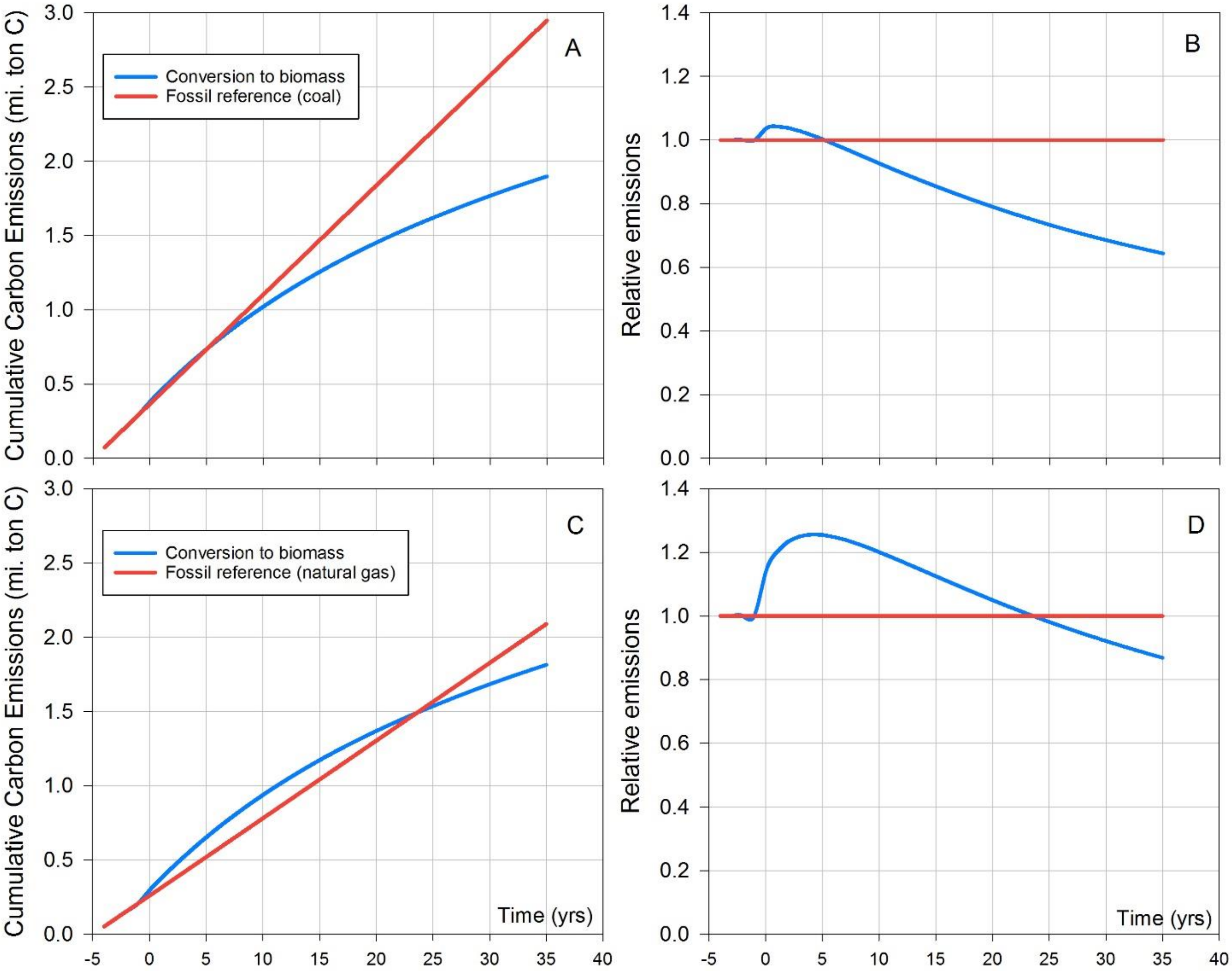

Figure 7. Cumulative net carbon emissions (CCE) for the "typical" transitions from coal and natural gas to biomass (a and c). Relative emissions for the same transition as above (b and d). Relative emissions are expressed as CCE from converting the plant to biomass divided by CCE from continuation of fossil fuel use.

For the biomass plant, the upstream emissions (forest operations, transport and processing), were adding up to 11% of the direct emissions, where for coal, mining and transport emissions were responsible for 8.5% of the direct emissions. For natural gas pumping and transport were 12.5% of the emissions (Figure 8). Although coal has higher energy content per tons than biomass, the transport emissions were higher for coal than for biomass due to a much longer average transport distance.

The emissions from mining of coal per unit energy were, however, lower in absolute terms than emissions from forest management, felling and processing of biomass, mainly due to the emissions from pelletizing and drying of wood pellets. In total, the upstream emissions were approximately 30% lower for coal than for biomass per unit energy produced. For natural gas, there was no data available and a standard factor was used to estimate upstream emissions. The upstream emissions for natural gas were however similar to the upstream emissions for coal.

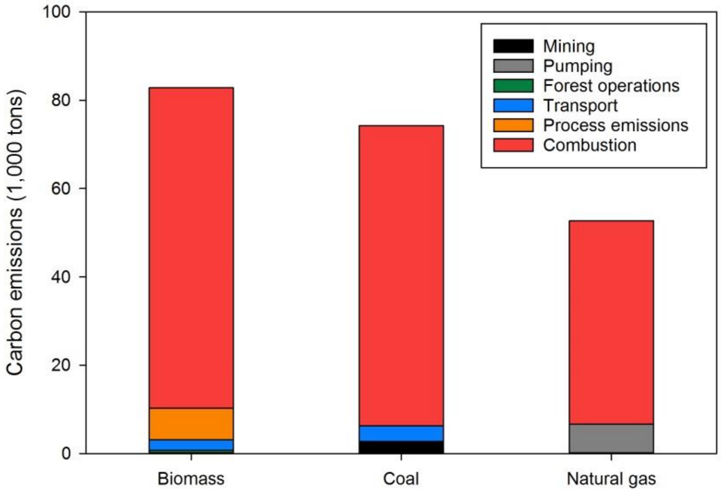

Figure 8. Direct carbon emissions for the mean biomass, coal and natural gas plants.

3.2.2 Carbon neutrality

It should be noted that the CCE curves for bioenergy (Figure 7a and c, blue lines) are larger than 0 which represents a net emission. Therefore, use of bioenergy cannot be considered carbon neutral. However, in time, if demand for bioenergy stabilizes at a certain level, the forest carbon stocks will also stabilize and the CCE will only represent the fossil fuels used in the supply chain (see decreasing slope in figure 7a and c). Moreover, if supply chain emissions in time becomes 0, the slope (annual CO2 emissions) of the bioenergy CCE will also reduce to 0. The forest carbon stock will in this case, however, still be lower than in a world without bioenergy and bioenergy will therefore not be entirely carbon neutral, but in this case not lead to additional net CO_2 emissions.

3.3 Transport modes and distances

Some plants sourced solely from Danish forests, where others sourced worldwide. For the “typical” biomass plants that sourced from Denmark, the upstream direct emissions were only 60% of the upstream direct emissions for plants sourcing from USA. CPT for typical biomass plant converted from coal and sourcing from Denmark was 5 years and the relative emissions 30 years after conversion was 0.67. For the same plant sourcing from USA, CPT increased to 9 years and RE(30) to 0.75. For a similar natural gas conversion, CPT and RE were 22 and 0.90 for the Danish sourcing strategy and 30 and 1.01 for the USA sourcing strategy.

Transport mode e.g. transportation by truck or by ship, has great implications on both CPT and RE(30), as transportation by truck has almost six times higher emissions per transported ton and distance than transportation by ship.

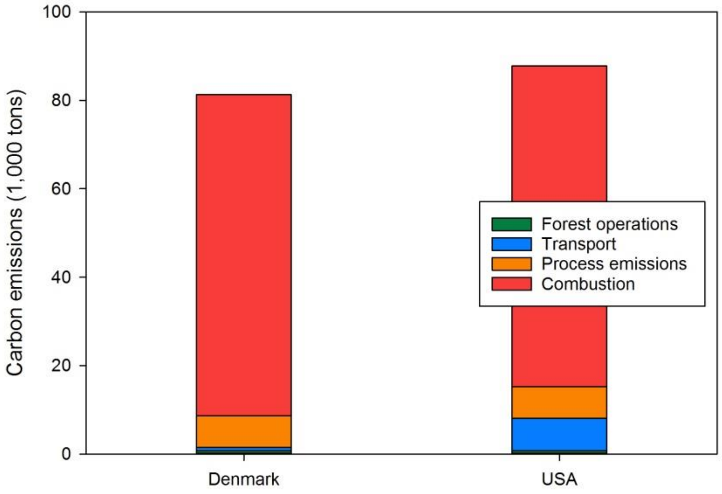

Figure 9. Direct carbon emissions for a typical biomass plant sourcing from Denmark and USA.

3.4 Wood pellets vs. wood chips

The lower heating value of wood chip and wood pellets differs, as the water content in wood chips is 45% and 10% in wood pellets. Thus, depending on the power plant, some of the energy from the burning of the wood chips may be lost in evaporation of the water in combustion. As such, for non-condensation heat and power plants, wood chips have higher combustion emissions per energy unit, than wood pellets (Figure 10). Moreover, pellets has lower transport emissions as the energy content is larger and less needs to be transported for the same energy output (Figure 10). Oppositely, wood pellet production uses energy (here assumed to be fossil), for the pelletizing process and for drying, where the wood chips only needs to be felled and chipped before combustion. Hence, wood pellets have larger emissions from processing than wood chips.

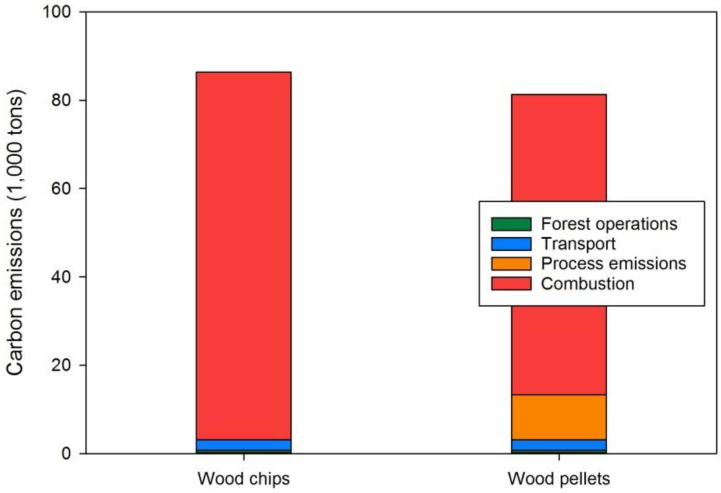

Figure 10. Direct carbon emissions for a mean biomass plant sourcing solely with wood chips a) and solely with wood pellets b). Possible differences in transport emissions caused by pellets typically sourced abroad are not included.

The two opposite effects of combustion and transport emissions leads to different results. For the "typical" heat and power plant using only wood chips, CPT was 7 years and RE(30) was 0.66. For wood pellets, CPT decreased to 5 years but RE(30) increased to 0.70. As such, the higher combustion emissions from the wood chips makes the emissions from combustion higher than for wood pellets leading to longer CPT, where the fossil process emissions make the long term benefit smaller, as these are not taken up by forests again, but represents a permanent increase of CO_2 in the atmosphere. Had we assumed that the pellets were dried with wood, this proportion would have been taken up and RE(30) would thus be similar or lower than for wood chips.

For a natural gas conversion using only wood chips, CPT was 22 and RE(30) 0.89, whereas, for the same CHP plant using only wood pellets, CPT and RE(30) was 24 and 0.94.

3.5 Fuel origin, contributions from indirect emissions and sensitivity analyses

The included plants had very different sources of biomass. Some plants had a high proportion of wood chips made from thinning and forest residues, where others relied on pellets produced from low quality stems and industrial residues. These differences have implications for the indirect emissions and hence for the calculated CPT and RE(30).

3.5.1 True residues with no indirect emissions

The conversion of a "typical" coal plant using only residues from forest operations (tops and branches) after the conversion had a CPT of 2 years and relative emissions 30 years after conversion at 0.47 (Figure 11). For a similar natural gas conversion only using residues with the basic assumptions, CPT was 8 years and RE(30) was 0.61.

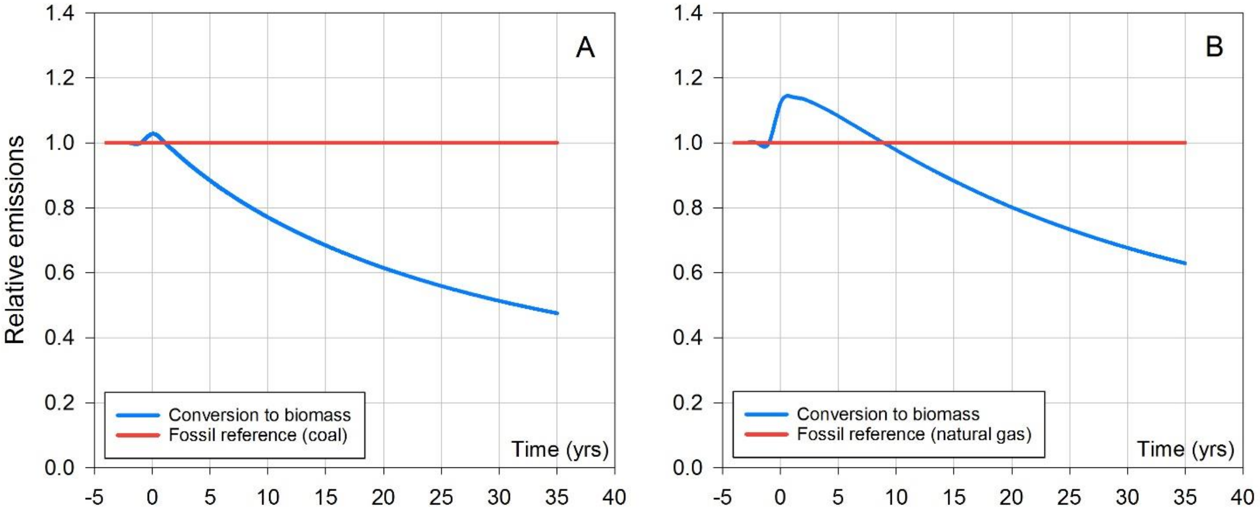

Figure 11. Relative emissions for the 'typical' heat and power plant using only residues converted from coal (a) and natural gas (b), with the basic assumptions.

In the basic model setting, the half-life of forest residues was 10, representing an average of the different biomes, from which the biomass was sourced. Biomass from other biomes has decay rates (half-lives) that are different. For half-lives of 5 years typical for the tropical biomes CPT decreased to 1 year and RE(30) decreased to 0.35. On the contrary biomass from northern boreal climate or large diameter stems with half-lives of 25 years, CPT was 3 years and RE(30) increased to 0.66. As such, sourcing small dimension forest residues from warmer climates with faster decay rates in the forests leads to shorter CPT and RE(30).

Tops and branches were considered true residues, however, stems that are removed in final harvest or thinnings that have no other economic value (typically damaged or rotten stems, unsuited for construction) are also considered a true residue. Stems, however, have longer half-lives than hervest residues and therefore using stems for energy has higher CPT and RE(30), as presented for the longer half-lives above. Some industrial residues also have no other use and are being left to decay or burned on site. Such stems and industrial residues are also considered true residues with CPT of 1-4 years and RE(30) around of 0.5-0.8, depending on the specific decay rate (not shown).

3.5.2 Stems with indirect wood use emissions (iWUC)

Stems used for energy production in most cases would be rotten, bend, damaged, or of a non-merchantable tree species and as such have no other use and can be treated as a residue from forestry. However, some stems that are burned may origin from quality timber, industrial timber or timber used for pulp and paper. Sourcing with such stems decreases supply of timber, increases prices, and may lead to product switch e.g. using concrete or steel in buildings instead of wood, leading to "indirect wood use emissions" (iWUC) or leading to expansion of managed forest into unmanaged forests “indirect land use change” (iLUC). In the basic model we assumed that 10% of the stems and industrial residues originated from such sources.

For the ‘typical’ plant converted from coal, sourcing only stems stems of which 10% are bearing indirect emissions (here represented by iWUC emissions), CPT was 10 years and the relative emissions 30 years after conversion was 0.77 (Figure 12a). For the similar natural gas conversion, CPT was 33 years and RE(30) was 1.04 (Figure 12d).

Doubling the amount of stems with iWUC emissions (20%) increased the CPT and RE(30) to 13 years and 0.81 for the coal case and a CPT and RE(30) increased to 44 years and 1.11 for natural gas. Halving it (5%) lead to CPT and RE(30) of 8 and 0.74 for the coal conversion and 30 and 1.00 for the natural gas conversion.

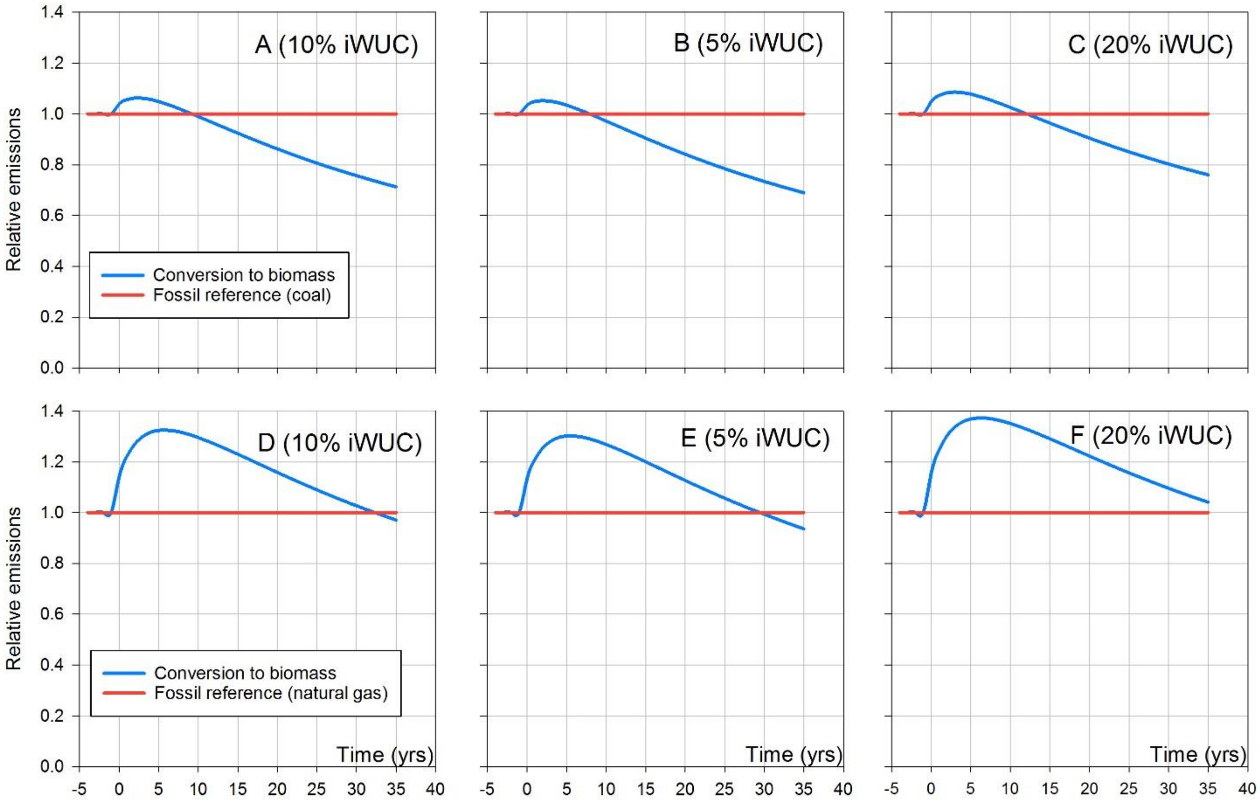

Figure 12. Relative emissions for the basic assumptions with 10% of stems having indirect wood use (iWUC) emissions, with coal a) and natural gas d) as the fossil fuel conversion. Relative emissions with 5% of the stems having iWUC emissions for a mean coal b) and natural gas e) plant conversion. Relative emissions with 20% of the stems having iWUC emissions for a mean coal c) and natural gas f) plant conversion.

3.5.3 Industrial residues with indirect land use emissions (iLUC)

For a heat and power plant sourcing industrial residues e.g. sawdust possibly used for wood panels, with 10% of the source leading to iLUC, CPT was 9 years for a coal plant conversion and RE(30) was 0.73 (Figure 13A). Increasing the share of biomass with indirect land use emissions to 20%

changed CPT from 9 to 13 years and RE(30) to 0.83, whereas halving it (5%) decreased CPT to 7 years and reduced RE(30) to 0.68 (Figure 13B and C).

By intensification of the forest management after the unmanaged forest have been converted to managed forest, CPT decreased to 12 years and RE(30) to 0.77 for a coal plant conversion with 20% iLUC emissions (Figure 13F), but had little effect on the results with a lower proportion of iLUC.

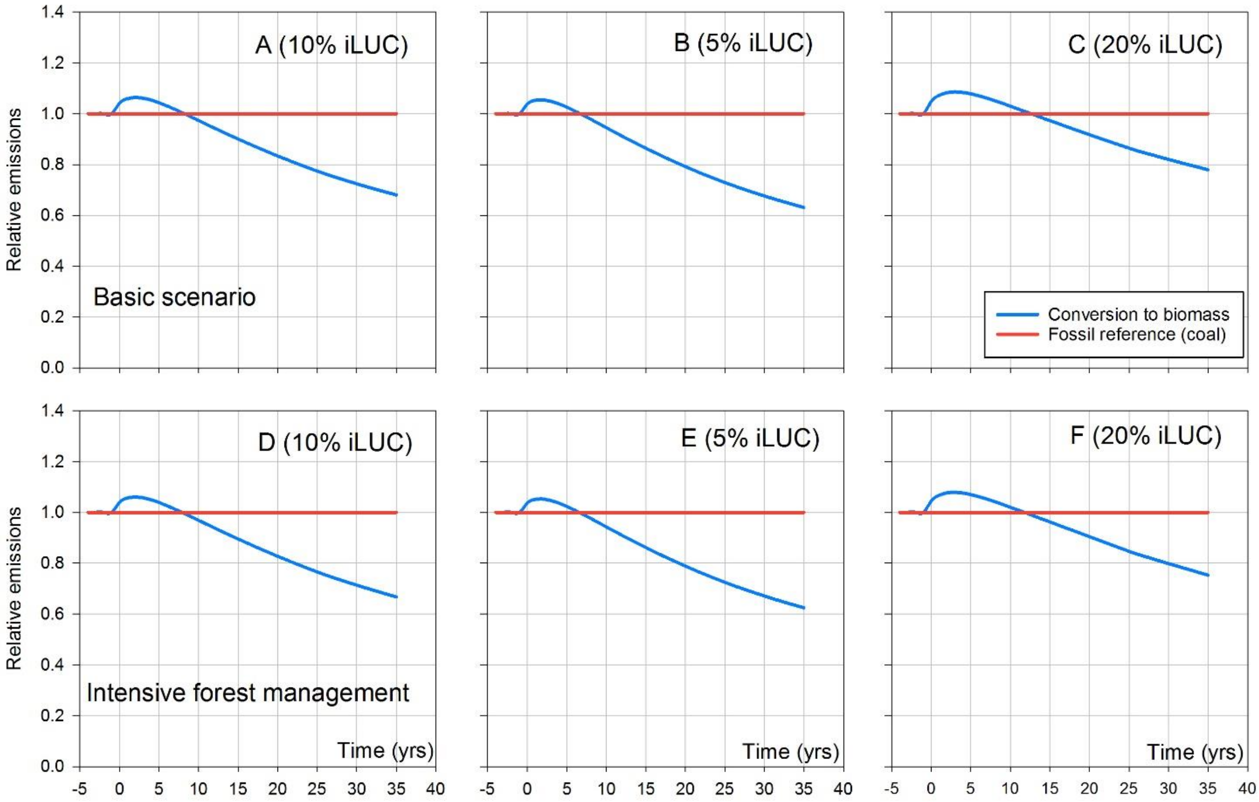

Figure 13. Relative emissions for a coal plant conversion using biomass with 10, 5, and 20% iLUC emissions and where forest after expansion are managed according to the basic scenario (a, b, c) and intensively (c, d, e).

For a conversion of a natural gas plant to biomass sourcing wood fuels with 10% of the source leading to iLUC, CPT was 28 years and RE(30) 0.99 (Figure 14A). Increasing the share of biomass with indirect land use emissions to 20% for the same plant changed CPT to 45 years and RE(30) to 1.12, while halving the sourcing of iLUC bearing biomass to 5% reduced the CPT to 24 years and the RE(30) to 0.92 (Figure 14B and C).

By intensification of the forest management in the forests sourced from, CPT decreased to 27 years and RE(30) to 0.97 for the “typical” heat and power plant converted from natural gas with 10% iLUC emissions (Figure 14D). Doubling the iLUC bearing emissions (20%) lead to a CPT of 41 years and RE(30) of 1.09, while halving the amount of biomass bearing iLUC (5%), produced a

CPT of 24 years and RE(30) was decreased to 0.91 in the intensive management case (Figure 14E and F).

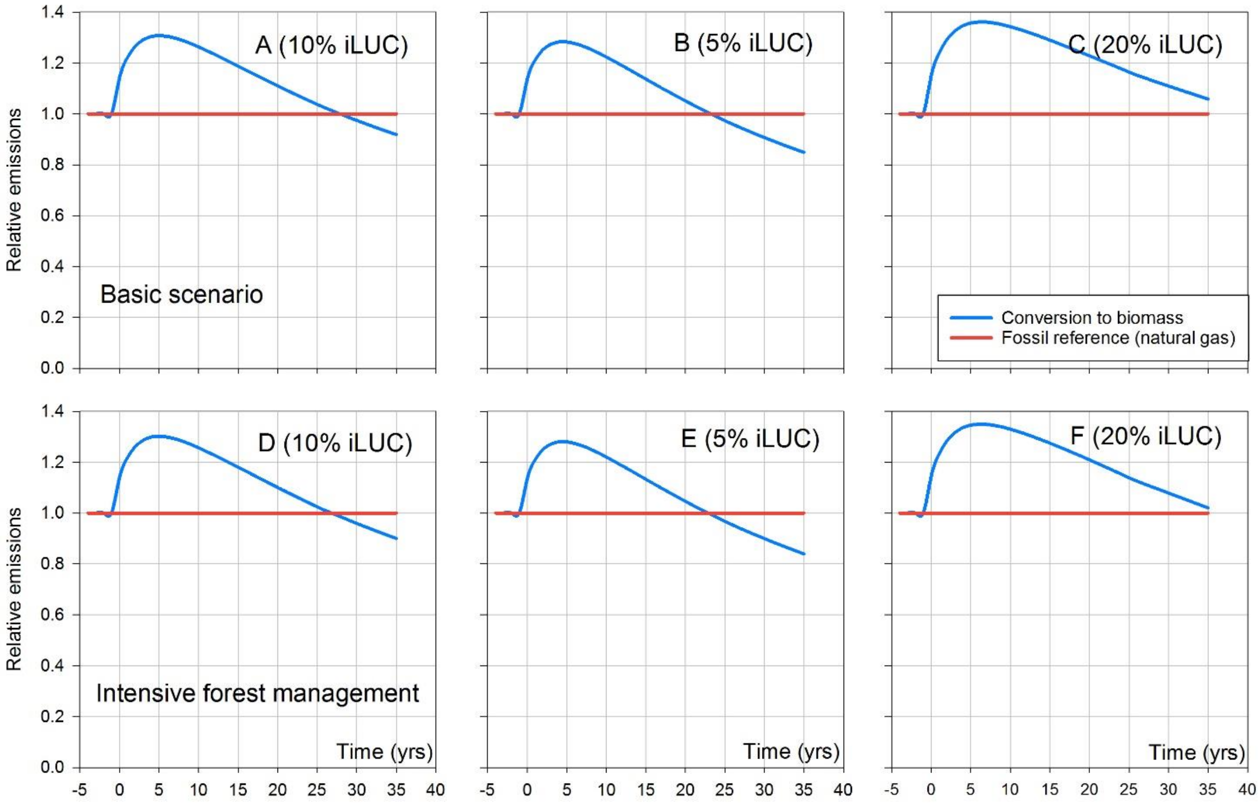

Figure 14. Relative emissions for a natural gas plant conversion using biomass with 10, 5, and 20% iLUC emissions and where forest after expansion are managed extensively (a, b, c) and intensively (c, d, e).).

3.5.4 Direct land use emissions

If plants are sourcing biomass that origin from deforestation or any other removal of biomass with no regrowth and if this can be attributed to increased demand on biomass for energy, CPT will never be reached. For a mean coal to biomass conversion emissions will permanently be 11% higher and for natural gas 37% higher (see also chapter 3.2.2).

3.5.5 Indirect fuel use emissions (iFUC)

The exclusion of iFUC lead to a 1 year reduction (6-5 years) in CPT for typical coal fired plants and a 2 year reduction for the typical natural gas fired plant CPT changed from 24 to 22. Changing the iFUC substitute to natural gas had no effect on CPT for typical coal and natural gas plants, as the reduction in electricity production for the typical coal and natural gas plant was very limited. Consequently RE(30) also only changed to a limited extend (+-0.02) (Figure 15).

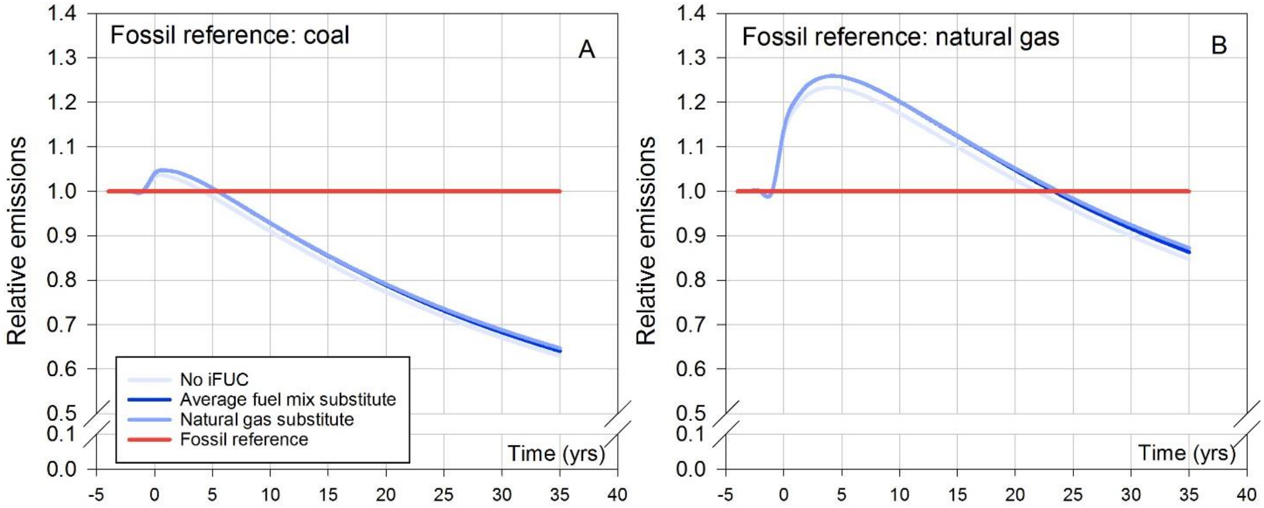

Figure 15. Sensitivity analyses on the implications of including or excluding iFUC and of which fuel mix is used as substitute.

The range in CPT among plants (from Figure 6) changed to 0-12 years for the coal plants by exclusion of iFUC and increased to 0-14 with natural gas as the iFUC substitute. For natural gas the corresponding range changed to 9-23 without iFUC, while with the natural gas substitute for iFUC the range of CPT increased to 9-72 years.

4. Discussion

In summary, the analysis showed that transition from coal to biomass had CPT between 0 and 13 years with the typical plant having a CPT of 6 years and transition from natural gas to biomass had CPT between 9 and 37 years, with the typical plant having a CPT of 24 years. Increased transport distances result in longer CPT. For the ‘typical’ coal to biomass transition a shift from national sourcing to sourcing from USA increased CPT three years. A corresponding sourcing shift for the ‘typical’ natural gas to biomass transition increased CPT seven years. Transport mode influence CPT, as transport by truck emits six times as much greenhouse gases than transport by ship. Transport, however, makes up 3% (range 1-10%) of the total direct GHG emissions, depending on transport distances. The choice of wood pellets versus wood chips had little impact on CPT. For the ‘typical’ coal to biomass transition, the use of wood pellets reduced CPT two years compared to using wood chips. For the ‘typical’ natural gas to biomass transition, the use of wood pellets increased CPT two years. The use of residual biomass resources reduce CPT. For the ‘typical’ coal to biomass transition, the use of residual biomass had a CPT of two years, and correspondingly for the ‘typical’ natural gas to biomass transition CPT was nine years. The inclusion of indirect (market mediated) effects (iLUC, iWUC and iFUC) generally extended CPT for transitions from both coal and natural gas to biomass (Figure 16). iLUC added 1 years to the ‘typical’ coal to biomass transition and 4 years to the ‘typical’ natural gas to biomass transition. iWUC added 1 years to the ‘typical’ coal to biomass transition and 3 years to the ‘typical’ natural gas to biomass transition.

iFUC added 1 years to the ‘typical’ coal to biomass transition and 1 years to the ‘typical’ natural gas to biomass transition.

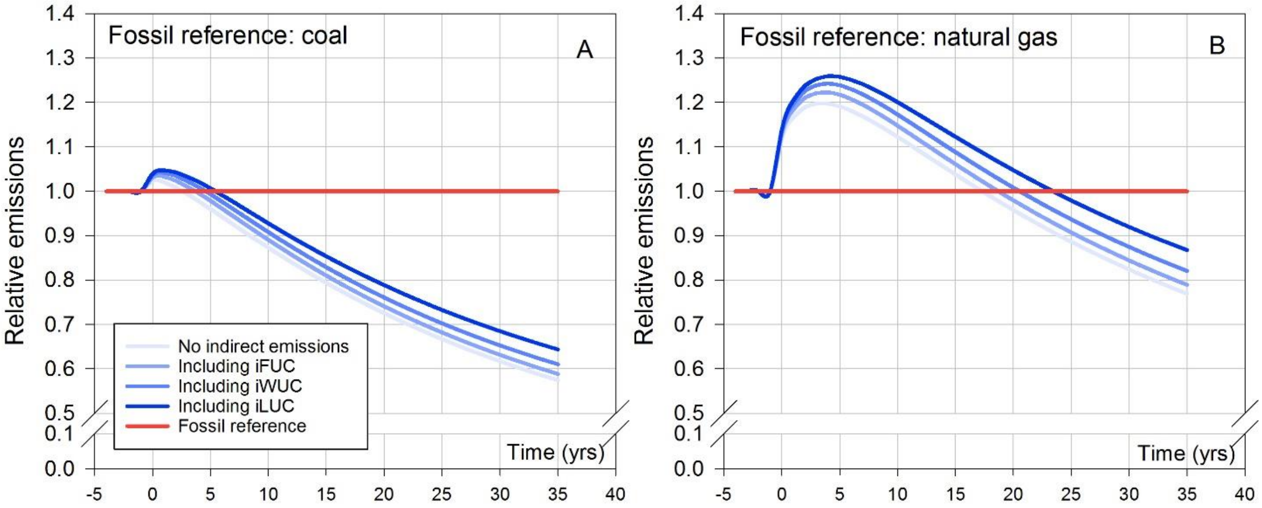

Figure 16.Cumulative impact on CPT for the ‘typical’ transition from coal (A) and natual gas (B) from the inclusion of indirect effects iLUC, iWUC and iFUC respectively.

4.1 Payback times

In all but one case CPT was reached within 22 years after the fuel transition, with the CPT for coal to biomass transitions below ten years, except for one at 11 years and one at 13 years, and the natural gas to biomass transitions from 9-22 years, except for one at 37 years. For transitions from both coal and natural gas, we found special cases where CPT was significantly longer than for the others. The main reasons for this were found in reduced electricity production after the fuel transition, which consequently led to high iFUC emissions, mostly influencing the natural gas plant. The special case for a coal to biomass transition sourced the main part of the biomass from USA and Canada leading to high transport emissions. Although the special case for the natural gas to biomass transition had a more regional sourcing strategy, still transport emissions here were larger than average. Finally, both cases almost exclusively based their sourcing on stems and industrial residues leading to increased risks of iLUC and iWUC emissions.

Oppositely, the cases with short CPT either had low or even negative iFUC emissions and/or a high proportion of true residues in their fuel mix. As such, electricity production after fuel transition and the fuel mix and origin is paramount to achieve short CPT and low RE(30). Cases with up to 50% stems and industrial residues in the fuel mix and sourcing within Europe achieved CPT below 10 years for coal to biomass transitions and 20 years for natural gas to biomass transitions. It is also evident that the CPT for natural gas transitions is more sensitive to sourcing strategy and indirect emissions. This corresponds with other findings in the literature, where the fossil fuel reference and leakage is among the key parameters determining CPT [30, 83].

CPTs reported here are in the lower end of payback times reported in the literature although we incorporated both indirect emissions and natural gas as a fossil fuel reference. Contributing to this outcome is the fact that we treat the biomass in the plants as residues for 90% of the biomass. Other studies assume in many cases that the biomass originate from dedicated harvest or from sources, where the supply already is equal to the demand before using biomass for energy. This would also result in higher CPTs for the cases presented here. CPTs reported here for sourcing strategies based on residues are in line with other studies (see e.g. [84, 85]. Additionally, the transitions analysed here were either for district heating plants or CHP plants with a large proportion of heat production. Such plants are more efficient than plants producing electricity only and the CPT's found in literature are correspondingly smaller for studies that analyze plants with heat production [30, 33, 83].

4.2 Methodological issues

Contrary to many other studies calculating emissions and CPT for use of biomass fuels versus fossil fuels, the analysis presented here is based on plant specific data on what and from where biomass is sourced, actual conversion efficiencies, and production data from actual fuel transitions. The analysis, however, is still vitiated with uncertain parameters, especially concerning assessments of how much biomass that leads to market mediated or indirect emissions. We recommend that this topic receive special attention in future studies.

This analysis builds on 40-year time series for each fuel transition. As the data we received from the participating utilities did not cover a 40-year period, we extrapolated from the first or last data point in the received data series to construct a data series spanning 40 years; from 5 years before the fuel transition to 35 years after. The purpose was to construct a time series long enough to estimate CPT and to cover a period corresponding to the lifetime of a CHP or district heating plant. By using the last point (or first) to extrapolate back and forth in time, we used the value closest to the data point we were trying to illustrate, however, this method does not capture variation between years and there is a risk that this year represent a special case. A short time series makes an assessment of this pitfall impossible. For the data material included here, this was only a problem for the natural gas to biomass transition with the long CPT. The time series after the fuel transition covered only two years, where the electricity production was very different than electricity production prior to the fuel transition. Had we extrapolated from the other year of the two years CPT would have been reduced to 29 years. The issue was assessed for all cases and was not found to change results significantly anywhere else.

For parameters where quantification was based on incomplete information, we often chose conservatively the case leading to the longest CPT. No information was available on the exact biomass sourcing locations and estimates on increment in forests were based on national forest inventories, which cover all possible growing conditions in each country, and not only suitable locations. As an example, in this study, the mean annual above ground increment of conifers in SE USA corresponds to 8.0 tonnes dry matter per hectare per year. Jonker, Junginger [86] analysed wood pellet production in SE USA based on coniferous species and modelled yield on productive sites to 9.7 tonnes dry matter per hectare per year. Forest yield directly influences CPT in cases where forest iLUC occurs an increased yield leads to reduced iLUC emissions as recapture of the released carbon is enhanced and hence to a shorter CPT.

Process energy for pelletizing is assumed to be supplied by fossil energy, which is probably not always the case. The analysis by Jonker, Junginger [86] assumed that energy for drying wood dust prior to pelletization was provided for by bark and shavings. The assumption used in our analysis leads to a worst-case scenario for biomass.

4.3 Conversion efficiency

A common assumption in the scientific literature is that the transition from fossil to biomass fuel leads to a decline in the efficiency with which the fuel is converted to electricity and/or heat; see e.g. Mitchell, Harmon [87] and Sterman, Siegel [88]. Madsen and Bentsen [33] demonstrated that a fuel transition on a CHP plant from coal to biomass can be done without loss of conversion efficiency, and this study corroborates that for a larger number of transition cases. On average, the coal fired plants had a conversion efficiency of 84% prior to and 83% after the transition to biomass. Similarly, for the natural gas fired plants; 88% efficiency before and 89% efficiency after transition to biomass. The high efficiencies stem from the plants producing either district heating or combined heat and electricity. While combined heat and electricity production is dominant in thermal electricity production in Denmark, the same is not the case in many other countries, and the results from this study cannot unambiguously be extrapolated to cover fuel transitions on thermal plants producing electricity only.

Some of the CHP plants included here experienced a shift in ratio between heat and electricity production after the fuel transition and in this analysis such shifts are attributed the fuel transition in the form of iFUC emissions. However, other underlying factors influence the operation of CHP plants and their heat-electricity ratio. The role of large centralized CHP plants change over time together with the build-up of electricity generation capacity from intermittent renewables; wind and solar power in Denmark. In addition, the increased electricity trading capacity through transmission grid interlinks influence the role of CHP plants. Finally, technical improvements introduced with plant refurbishment, e.g. steam turbine by-pass has allowed some CHP plants in periods to produce district heat only.

4.4 Indirect emissions (Leakage)

Indirect emissions or leakage cover GHG emissions derived from market mediated effects or telecoupling [89, 90]. Often indirect effects contribute most to bioenergy supply chain GHG emissions [91-93], but are the effects that build on the weakest scientific foundation [94, 95]. While there is scientific consensus on the existence of indirect GHG emissions related to bioenergy production, the quantification of indirect GHG emissions remains controversial. Generally, there is scientific consensus that using true residues, i.e. wood assortments for which there is no alternative use or market, for bioenergy purposes lead to short carbon payback times and that the use of these can provide rapid climate benefits [25, 30, 33, 87, 96, 97].

In the present study we included both iLUC, iWUC and iFUC in an attempt to capture the dynamics of all possible indirect emissions, however, our basic assumption was that only 10% of the biomass (stem and industrial residues) used by the CHP or DH plants were vitiated with indirect emissions. Even with the 10% indirect emissions assumed here, the CPT was much longer for stems and industrial residues than for true residues. In the sensitivity analysis, we increased fraction of biomass linked to indirect emissions to 20%, which returned even longer CPTs. The model we developed here would, if we assumed that all biomass was vitiated with indirect emissions, return CPTs of decades to centuries, which is in line with other studies also including leakage [83, 96].

Buchholz, Hurteau [96] and Bentsen [25] report that differences in model choice and inclusion of leakage are among the main cause of the observed large differences in carbon payback times across various studies, which points to the importance of analytical transparency, model calibration and seeking consensus on model choices. The model we present in here is such an attempt as it includes all possible leakage effects, but report their contribution separately.

With the assumption that 10% of stems and industrial residues were vitiated with indirect emissions, both iLUC and iWUC was addressed, and that changes in electricity production bared an iFUC emission. There is little empirical evidence to support assumptions on what fraction of a specific biomass assortment or a specific supply chain that can create indirect emissions. Global trade models, like the GTAP, attempt to model such dynamics, but these are typically very coarse in spatial resolution and limited in the number of product categories included [98]. Locally, competition and price elasticities can look differently than on the global market. For the category stems, we assumed that 10% of the biomass would create indirect emissions, as there is still a large price difference between logs that can be used for wood products and logs, which have no other use than decay in the forest floor. In Danish forestry, the current net price for sawn timber, pulpwood, and fuel wood averages 450 (60 €), 260 (35 €) and 330 (44 €) DKK m^{-3}, respectively [81]. However, including the costs of extraction, chipping, and transport reduces the net-prices to roughly 405 (54 €), 190 (26 €), and 110 (15 €) DKK m^{-3}. As such, there is currently little risk that forest owners will sell timber suited for sawn wood or pulp as energy wood and hereby put pressure on Danish markets.

This said, small loads of quality timber in forest harvests with large amounts of energy wood, may be used for energy, if the extra cost of separate transporting exceeds the price gain.The 10% in this study represents quality timber, with a product half-life of 35 years [52] and a substitution factor of 1.4 [54]. The net prices of pulp, paper and wood fuel assortments are closer and may with increased pressure on the bioenergy market switch and thus favour the sale of wood in pulp and paper quality for fuel purposes. The half-life of paper and cardboard is 2 years [52], meaning that in a carbon debt and payback time perspective using pulp and paper wood for energy has lesser influence on the payback time, than had it been sawn timber quality. However, the net price difference between wood fuel assortment and timber assortments remains large and hence there is little risk that bioenergy demand will affect the sawn timber market.

As for stems, there is no data that describes how large a fraction of the industrial residues that have indirect emissions. However, 40-50% of the biomass in timber logs is lost at sawmills in the production of sawn timber [53], meaning that there is an equal amount of timber and industrial residues available for the market. On the other side, the production of wood based panels (main product from industrial residues), only correspond to app. 10% of the amount of sawn timber in Denmark [82], and possibly also in other countries, making a large proportions industrial residues available for other products such as energy production. As such, this is reducing the risk that demand for bioenergy will affect consumption of wood boards and panels. However, with increasing use of biomass for various products, that is made by innovative use of forest resources, the proportion of industrial residues that may be vitiated with iLUC or iWUC will increase with increased pressure on the markets.

Increased demand for bioenergy may also lead to harvest of biomass in forest compartments of poor quality for timber, especially in countries were forests are managed extensively, relying on natural regeneration and no tending after harvest. Such forestry practices will reduce cost after felling and may make it profitable to harvest low quality/price compartments, which will increase the risk of iLUC by additional harvesting. Contrary, in intensively managed forests vitiated with higher costs (planting and tending) after interventions the low price of bioenergy compared with other assortments may make it less profitable to harvest low quality compartments and make the risk of iLUC by additional harvesting less. For our data most of the biomass origins from northern European countries e.g. Scandinavia, Baltic or Germany, where most forests are intensively managed which is reducing the risk of iLUC. Moreover, compartments with poor quality wood often has a protective function to forests e.g. forest edges sheltering the remaining forest, which is enhancing especially forest regeneration or are too wet to be harvested. National forest acts in northern European countries often protect previously unmanaged forests as well as wet forests, making these unavailable for additional harvest. Overall, this is leaving only little parts of forests available for additional harvest in the countries where most of our data origins. Additionally, the forest carbon stock in most European forest have been increasing over several decades or centuries[99, 100], indicating that overutilization of the forest resource is limited. Therefore, we believe that the risk of iLUC from additional harvest is limited in most of Europe in the period in scope, leading us to believe that our assumption that 10% (5-20%) of the stems and industrial residues bears iLUC emissions is reasonable for this data.

It should however be noted that in other countries with large extensively managed forest areas, where regulations are poor or absent, with high levels of corruption and poorly developed forest sectors, there is a much larger risk of iLUC occurring, especially in the form of additional harvest. We encourage that the issues of iWUC and iLUC for bioenergy receives much more scientific attention in the future.

4.5 Future sourcing strategies

This study points to a number of issues that must be taken into consideration in planning and documenting future biomass strategies. Truly residual biomass must be prioritised over biomass with other applications should there be a market for it. Shorter transport distances must be prioritised over longer although transport contributes little to the total supply chain GHG emissions. Displacement of coal with biomass should be prioritised over displacement of natural gas with biomass. In addition, the current and future role of electricity producing units must be taken in to consideration to address potential indirect effects in the form of iFUC.

Sustainable sourcing strategies must also consider the impact of biomass harvest on other ecosystem services. Producing and harvesting biomass in forests to mitigate climate change often exhibits synergies and trade-offs with other ecosystem services, e.g. biodiversity protection, ground water protection, and visual impacts [101-103]. Many sustainability issues are already addressed by the current industry agreement to ensure and document sustainable biomass sourcing in the Danish energy sector [56]. A recent political decision will, in the near future lift the industry agreement from a voluntary industry initiative to a national law with an expected expanded focus on conserving carbon in forest ecosystems and reducing carbon debts. Whether indirect effects (iLUC), as they are included in e.g. the Dutch sustainability verification and documentation framework [56], will be included in the Danish law, is still unknown.

5. Conclusions

The purpose of this study was to analyse the climate impacts through carbon emissions to the atmosphere and the timing of such following the transition from coal or natural gas to forest biomass on district heat and combined heat and power plants in Denmark.

Based on the analysis we conclude that over the typical life-time of a district heat or combined heat and power plant, the transition from fossil fuels to forest biomass reduced emissions to the atmosphere relative to continued use of fossil fuels.

For transitions from coal to biomass, reduced CO_2 emissions to the atmosphere was achieved on average within 6 years (range 0-13 years). After 30 years of operation CO_2 emissions would have been reduced by 15-71% relative to continued use of coal depending on supply chain configuration. For transitions from natural gas to biomass, reduced CO_2 emissions to the atmosphere were achieved within 24 years (range 9-37 years). After 30 years of operation CO_2 emissions would have been reduced by -4-25% relative to continued use of natural gas depending on supply chain configuration.

We also illustrated that the shortcut to fast CO_2 emissions reduction and large emissions savings relied on sourcing biomass locally and by using small dimensioned true residues with no alternative use (no indirect emissions) and fast decay rates, had these been left in forests. On the contrary sourcing biomass that had a larger risk of inducing indirect emissions (iLUC and iWUC) significantly reduced the emissions savings and extended the period in which biomass had higher CO_2 emissions than continued use of fossil fuels. We therefore emphasize that indirect emissions receive more attention in future research.

Finally, we demonstrated that reduced electricity production capacity, leading to iFUC emissions, only had limited general effects on the results. However, this effect was large in one special case.

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Appendix 1: Assessment by the reference group

Green Transition Denmark, Danish Society for Nature Conservation and Concito have participated in the reference group for the project: ‘CHPs in transition’ undertaken by IGN at the University of Copenhagen.

The output of this project is the report “CO2 emission mitigation through fuel transition on Danish CHP and district heat plants”

Throughout the project, the reference group has been involved several times at various stages of the project.

The process has been transparent, and we are satisfied with the level of involvement and information shared as well as the overall undertaking of the project.

The choice of review panel was discussed with and accepted by the reference group.

Appendix 2: Assessments by scientific reviewers

Comments and suggestions received from the scientific reviewers are listed in the table below together with the author's responses and actions taken. Line numbers refer to the first draft of the report and does not match line numbers in the final report.

#	Reviewer comments	Author response
A	*Thomas Buchholtz*	
	General comments	
A1	The case studies need to be presented. Since it is only 10 case studies, I think you can introduce them with both baseline and bioenergy scenario at least in the appendix if it is deemed to detailed in the main study (but I would highly recommend to include them). The most important metrics would include: Bioenergy system type, (CHP, heat only), Bioenergy system start time, (size), souring of biomass, counterfactual for heat when not matched by system size (IFUC) as well as counterfactuals as they pertain to forest management and wood products.	In an earlier version of the report, the individual cases were presented in detail, however, due to the non-disclosure agreement between the project group and the data providers we had to anonymize presentations and results so that no individual plant or data provider could be identified. We have expanded table 2 to provide as much relevant information as possible.
A2	The counterfactuals need to be potentially revised and presented in detail. Depending on the time of the commencement of the bioenergy system, coal might not be an appropriate counterfactual anymore. It might have been in the 80ies, but not in the 2010ths. It might differ a lot from case to case. This needs to trickle down to the conclusions and abstract as well. While systems that started in the 80ies probably easily have reached their CPT (compared to coal) by now, new systems should be compared to natural gas (CPT >20 years it seems). Also, for IFUC, when is heating oil used, when is natural gas used if e.g. systems decreased or increased in size? I would assume that differs significantly based on year of commencement.	The purpose of this analysis was to, retrospectively, analyse the effect on GHG emissions from historical fuel transitions. It is assumed that if the individual plants had not shifted from coal or natural gas to biomass, they would have, in lack of better alternatives, continued for an unknown period of time on coal or natural gas. We fully agree that projecting fuel transitions into the future, coal and increasingly also natural gas is not a relevant counterfactual. The purpose of this analysis, however, was not to project future fuel transitions but to analyse the GHG effects of historical fuel transitions. To make this point more clear we reformulated aim 1 into: *Inform the scientific, public and policy debate on the potential CO2 emissions savings of using forest biomass for heat and electricity production instead of fossil fuels.*
A3	Introducing the LCA assessment. I think it would help tremendously to introduce the LCA elements in a graph and discuss them. To some extend this can overlap with Figure 3 but that figure is more a GHG flowchart than an LCA graph which would be simpler. I would recommend to separate out baseline and bioenergy scenarios in that graph	We have made a new figure 3 that presents the processes and LCA elements included in the analysis.

A4	Result presentation. Results should be presented on a case by case. How representative is the average? I guess the systems were vastly different (heat only vs CHP, sourcing of wood, commencement date, etc.). As mentioned above, you have 10 cases that is still a number you could handle and introduce one by one with a baseline vs. bioenergy scenario vis a vis. It is hard to read between the lines when it is all lumped together. For instance, did some of those systems use a lot of imported pellets from the southern US? That would have a very different outcome than a system with a comparable commencement date that would use industry residues only. Reporting an average seems to be potentially very misleading.	See our response to #A1 on confidentiality and anonymity.
A5	Forest management. I don't think it is defensible to compare a forest management scenario to a no-forest management scenario. I think it is more appropriate to compare a less-intense forest management scenario to a more-intense forest management scenario	The analysis does not compare forest management with no-management, but this was not communicated clearly in the first version of the report. We have elaborated on this in section 2.5.2.
A6	Forest C stocks. First, do you assume new stands, i.e. start at 0 stocking? Or do you assume existing forest C stocking and then project different C stock trends with and without biomass removal? This is unclear to me. If this is starting with an existing forest, did you assume even distribution of age classes? Second, is this a stand level analysis or landscape level analysis? Did you model repeated harvests over the years? I assume so but it would be helpful to spell it out again. Both points would benefit a lot from a graph where you show forest C stocks (and if it is only for a conceptual illustration) at year 0 out to year 40 for both baseline/counterfactual and bioenergy scenario.	Here we have added a new section to the report (2.4.5), where this is spelled out.
A7	IFUC. I don't see the value in adding this element. I think it is simply part of the counterfactual. It is simply a different baseline/bioenergy scenario where fossil fuel emissions are accounted for in either scenario. These are not indirect emissions from my perspective. I find the iFUC concept somewhat confusing. It could be bypassed by 'just' clearly describing (verbally and in a figure/flowchart) the baseline (or counterfactual) and bioenergy scenario. See also bullet point 'Introducing the LCA assessment'.	We agree that the indirect fuel use change could have been included in the counterfactual. We chose to keep iFUC and other indirect effects separate as it enable us to present the contribution of indirect effects separately. As we write, the quantification of indirect effects is controversial and we wanted to demonstrate how inclusion/exclusion of indirect effects affected the results.

A8	ILUC for biomass feedstock. I don’t think your economic argument for ILUC works in the conclusion. You quote a price of ~25 Euro/m3 for pulpwood in Europe. Industrial pellets sell for ~150 Euro/ton.	We have found no evidence neither confirming nor rejecting this and this is a topic that deserves more scientific attention, as these two markets are close. This is however covered to some extend in our sensitivity analyses, where marked mediated indirect emissions are varied from 5 to 20%.
	Specific comments	
A9	Abstract, Line 107-109: You need to state here more clearly, what your baseline assumptions are. Do you compare to coal? Natural gas? Other renewable electricity options? This is crucial and I think not only stating the baseline assumption but also a justification would deserve to be mentioned in the abstract. Also, for the bioenery scenario, what kind of biomass? It also would be worthwhile to briefly list the crucial LCA steps undertaken. Where does the LCA start, where does it end, which steps were potentially not included in the boundary and why (e.g. de minimis, or just another focus)?	This is now also stated in the aim of the report that we compare to fossil fuels (coal and natural gas) Also stated in the aim of the report. We think discussions on justifications is too long for an abstract and the crucial steps are already mentioned. A new figure 3 illustrate the processes and flows included in the analysis.
A10	Abstract, Line 121: Show what drives these results. Is it feedstocks? CHP vs heat only? Fossil fuel baseline scenario?	This is mentioned later in the abstract.
A11	Abstract, Line 125: Secondary (Industrial) residuals from sawmills etc or primary residuals from forest operations? If primary residuals, it is worth to state what these are to show that these are truly residuals (tops and branches) and cannot potentially be used for other products such as pulp (in that case it would not be residuals – market conditions would need to be discussed).	Both. This has been elaborated in the abstract. It has been elaborated that it is unusable residues.
A12	Introduction, Figure 2: Or where does imported biomass come from? Any trends?	For simplicity, we have not included the trends in biomass sourcing origin in the introduction. The origin of biomass fuels used by the plants analysed is presented in the data section.

A13	Introduction, Line 200: Just a thought: I think the sustainability question in general is focused a lot on habitat, social and ecological functions. GHG implications are often not covered. It helps sometimes to discuss both issues (sustainability/GHG implications) as separate items. You can have sustainable management but go horribly wrong on GHG. The other way round is also possible. I can explain more if it helps.	We agree that sustainability is not equal to GHG emissions and vice versa. In section 1.3 we introduce the general sustainability debate in Denmark and highlight some of the more common aspects of sustainability debated, and the political actions taken in response. In section 1.4 we narrow the focus to the scope of this study, GHG emissions.
A14	Introduction, Line 218: Section 1.3 and 1.4 go in the direction of my comment above. I think it really helps to treat both issues seperately.	We agree and have done so in section 1.3 and 1.4.
A15	Introduction, Line 229: Schlamadinger and Marland 1995/1996 started the concept. Schlamadinger, B., Spitzer, J., Kohlmaier, G. H., & Lüdeke, M. (1995). Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy*, *8*(4), 221–234. https://doi.org/10.1016/0961-9534(95)00020-8 Schlamadinger, Bernhard, & Marland, G. (1996). The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy*, *10*(5), 275–300.	We have clarified that the TERM carbon debt probably entered the scientific vocabulary with the 2008 paper in Science, while the CONCEPT of carbon debt dates back to 1995-96 to Schlamadinger et al. (1995, 1996) and Leemanns et al. (1996).
A16	Introduction, Line 246-251: It might help to differentiate those in terms of (fossil fuel) baseline as well as energy system in terms of energy outputs (CHP, Heat). Replace with ’feedstock origin and forest management’ since this also incorporates secondary residues. It might be worthwhile to call out the forest biomass conditions analyzed here if they were already clear at the beginning of the study	We have differentiated between fossil fuel baseline, energy system outputs as well as between feedstock origin and forest management system and added a number of examples. We have clarified that the cases treated here shifted from coal or natural gas to either wood pellets or wood chips. Biomass conditions were not known in detail when the study was initiated.

A17	Methods and data, Line 308: I would strongly suggest to add a graph that shows the LCA elements and boundary. I would also strongly suggest to better explain the basic assumptions on forests.	A new figure 3 illustrate the processes and flows included in the analysis.
	Do you start with a newly established forest, i.e. a 0 carbon stock at the beginning? Or do you assume an existing forest C stock and then project C stocks out over time under baseline and bioenergy scenarios? Do you track just one stand (initial one-time harvest) or do you model repeated harvests within a landscape over a 30 year timeframe?	See our response to #A5 and 6. The newly added section 2.4.5 explains in more detail forest assumptions.
	I would strongly suggest to have a paragraph on baseline and one on bioenergy scenario descriptions plus an extensive justification for both scenarios. For instance, it is very controversial to compare bioenergy to coal by now as coal is shut down (in general) across Europe. Therefore, the baseline scenario might be arguably not the continuation of coal but a conversion to another fossil fuel (e.g. natural gas) or some other renewable alternative. This is not really clear here in the methods section.	See our response to #A2. Furthermore, the aim of the study has been reformulated to make this clear.
A18	Methods and data, Table 1: Does this mean you start with newly established forests? Or do you assume an existing forest with an existing carbon stock and existing carbon stock trend under a baseline scenario? This needs to be spelled out much clearer and might also deserve a graph.	The forest baseline conditions are furher explained in the newly added section 2.4.5.
A19	Methods and data, Line 336: Good info. So this means you start with existing forest C stocks and model out C stock trends over time over both scenarios?	Yes, see the newly added section 2.4.5 where this is explained.
A20	Methods and data, Line 499: It is still unclear to me how you used all the forest C uptake info above in the model. Did you assume existing forest C stocks with an even age class distribution? What were your forest management conditions under both baseline and bioenergy scenario by region? It might be good to have a table here that summarizes these assumptions.	We have elaborated on this in section 2.4.4 and added a new section 2.4.5 describing how the forest model works.

A21	Methods and data, Figure 4: Ok, maybe this is the figure I am looking for. So you starting with newly established forests? How would the newly established stand be managed under the baseline scenario? I assume this is the bioenergy scenario? Did you stagger the stand establishment over time to get to a landscape model or did you track only one stand?	We have elaborated on this in section 2.4.4 and added a new section 2.4.5 describing how the forest model works.
A22	Methods and data, Line 520: This is crucial feedstock info. So you used two feedstock alternatives for the bioenergy scenario. I would strongly recommend to spell all those alternatives out in one dedicated section and potentially a graph in the methodology for each LCA accounting element (e.g. Feedstock, in forest processing, transport, (wood products elements such as product manufacturing and in-use and post-use fate), energy generation, etc). You do this to some extend below but I think it would help to show in a graph, at least, how these LCA elements fit together by scenario (and potentially sourcing region).	We have included a new figure 3 illustrating processes included in the analysis.
A23	Methods and data, Line 568: Not sure why that matters? Do you compare in any scenario managed vs. unmanaged forests?	This has been elaborated in section 2.4.5 and 2.5.2.
A24	Methods and data, Line 628: Where there situations where a current CHP plant powered by e.g. coal was replaced with a heat only biomass system or the other way around? Is this what you are after? I don’t know if I would introduce a iFUC concept in this case. It is simply a differen baseline/bioenergy scenario where fossil fuel emisisons are accounted for in either scenario. These are not indirect emissions from my perspective. I find the iFUC concept somewhat confusing. It could be bypassed by ’just’ clearly describing (verbally and in a figure/flowchart) the baseline (or counterfactual) and bioenergy scenario.	See our response og #A7 on iFUC.
A25	Methods and data, Line 659: Ok, so this provides more details. While this discusses counterfactuals just in the context of feedstocks, I think counterfactuals need to be discussed more broadly as a bioenergy vs. baseline scenario ’package’.	Other elements of the counterfactual ‘package’ hereunder indirect effects are further discussed in section 2.5.2 and in the discussion.

A26	Methods and data, Line 665: I think this is too general for all regions. E.g. it is not known to me that any residues are burnt at all in central Europe.	This is a part of the counterfactual, a world without bioenergy. Before bioenergy emerged it was common in Europe to pile and burn forest residues.
A27	Methods and data, Line 670: Undersized for what? Pulp? Then it is harvest residue. Did you also consider a scenario where these stems would not be cut in the first place (forgone pre-commercial thinning)? This question might be easily put aside if you spell out baseline/bioenergy scenarios above.	Yes, then it is considered a residue. Yes this is a case where forest thinnings are e.g. 5-20% lower and where bioenergy induces iLUC by additional harvest, which is reducing forest carbon stock.
A28	Methods and data, Line 674-676: This is very general. Again, big differences by sourcing region. Did you do a sensitivity analysis on this? If yes, maybe mention here the sensitivity bounds?	Sensitivity analyses are presented here and described further in the subsequent sections.
A29	Methods and data, Line 677: This is a confusing definition for me. Why is it needed? Or are you just in need a term for dedicated agricultural biomass feedstocks?	This is the definitions from the dataset we received from the utilities.
A30	Methods and data, Line 694: I disagree. Especially in the European context. We see considerable overlap of bioenergy and pulp markets.	We have found no evidence neither confirming nor rejecting this and this is a topic that deserves more scientific attention, as these two markets are close. This is however covered to some extend in our sensitivity analyses, where marked mediated indirect emissions are varied from 5 to 20%.
A31	Methods and data, Line 704: Wouldn't the baseline scenario be a scenario where you harvest less, rather then nothing? I don't think the extreme version – no harvest vs. Harvest, is representative. Isnt it more a situation where you compare a low-level harvest (e.g. just removing valuable sawlogs) vs a higher level harvest (removing small-diameter trees along with sawlogs)?	iLUC covers this. See section 2.5.2, where we have elaborated on this point.

A32	Methods and data, Line 735: There is literature on this topic. If it is inconclusive in the case of Denmark, it would be important to show results through a variety of baseline assumptions, not only natural gas. Is there a grid emissions factor goal (e.g. tons of CO2e/MWH)? That could also serve as a reference point (does the bioenergy system help in achieving this goal or not)?	We agree that there is a lot of literature on this mainly modelling the dynamics of energy systems and their response to changes in electricity production. There is, however very little historical information AVAILABLE on how changes in production on a specific plant migrated through the energy system. Furthermore, the marginal electricity production is dependent on time horizon, where the short term marginal often is assumed to be fossil fuel on power plants in condensation mode, while the longer term marginal converges towards average electricity production. Our approach for this analysis was discussed with the Danish TSO (Energinet) and the Danish Energy Agency. We have not included grid loss in the analysis as we have assumed that the shift form fossil to biomass fuel would not require an upgrade of the grid.
A33	Methods and data, Line 738: IFUC has not been introduced yet.	IFUC is introduced above in section 2.5.2.
A34	Results, Line 758: It was not clear to me that you went back to the 80ies. It might be worthwhile to spell this out further in the introduction that you assessed older plants as well as very recent or potentially future conversions. I think this plays a major role since baseline/counterfactuals (besides energy efficiencies at the plant) differ quite a bit over time. It was a viable assumption in the 80ies in Denmark to continue on coal but not so anymore in 2020.	The time frame of our analysis and data is further elaborated in section 2.2.1.
A35	Results, Line 777-780: This is crucial. Feedstock type drives results. Another major driver I assume would be overall plant efficiency. Were all of them CHPs? I am not quite sure	See table 2 for plant specific information on DH or CHP. It should also be noted that the CHP plants has a very large proportion of their production being heat, so there is not such a big difference between DH and CHP with regards to plant efficiency.

A36	Results, Figure 6: This graph is only of limited value from my perspective. Are these comparisons for CHP, electricity, heat plants? Are all of them compared to a natural gas baseline? What drives results here? What is the unit for the Y axis? I assume years. But what does it start with negative 5?	The graph shows all cases that shifted from coal against a coal baseline and cases that shifted from natural gas against a natural gas baseline. The graph does not distinguish between district heating and CHP cases. In all cases heat production constitute a large part of the total production. The purpose of the graph is to illustrate the CO_2 emission profile of the hypothetical typical case and how the actual cases are distributed around the typical case. Units have been added to the X axis on this and subsequent graphs. The unit is years. Negative 5 represents the 5 years before conversion.
A37	Results, Line 784: So the plants presented in figure 6 are electricity only?	No, we do not distinguish between district heating and CHP cases in the graph. The issue with electricity production is further elaborated and discussed under indirect effects and iFUC.
A38	Results, Line 786: This suggests a precision that is not there in my opinion. Maybe report in whole integers?	Agreed, numbers are now reported in integer kilo tonnes.
A39	Results, Figure 7: Label y-axis. Why does it start negative?	X-axes are now labeled with years. Negative 5 represents the 5 years before conversion.
A40	Results, Line 882: Please be specific, is this CHP or heat only? I would suggest to rephrase sentences like this. It is not so much what the original plant burnt but what would be there instead of a bioenergy plant. For instance, I would suggest to write ’for a situation where coal would be used instead of biomass...’ It is important to note here that a lot of these coal power plant reach their end of life (30 yrs?) and would be replaced anyway with new systems as they are available at that time. This changed from the 80ies to the 2020ies considerably.	See description of the typical plant in section 2.6. See our response to #A2, where the aim of the report has been rephrased to make this clear.
A41	Results, Line 902: As mentioned above, I don’t think this is an appropriate comparison. It is more appropriate to compare a managed forest with a forest that is managed differently under a bioenergy scenario either by reducing rotation lengths or by increasing harvest volumes (e.g. more pre-commercial thinnings or removal of small stems that would be left in the stand otherwise).	See our response to #A5 and 6 on forest management and the newly added section 2.4.5 and the elaboration in 2.5.2.

A42	Results, Line 908: I would rephrase. It is not so much about converting a natural gas plant to biomass sourcing but about a scenario where a natural gas plant would continue its operation, be updated if it reached its end of life, or a new bioenergy system be installed. The driver is multifold and needs to be considered in each individual case. Is it end of life, climate driven, price driven? And at what time to decide on a fitting counterfactual. 80ies? 2020ies?	The underlying assumptions and methodological approach is explained in the methodology and data section. The purpose of this study was not to hypothesize over how fuel transitions could have played out, but to study the impact of what actually took place in the individual fuel transition cases. The limitations of our approach are presented in the methodology and data section.
A43	Results, Line 926: Isn’t iFUC already covered above since you compare coal and natural gas as well? See my comments on iFUC above. I don’t think it is a good choice to call those ’indirect’ if I understand the application in this study correctly. I think it would be more helpful to describe the counterfactual/baseline and bioenergy scenario more in detail and show where fossil fuels (for heat and or electricity) occur.	See our response og #A7 on iFUC.
A44	Discussion, Line 940: What is the typical plant? This is very unclear to me. Is it CHP? Converted in the 80ies? At the end of their lifetime? What were the most likely replacement alternatives at the time of conversion? Is there anything like a typical plant or are the cases so different that you barely can speak of a representative case? As I mention above, I would recommend to not talk about a plant but a scenario. Reading between the lines (the study should be improved in clarity in this regard) some systems used to be CHP and were converted to electricity only or the other way around. This needs to be spelled out better. Is there any evidence that you can talk about a typical plant?	The typical plant just represents the data sample, a mixture of DH and CHP plants that does not differ substantially in efficiency. See also section 2.6.

A45	Discussion, Line 981: This is an important statement. Two things:	
	Was that percentage the same for all systems analyzed? Were there significant differences in sourcing patterns?	The percentages were plant specific and differed substantially. See also our response to #A1 and 4.
	I partly disagree. In the paragraph above you write that CPB is driven by fossil fuel reference and leakage. Here you write it is driven by feedstock. I think you should reconcile those two statements and just say that all three factors are the major drivers which I think is correct. In this sentence here, I think the bigger driver is that you look at CHP/heat plants. Rarely does another study do that, most of them focus on electricity only. I would call this out specifically. District heating at the scale ’typical’ for Scandinavia is not known to me anywhere else with only a few (but notable) exceptions. I think it is important to stress that again.	In the revised report, we have stressed that feedstock together with fossil fuel reference and leakage significantly contributes to carbon payback times.
A46	Discussion, Line 986-987: None of these look at CHP/heat only. This needs to be discussed or other references sought. E.g. Timmons et al. And Lamers& Junginger do it.	The discussion on the differences between electricity only and district heat/CHP is presented in section 4.1 and we also reference Timmons et al. and Lamers & Junginger.
	This is the first time I read this, I think. Please introduce each case in the methods section (tabular format? Include counterfactual and bioenergy scenario)	See our response to #A1 on our limitations to disclose details about the individual cases. See also section 2.2.1.
A47	Discussion, Line 1013-1016: I am not so much concerned about productivity of these forests. I am more concerned about your assumptions on forest management with and without biomass feedstock. See comments above.	See our response to #A5 and 6. Forest management assumptions have been further elaborated and clarified in sections 2.4.5 and 2.5.2.
A48	Discussion, Line 1048: I think it is worth here to define this again – no stemwood that could potentially be used for other wood products. A lot of studies label anything that is not of sawlog quality ’residue’ which is not acceptable.	We have stressed that true residues are wood assortments for which there is no alternative use or market other than energy purposes.

A49	Discussion, Line 1052-1053: This is definitely not true for wood sourced from pine plantations in the southern US. All of it is stemwood and the cutoff dimenions for pulp are really small with top diameters approaching less than 7 cm. Use of branches and tops is very, very uncommon for bioenergy use in the southern US.	Although this may be true, only a small part of our data origins from USA (6.5%). Therefore this is covered in the sensitivity analyses where up to 20% of stem bioenergy is vitiated with iLUC.
A50	Discussion, Line 1070-1072: I disagree. The comparison is not sawlog vs biomass but pulp vs. Biomass. Payments to the forest owner ('stumpage') for those two product categories can significantly overlap in Europe and the US. Just quoting an example from Denmark is not representative in this context of international supply chains, I believe. You make the case that most of the biomass is derived from Denmark and the Baltics (see Figure 5), so at the least, I would suggest to also quote numbers from the Baltics. But that would only be acceptable, I think, if you can generalize that finding across all 10 systems analyzed. How much did they vary in where the wood was coming from?	We have found no evidence neither confirming nor rejecting this and this is a topic that deserves more scientific attention, as these two markets are close. This is however covered to some extend in our sensitivity analyses, where marked mediated indirect emissions are varied from 5 to 20%.
A51	Discussion, Line 1074: What is your audience here? Would it make sense to provide this in Euro as well? This translates to ~25Euro/m3 which is similar to e.g. Germany. How does that relate ~150 Euro paid for industrial pellets per ton (delivered) in Europe? I don't think these numbers back up your argument.	Our audience is mainly Danish, but we have added prices in EUR as well. Furthermore we believe that the various competition situations in different sourcing countries are represented in our sensitivity analyses, where marked mediated indirect emissions are varied from 5 to 20%.
A52	Conclusion, Line 1140: As mentioned above, the choice of baseline is important. If you have a current coal CHP it does not mean that this is automatically your counterfactual. If regulations force you to switch fuels, the counterfactual might just as well be a switch to other renewables or from coal to natural gas. In other words, a comparison to coal as counterfactual is in my opinion not defensible anymore in 2020 Europe.	See our response to #A2, where the aim of the report has been rephrased.
A53	Conclusion, Line 1144: See comment above. Ending coal does not automatically justify a coal scenario as counterfactual. The counterfactual for Europe and elsewhere would be what other technology is applicable (economically, politically) at the time of conversion. This changed over time.	See our response to #A2, where the aim of the report has been rephrased.

B	*Jette Bredahl Jacobsen*	
	General comments	
B1	The basic premise of the report is to calculate CCE, CPT, RE *as compared to* coal and natural gas. While this was a relevant question when transition away from fossil fuel started, I am more skeptical about how relevant a question it is today if we want to inform society about the climate impact of using biomass for energy where we have other green energy options. As also specified below, I suggest that the aim of the report is reformulated.	While CPT and RE are measures that are derived as compared to coal or natural gas, the CCE is a measure which is independent of the reference. As such CCE can easily be recalculated to CCE per GJ from the figures given in the report and compared to any other reference energy system e.g oil, solar panels, heat pumps etc. However, the quantification of these other energy forms are outside the scope of this report, but very interesting. Therefore we are reluctant to reformulate the aim of the report as CCE can be used inform the about the CO2 emissions from bioenergy and compared with any other energy form.
B2	By biggest concern is that the report does not answer the two aims it sets out to have: "1) inform the scientific, public and policy debate on the potential climate impact of using forest biomass for heat and electricity production, and 2) inform utility companies on their future fuel sourcing". It uses a rather limited approach – calculating CCE, CPT, RE. Which is one aspect of the climate impact of using forest biomass. I suggest this is framed as the primary aim with the report: to calculate these measures and use this to inform… (specifically for point 2), see below)	We acknowledge that climate impacts holds other effects than CO2 e.g. other climate gasses, albedo, etc. Therefore we have reformulated to *1) inform the scientific, public and policy debate on the potential CO2 emissions savings of using forest biomass for heat and electricity production instead of fossil fuels (coal or natural gas), and 2) inform utility companies on their future fuel sourcing*
B3	Also, I suggest you include a section in the report describing these measures and why they are criticized, which points are the most critical. You just mention that their use is controversial. But as a reader, I don't feel very informed with a lot of details about measures which are overall "controversial" but I don't now why. So you describe how you calculate them. But it would be good to have a section about how you can look at the climate impact of biomass. What measures are available. What are the pros et cons of the measures you have chosen, and why you have chosen these	It is not the measures that are controversial, but merely what to include or exclude in the calculus e.g. iLUC, iWUC etc. In the model presented here we have acknowledged and included all aspects, hereby attempting to reduce the debate to the quantification of these aspects.

B4	In terms of informing about the climate impact of using forest biomass, I think it is needed to explain every single time mentioned that it is as compared to coal or natural gas. This is the reference in the entire modelling. And can be argued to be of less relevance today (as there are other green energy sources available which would likely be preferred over the others, see also my overall comment). So while I can see that this is the premise set up in the modelling, it is probably not the most relevant approach to answer the question of the potential climate impact of using forest biomass. This goes back to the choice of the measures you calculate: I would have liked to see calculus addressing the assumption of climate neutrality. Not as compared to coal or natural gas. But as compared to zero emission. I acknowledge this is outside the scope of this project. But if you include a small critical section as suggested above, it could be worth mentioning.	As noted by the referee the reference energy system is the fossil fuel which each power plant converted from throughout the modelling. We will do our best to make this clear. The referee requests calculus addressing the bioenergy scenario compared to a zero emission scenario. This calculus is already presented in figure 7 a and c, in which cumulative net carbon emissions (CCE) are presented (blue lines indicate bioenergy). The zero emission scenario is a scenario where the line is placed at the x-axis (no net emissions). This was not described in the text. Therefore, we have included a section where this is addressed.
B5	Second, I am a bit puzzled by the setup – you claim to rely on real data and therefore be much better than earlier attempts. But there are an enormous amount of assumptions (as also acknowledged later in the text). Isn't your contribution not rather that you expand earlier models by being (a bit) more specific on the sourcing region of the biomass? And maybe some other details?	The data presented in this study is to our knowledge much better than in most other attempts to model climate impact from energy production using biomass. This said, the data are by no means perfect nor complete and therefore we are forced to make many assumptions. So, yes it is more specific and detailed but not perfect as data simply does not exists.
B6	My biggest concern with the modelling is your assumption of the forest harvesting – basically assuming that the carbon stock in the forest is unchanged because harvest is unchanged (except from whether to use residues or not). You only allow harvest to be distributed to different uses. In other words, managed forest is managed forest. This assumption of an equilibrium is by many raised as an issue (e.g. Klimarådet in 2018), and it is a well-known economic result that increased demand leads to lower stocks in the forest. I find it problematic that it is completely ignored. It should at least be mentioned as a caveat.	Here we have failed to communicate clearly. The forest carbon stocks are not assumed to be in equilibrium. Every time biomass for energy is removed from the forests it affects the forest carbon stocks in the model. The question is only whether it affects the living or dead forest carbon pool. Harvest residues for example are considered a true residue, which if not used for energy is left in the forest (the dead forest carbon pool). When this is removed and released by burning the dead forest carbon pool is reduces in size and a net emissions has occurred. Equally, if the biomass origins from living trees that would in the absence of bioenergy not have been harvested affects the living forest carbon pool. As such, the forest model presented here estimated both how the living and dead forest carbon pools are affected by removal of biomass.

B7	Your handling of iLUC, iWUC, i---etc is superficial and relies on crude assumptions. This is also acknowledged in a few places. Yet, when I read the results and the discussion they play a large role. Somehow I feel a bit that you put a lot of emphasis on them and their importance for the results – provided that you according to the abstract e.g. do not really trust them and call for further research. I suggest you become a bit more specific in your communication in the result and discussion section – are these main results or are they just first rough estimates that we should not really trust after all?	The indirect effects (iWUC, iLUC and iFUC) have a relatively large impact on the results and are based on crude assumptions. However, for a large part of our data set we do trust our assumptions on these, but in smaller parts of our data (e.g. USA, Ghana, Canada) we are more uncertain. To our best knowledge, there is no data available on this and therefore we have only made crude assumptions. Making more fine grained assumptions would (wrongly) indicate that we had data on this, but as said these data are not present and therefore this make us call for further research on this topic.
B8	Going back to the second of the two aims raised above: future use: it is only treated in a small section in the discussion. Isn't it a bit brief to have a report of 53 pages and only half a page answering the second part? I suggest this second aim is reformulated to something like "what the results of the report can be used to in terms of informing about future sourcing". And then I also suggest that you here write the "obs"points of what to look at: transport, residues as already mentioned. But then also the caveats of your modelling: iLUC, LUC, iWUC, changed carbon stocks on site.	The whole second part of the results section is about the impact of transport and the impact of using the different types of biomass types e.g. stems, harvest residues etc., which from our point of view answers the second aim of the report. The half page mentioned is just summarizing what we have found throughout the report. Regarding the caveats of the modelling we thoroughly discuss the caveats of iLUC/iWUC and IFUC in the chapters before the half page sum up and as mentioned we do model changes in forest carbon stock.
B9	Almost finally: you completely ignore the most criticized aspect of climate effects of the use of biomass: the huge increase and the aggregated effect. Is there land enough for supplying global future biomass consumption? While this is clearly outside the scope of the project, I suggest that you mention it. Especially if you want to inform about future use	Surely, this is a topic which has great impact on the results especially for iLUC and iWUC and this is exactly the research we are calling for. We have included a section in the discussion where we have discuss these aspects.

B10	Finally, regarding the writing style: I often got a bit confused about your mentioning of one way of modelling overall – where I was then missing the details, and then the details came further along. But sometimes contradicting the overall principle described. This confused me. I have commented it a few places in the text, in other places I was just left confused. I think two things are worth doing here: 1) check that there is consistency in your generic descriptions and the detailed descriptions, 2) guide the reader in the structure – e.g. when you make the generic descriptions write that details is specified in the next section, og introduce the structure of a chapter in the beginning of the chapter. I acknowledge this is a matter of style. So please just take it as suggestions of how I like to read a text☺	We have checked for consistency between overall and specific model descriptions and tried to guide the reader through the method section by adding a figure where each process is shown (see new figure 3)
	Specific comments	
B11	Abstract, Line 101: I guess this one is retrospective? and number 2) forward looking? if so, it may be a good idea to emphasize here	That has been corrected.
B12	Abstract, Line 132: I don't get this sentence. Why however. You analysed something... what was the result? How can that be "however" Also, I would suggest that you either elaborate here on your results - or simply leave it out. Mention iluc, iwuc ifuc and that it may change results considerably, but that it is left out here?	We have revised the paragraph and left out some details on the results for increased clarity.
B13	Introduction, Line 148: Are you sure about the date? and "passed"?	It has been corrected that the climate act was passed in the Parliament in June 2020.
B14	Introduction, Line 160: I would leave transport out here. It requires different technologies and may cause the potential to be exaggerated in the communication here	Agreed. We have revised the paragraph with a focus on heat and electricity production.
B15	Introduction, Line 163: I would mention the source explicitly here. You have just been talking about DK, and this is an IPCC report. And that makes it quite different.	We have clarified that the perspectives on bioenergy for climate change mitigation as reported by the IPCC has a global scope.

B16	Introduction, Line 175: This chapter seems to indicate complete agreement of the use of biomass. But throughout this period there have been critical voices, especially among the NGOs. Maybe it would be worth to insert a few paragraphs about when this critique was raised? policy wise and in the scientific literature? It might be worth specifying these priorities and drivers?	The purpose of this paragraph is to outline the policy framework for biomass use in Denmark to explain why biomass has played such a large role in the transition away from fossil energy. The critical voices and the debate on sustainability and climate impacts of bioenergy is treated in sections 1.3 and 1.4. The sentence has been revised for clarity and the part with political priorities and economic drivers has been deleted.
B17	Introduction, Line 205: Ok, so you may ignore my comment above. But I think you could elaborate a bit here about the concerns, especially the climate benefits as this is what you address in this report	See our response to #B16.
B18	Introduction, Line 220: Maybe make it even clearer: the use of bioenergy is accounted for as carbon neutral and potential changes in the stock is accounted for under LULUCF... it is not really "although"	We have clarified that bioenergy is accounted for as carbon neutral and that biomass harvest and changes in carbon stocks are accounted for in the LULUCF compartment om the climate accounts.
B19	Introduction, Line 221: Why however? this comes as a result of the first two	‘However’ is deleted.
B20	Introduction, Line 223: A longer time span... it is a bit vague. It can be understood in different ways - that the time horizon is long, that fluctuations over some time interval is sustainable... and this becomes quite determining for the results. So what I raise here is that the "i.e." sentence can be understood in different ways and is not so unambibiously defined as the sentence here indicate. So I suggest to reformulate it	We have clarified that preconditions for forest biomass to contribute to climate change mitigation is that harvest does not exceed growth and that carbon stocks in the forest is maintained or increased.
B21	Introduction, Line 233: You just tell that how to do the quantification ia controversial. Then I think it would be relevant to tell what the controversy is about. Otherwise the mentioning of specific findings seems a bit irrelevant	We have revised the paragraph and clarified that quantification of carbon debt is uncertain (not controversial) and added examples of what the uncertainty arises from.
B22	Introduction, Line 241: I don't get this one. It is historic. What is the first one? And why so bit a difference if it is "much the same approach"?	We have clarified that the Taeroe paper treats a hypothetical and generic case projecting the GHG effect of a potential fuel transition, while the Madsen paper treats a historical fuel transition on a specific plant. ‘Much with the same approach’ has been deleted.

B23	Introduction, Line 249: But this means that you can e.g. only calculate cpt for burning which took place long long ago. you still rely on assumptions. So I think you need to specify which concrete aspects you expand the studies by and look at real data	We have clarified that our study build on a combination of real data and models and assumptions.
B24	Introduction, Line 253: Carbon debts and payback times is in my view a bit limited to answer the first aim. It shows aspect of the climate impact. But does not fully reflect the "potential climate impact". Please consider whether this is really the aim - or if the aim is not more narrow	See our response to #B2.
B25	This one becomes more critical I think. inform utility companies on their future sourcing... this does indeed rely on a lot of assumptions. Probably most notably that the alternative in the future is likely not coal and natural gas. What you have described above that you want to do does not seem to be able to answer this question. But maybe it comes later? If so, I suggest to introduce it before	See our response to #B4 and 8.
B26	Methods and data, Line 266: Why 40 years? This must heavily affect the CPT?	It is a methodological choice that reflects a lifetime of a powerplant. It has no influence on CPT.
B27	Methods and data, Line 278: But you rely on actual data you state above. Which 40 year period did you consider? Must be quite important for the results.	The period we focused are specific for each powerplant included in the analysis. This has no effect on the results.
B28	Methods and data, Line 292: Incomplete sentence	Corrected.
B29	Methods and data, Line 300: Aren't you missing the potential substitution of other energy sources? The effect it has if e.g. biomass replaces coal, and thereby causes that it is not replaced by something else? It is not really captures by EIFUC, or is it? If it is it must include quite some assumptions.	The CCE for bioenergy is independent of the reference. The reference is calculated as an independent CCE for the fossil system. So this is not missing
B30	Methods and data, table 1, No. 2: How does this enter your model? Since it is in unmanaged forests it can only be through iluc and luc? And if so... are you then assuming that if unmanaged and land use is changed, then this does not change? Seems a rather rough assumption	Here we have made a mistake, as it is only the soil carbon pool that is not affected. There is no evidence of a higher soil carbon pool in European temperate forest (see references). The forest floor is modelled and here we model a change/decrease when bioenergy is extracted. Text is corrected in table 1.
B31	Methods and data, table 1, No. 12: This could be elaborated.	This is further elaborated in section 2.5.2.

B32	Methods and data, table 3, No. 2: Quantified or just mentioned? please specify how detailed info you got... goes for several of them. e.g. do you have info on how much the sourced from each region in each country each year and what forest and resource type it was? or only aggregated? or only by types, not quantities?	Details on data and information received from the data contributors is described in the text in section 2.2.1.
B33	Methods and data, Line 338: So how did you handle this variation in data quality? lowest common denominator?	The variation in the data quality was treated separately for each utility. Unfortunately, we have been deemed secrecy regarding utility specific data.
B34	Methods and data, Section 2.4: I think this chapter needs a bit of rewriting. You say something generic sometimes, and then contradicts it further down. Further, I am wondering how important the country specific assumptions are for the results? While I follow the wish for using the best available data, I am also worried about how much the different approaches varies for the different countries. Could you not approach it identically for the different countries - and then do sensitivity analysis if you assume more detailed info? Also, I am not sure I understand exactly how you in each place determines which types of wood is harvested. It would be good to make that very explicit as it largely determines the results	We have rewritten the entire section, also adding a paragraph to improve readability and understanding. Forest growth matters only for iLUC and we have already made a sensitivity analysis for this (See section 3.5.3. The analyses here in this chapter serves the purpose to justify the levels of growth for each region.
B35	Methods and data, table 7: A reference year is missing here.	A data reference year (2015) has been added to the table caption. Data for Denmark, Estonia, Latvia, Lithuania and Belarus comes from the Forest Resource Assessment 2015. Data for USA are based on a USDA online data base updated 55-10-2019.
B36	Methods and data, Line 431: But is that so important to have focus on the less common species? If you in any case go by NSP? Why not simply work with the NFI? It may be completely fine, I just don't follow the line of argument here	The tables provide an overview of the forest sector in the main sourcing countries. We believe that this overview is important to document that the main forest species are in fact Norway spruce, Scots pine and birch but also to provide the reader with an understanding that the use of the three species as model species is an approximation.

B37	Methods and data, Line 449: And what is then the entry in your modelling? the average growth per hectare? or do you take into consideration age distribution? Why not use the same approach as you do in "basisfremskrivningen"?	Average growth per hectare for each specific region.
B38	Methods and data, Line 451: A standard growth model specific for the Baltic? Please specify which standard growth model was used.	The growth model applied is illustrated in Figure 4.
B39	Methods and data, Line 563: Intensification can include lowering the stock (e.g. shortening rotation age due to higher prices and increased demand). This would be the expected pattern we would see. I find it problematic that you have not included this potential action.	Such intensification scenarios are included, but it is here treated as additional harvesting i.e. more trees are removed from the forest. This has been elaborated in 2.4.5 and 2.5.2.
B40	Methods and data, Line 595: Rather simplified approach.	0.17% of the biomass input refers to dedicated bioenergy. Therefore we chose to use a simple approach to save time. Any attempt to do more specific modelling would not affects the results.
B41	And data, Line 610: Which is questionable though with the large role biomass is expected to play globally - as you also mention in the introduction.	I think we agree with referee here but have been misunderstood. Biomass for energy will affect the consumption of wood and may change wood consumption patterns. But not general consumption patterns. As such substitution of other products when energy wood demand increases is here either modelled as additional harvesting (iLUC), which is lowering the forest carbon stock or by iWUC, where demand shifts to other products hereby inducing indirect carbon emissions.
B42	Methods and data, Line 674: But the evidence for this assumption is missing, right?	Correct. That is why we call for further research on this topic.
B43	Methods and data, line 712: In which period? it must be specific to a period.	Most of the data origins from 2002-2018. So this is the period although it's a proxy with all the mentioned caveats.
B44	Discussion, Line 997: As also mentioned above I find it confusing with the time series and time period - actual data and projections. It could be explained better. As I understand it: you use data for 20 years to simulate a hypothetical 40 year period. Is this correct? if so, it would clarify a lot if that is explained clearly earlier	We have rewritten section 2.2.1 to clarify this.

B45	Discussion, Line 1125: And given the technological and price development here, we will expect it to have a large impact on your calculus, right?	Yes
B46	Discussion, Line 1128: You may wish to mention biodiversity explicitly.. "and biodiversity"	We do further down.
B47	Discussion, Line 1131: Maybe addressed rather than covered? Given the ongoing discussion of whether it is sufficient? cover almost mean do not worry more.	Agreed. We have changed the wording to 'addressed'.

Appendix 3: Forest growth and yield models

Table 13. Yield table for Norway spruce (from Møller, 1933). Site class 21 m (index age=50 yrs), rotation age 70 years.

H_{50}=21	After thinning				Thinning			Before thinning			Production		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	m^3ha^{-1}	m^3ha^{-1} yr^{-1}	m^3ha^{-1} yr^{-1}
18	7.0	4825	24.0	104			19			123	123	6.8	6.8
20	8.0	3950	24.6	118	875	4.1	20	4825	28.7	138	157	7.9	17.0
22	8.9	3300	25.2	133	650	3.8	20	3950	29.0	153	192	8.7	17.5
24	9.9	2790	25.7	148	510	3.6	21	3300	29.3	169	228	9.5	18.0
26	10.8	2350	26.1	162	440	3.7	23	2790	29.8	185	265	10.2	18.5
28	11.7	2020	26.5	177	330	3.3	23	2350	29.8	200	303	10.8	19.0
30	12.6	1725	26.8	191	295	3.4	25	2020	30.2	216	342	11.4	19.5
32	13.5	1490	27.1	205	235	3.2	25	1725	30.3	230	381	11.9	19.5
34	14.4	1300	27.4	220	190	3.1	25	1490	30.5	245	421	12.4	20.0
36	15.3	1130	27.7	234	170	3.1	27	1300	30.8	261	462	12.8	20.5
38	16.7	992	27.9	248	138	3.0	27	1130	30.9	275	503	13.2	20.5
41	17.5	830	28.2	269	162	4.2	41	992	32.4	310	565	13.8	20.7
44	18.7	700	28.5	289	130	4.0	41	830	32.5	330	626	14.2	20.3
47	19.9	595	28.8	308	105	3.9	42	700	32.7	350	687	14.6	20.3
50	21.0	510	29.0	326	85	3.5	42	595	32.5	368	747	14.9	20.0
53	22.0	442	29.2	343	68	3.4	41	510	32.6	384	805	15.2	19.3
56	22.9	385	29.4	359	57	3.3	41	442	32.7	400	862	15.4	19.0
59	23.7	339	29.7	374	46	3.0	40	385	32.7	414	917	15.5	18.3
62	24.5	300	29.9	389	39	2.9	39	339	32.8	428	971	15.7	18.0
66	25.4	257	30.2	405	43	3.7	53	300	33.9	458	1040	15.8	17.3
70	26.2	222	30.4	420	35	3.4	51	257	33.8	471	1106	15.8	16.5

Table 14. Yield table for beech (from Møller, 1933). Site class 32, Rotation age 120 years.

H_{100}=32	After thinning				Thinning			Before thinning			Production		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	m^3ha^{-1}	m^3ha^{-1} yr^{-1}	m^3ha^{-1} yr^{-1}
18	6.8	5500	14	79			19				98	5.4	5.4
20	7.9	4360	15.4	93	1140	3.2	19	5500	19	112	131	6.6	16.5
22	8.9	3521	16.5	107	839	3.1	20	4360	20	127	165	7.5	17.0
24	10	2821	17.4	120	700	3.5	21	3521	21	141	199	8.3	17.0
27	11.5	2246	18.5	140	575	3.8	31	2821	22	171	250	9.3	17.0
30	12.9	1791	19.5	160	455	3.9	32	2246	23	192	302	10.1	17.3
33	14.2	1451	20.3	179	340	3.8	33	1791	24	212	354	10.7	17.3
36	15.5	1199	21.1	198	252	3.5	33	1451	25	231	406	11.3	17.3
39	16.7	1007	21.7	218	192	3.3	33	1199	25	251	459	11.8	17.7
42	17.8	857	22.3	237	150	3.1	33	1007	25	270	511	12.2	17.3
45	18.9	737	22.8	255	120	3.0	33	857	26	288	562	12.5	17.0
48	20	643	23.3	274	94	2.7	32	737	26	306	613	12.8	17.0
52	21.4	544	23.9	297	99	3.5	43	643	27	340	679	13.1	16.5
56	22.7	467	24.4	320	77	3.2	42	544	28	362	744	13.3	16.3
60	23.9	406	24.9	342	61	3.0	42	467	28	384	808	13.5	16.0
64	25	355	25.3	362	51	3.0	41	406	28	403	869	13.6	15.3
68	26.1	315	25.7	383	40	2.6	39	355	28	422	929	13.7	15.0
72	27.1	281	26.1	402	34	2.5	39	315	29	441	987	13.7	14.5
76	28	253	26.4	420	28	2.3	38	281	29	458	1043	13.7	14.0
80	28.9	228	26.7	436	25	2.3	38	253	29	474	1097	13.7	13.5
85	29.8	203	27.1	456	25	2.7	45	228	30	501	1162	13.7	13.0
90	30.7	181	27.4	473	22	2.7	45	203	30	518	1224	13.6	12.4
95	31.4	162	27.6	487	19	2.6	45	181	30	532	1283	13.5	11.8
100	32	146	27.8	499	16	2.4	45	162	30	544	1340	13.4	11.4
105	32.4	132	28	509	14	2.4	45	146	30	554	1395	13.3	11.0
110	32.8	119	28.2	518	13	2.5	44	132	31	562	1448	13.2	10.6
115	33.1	108	28.3	525	11	2.3	44	119	31	569	1499	13.0	10.2
120	33.4	98	28.4	531	10	2.3	43	108	31	574	1548	12.9	9.8

Table 15. Yield table for Norway spruce (from Vuokila and Väliaho, 1980). Site index 27 m (index age=100), rotation age 80 years, 4 thinnings and removal of 30%.

H_{100}=27	After thinning				Thinning			Before thinning			Production		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	m^3ha^{-1}	m^3ha^{-1} yr^{-1}	m^3ha^{-1} yr^{-1}
25	7.7	2000	8.4	31				2000	8.4	31	31	1.2	
30	10.0	2000	15.6	71.7				2000	15.6	71.7	72	2.4	8.1
35	12.2	1117	15.3	86.7	883	7.3	37.2	2000	22.6	123.9	124	3.5	10.4
40	14.1	1117	21	138				1117	21.0	138	175	4.4	10.3
45	15.9	703	18	134.1	414	8.2	57.5	1117	26.2	191.6	229	5.1	10.7
50	17.4	703	22.3	184.9				703	22.3	184.9	280	5.6	10.2
55	18.9	446	18	163.5	257	8.2	70	703	26.2	233.5	328	6.0	9.7
60	20.2	446	21.4	209.8				446	21.4	209.8	375	6.2	9.3
65	21.4	282	16.7	176.4	164	7.7	75.6	446	24.4	252	417	6.4	8.4
70	22.4	282	19.4	218				282	19.4	218	458	6.5	8.3
75	23.4	282	21.8	254.1				282	21.8	254.1	494	6.6	7.2
80	24.3	282	24.1	290.1				282	24.1	290.1	530	6.6	7.2

Table 16. Yield table for Norway spruce (from Vuokila and Väliaho, 1980). Site index 24 m (index age=100), rotation age 90 years, 3 thinnings and removal of 30%.

H_{100}=24	After thinning				Thinning			Before thinning			Production		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^{2}ha^{-1}	m^{3}ha^{-1}	ha^{-1}	m^{2}ha^{-1}	m^{3}ha^{-1}	ha^{-1}	m^{2}ha^{-1}	m^{3}ha^{-1}	m^{3}ha^{-1}	m^{3}ha^{-1} yr^{-1}	m^{3}ha^{-1} yr^{-1}
25	5.9	2000	3.1	10.5				2000	3.1	10.5	11	0.4	0.4
30	7.9	2000	8.2	30.8				2000	8.2	30.8	31	1.0	4.1
35	9.9	2000	14.2	65				2000	14.2	65	65	1.9	6.8
40	11.6	975	12.6	69.8	1025	7.6	37.6	2000	20.2	107.4	107	2.7	8.5
45	13.3	975	17.5	111				975	17.5	111	149	3.3	8.2
50	14.8	975	22	153.6				975	22	153.6	191	3.8	8.5
55	16.1	565	16.7	129	410	9.5	69.4	975	26.2	198.4	236	4.3	9.0
60	17.4	565	20.2	171.1				565	20.2	171.1	278	4.6	8.4
65	18.5	565	23.4	209.7				565	23.4	209.7	317	4.9	7.7
70	19.5	330	16.8	161.7	235	9.7	87.1	565	26.5	248.8	356	5.1	7.8
75	20.5	330	19.5	199.8				330	19.5	199.8	394	5.3	7.6
80	21.3	330	21.9	232.2				330	21.9	232.2	426	5.3	6.5
85	22.1	330	24.1	264.6				330	24.1	264.6	459	5.4	6.5
90	22.8	330	26.3	296.7				330	26.3	296.7	491	5.5	6.4

Table 17. Yield table for Scots pine (from Vuokila and Väliaho, 1980). Site class 27 m (index age=100 yrs), rotation age 90 years, 4 thinnings and removal of 30%.

H_{100}=27	After thinning				Thinning			Before thinning			Produktion		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^{2}ha^{-1}	m^{3}ha^{-1}	ha^{-1}	m^{2}ha^{-1}	m^{3}ha^{-1}	ha^{-1}	m^{2}ha^{-1}	m^{3}ha^{-1}	m^{3}ha^{-1}	m^{3}ha^{-1} yr^{-1}	m^{3}ha^{-1} yr^{-1}
20	7	2000	11.1	40				2000	11.1	40	40	2.0	
25	9.4	2000	16.9	77.7				2000	16.9	77.7	78	3.1	7.5
30	11.6	1129	15.3	87.3	871	7	37.5	2000	22.3	124.8	125	4.2	9.4
35	13.6	1129	19.8	128.6				1129	19.8	128.6	166	4.7	8.3
40	15.4	670	16.4	121.3	459	7.4	51.9	1129	23.8	173.2	211	5.3	8.9
45	17	670	19.9	159.1				670	19.9	159.1	249	5.5	7.6
50	18.4	670	22.9	197.6				670	22.9	197.6	287	5.7	7.7
55	19.7	415	17.9	166.6	255	8	71.4	670	25.9	238	327	6.0	8.1
60	20.9	415	20.7	201.1				415	20.7	201.1	362	6.0	6.9
65	22	415	23.1	234				415	23.1	234	395	6.1	6.6
70	23	263	17.6	187.4	152	7.8	80.3	415	25.4	267.7	429	6.1	6.7
75	23.8	263	20	217.8				263	20	217.8	459	6.1	6.1
80	24.6	263	21.8	244.7				263	21.8	244.7	486	6.1	5.4
85	25.3	263	23.7	272.3				263	23.7	272.3	513	6.0	5.5
90	25.9	263	25.5	300.4				263	25.5	300.4	542	6.0	5.6

Table 18. Yield table for Scots pine (from Vuokila and Väliaho, 1980). Site index 24 m (index age=100), rotation age 100 years, 4 thinnings and removal of 30%.

H_{100}=24	After thinning				Thinning			Before thinning			Production		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	m^3ha^{-1}	m^3ha^{-1} yr^{-1}	m^3ha^{-1} yr^{-1}
20	5.6	1800	6.3	19				1800	6.3	19	19	1.0	
25	7.7	1800	11.1	42.4				1800	11.1	42.4	42	1.7	4.7
30	9.7	1800	15.6	73.6				1800	15.6	73.6	74	2.5	6.2
35	11.4	1018	13.7	77.2	782	6.3	33	1800	20	110.2	110	3.1	7.3
40	13.1	1018	17.4	109				1018	17.4	109	142	3.6	6.4
45	14.6	605	14.2	100	413	6.5	42.8	1018	20.7	142.8	176	3.9	6.8
50	15.9	605	17.1	128.7				605	17.1	128.7	205	4.1	5.7
55	17.1	605	19.6	157.5				605	19.6	157.5	233	4.2	5.8
60	18.2	374	15.2	131.2	231	6.8	56.2	605	22	187.4	263	4.4	6.0
65	19.2	374	17.5	156.8				374	17.5	156.8	289	4.4	5.1
70	20.1	374	19.4	180.9				374	19.4	180.9	313	4.5	4.8
75	21	236	14.7	143.8	138	6.5	61.6	374	21.2	205.4	337	4.5	4.9
80	21.7	236	16.6	165.8				236	16.6	165.8	359	4.5	4.4
85	22.4	236	18	185.2				236	18	185.2	379	4.5	3.9
90	23	236	19.4	204.8				236	19.4	204.8	398	4.4	3.9
95	23.5	236	20.8	224.4				236	20.8	224.4	418	4.4	3.9
100	24	236	22.3	244.2				236	22.3	244.2	438	4.4	4.0

Table 19. Yield table for birch (from Oikarinen 1983). Site class 22 m (index age=50 yrs), Rotation age 60 years, 2 thinnings and removal of 30%.

H_{50}=22	After thinning				Thinning			Before thinning			Produktion		
T	H	N	G	V	N	G	V	N	G	V	Total	MAI	dV
	m	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	ha^{-1}	m^2ha^{-1}	m^3ha^{-1}	m^3ha^{-1}	m^3ha^{-1} yr^{-1}	m^3ha^{-1} yr^{-1}
15	7.1	2000	3.6	11				2000	3.6	11	11	0.7	
20	10.3	2000	10.4	47				2000	10.4	47	47	2.4	7.2
25	13.1	1258	10.9	62	742	4.6	26	2000	15.5	88	88	3.5	8.2
30	15.4	1258	15	101				1258	15	101	127	4.2	7.8
35	17.4	1258	18.6	141				1258	18.6	141	167	4.8	8.0
40	19.2	714	15.2	127	544	6.5	54	1258	21.7	181	207	5.2	8.0
45	20.7	714	18.2	164				714	18.2	164	244	5.4	7.4
50	22	714	21	201				714	21	201	281	5.6	7.4
55	23.1	714	23.6	238				714	23.6	238	318	5.8	7.4
60	24.1	714	26.1	275				714	26.1	275	355	5.9	7.4

Appendix 4: Indirect Fuels Use change (iFUC)

Statistical analysis of indirect fuel use change with reference to district heat production. Included fuels on individual plants constitute 5% or more of the total fuel use. Two units were excluded from the analysis as the transition to biomass took place recently and consequently the time series were too short (2-3 years). Parameter and P values listed in bold are significant on a $p < 0.05$ level. Individual plants are anonymised.

Plant		A		B		C		D	
Fuel	Factor	Estimate	P value	Estimate	P value	Estimate	P value	Estimate	P value
Coal	Wood use	-0.2441	0.5515						
	Fuel capacity	4.5140	0.3624						
	Heat production	**-0.8556**	**0.0147**						
	Electricity production	**1.9012**	**0.0028**						
Fuel oil	Wood use	**-0.7659**	**0.0115**						
	Fuel capacity	0.7763	0.7807						
	Heat production	-0.2221	0.1798						
	Electricity production	-0.0378	0.9707						
Natural gas	Wood use	-0.1001	0.7520					0.0207	0.1505
	Fuel capacity	**-11.3956**	**0.0238**					0.8731	0.3405
	Heat production	**0.9803**	**0.0032**					**0.5357**	**0.0003**
	Electricity production	**0.9418**	**0.0189**					**-1.8021**	**<0.0001**
Gas oil	Wood use							0.1536	0.3718
	Fuel capacity							-0.8391	0.5807
	Heat production							-0.0257	0.8949
	Electricity production							0.0098	0.9465
Biogas	Wood use					-3.37e-5	0.9945	-0.0236	0.2735
	Fuel capacity					-0.3895	0.5293	0.1291	0.8021
	Heat production					0.0765	0.2064	0.0462	0.4269
	Electricity production					0.0669	0.5112	**1.1256**	**0.0036**
Straw	Wood use	-0.0518	0.5046			0.1289	0.1305		
	Fuel capacity	0.6248	0.4947			-2.6578	0.7481		
	Heat production	0.0610	0.2251			0.1974	0.7829		
	Electricity production	0.0731	0.3178			0.2788	0.8363		
Wood chips	Wood use			-0.0159	0.8904	-0.0288	0.1035		
	Fuel capacity			1.7624	0.1952	-2.9499	0.1450		
	Heat production			**0.9796**	**<0.0001**	0.3506	0.0748		
	Electricity production			29598	0.5736	**1.2188**	**0.0159**		
Wood and biomass waste	Wood use			-0.0148	0.3931				
	Fuel capacity			-0.1504	0.3261				
	Heat production			-0.0206	0.2874				
	Electricity production			-3161	0.5911				
Wood pellets	Wood use	0.9516	0.1949						
	Fuel capacity	9.7699	0.2495						
	Heat production	0.4857	0.2676						
	Electricity production	-0.7279	0.2658						
Waste	Wood use	0.0176	0.9247	0.1697	0.1571	-0.0742	0.1833	0.0054	0.8883
	Fuel capacity	-3.1558	0.2433	-3.0004	0.0629	2.0040	0.7266	-0.4934	0.5957
	Heat production	0.0262	0.8466	-0.2059	0.2171	0.2818	0.5777	0.1075	0.3127
	Electricity production	-0.0899	0.4940	-1122	0.9858	-0.1012	0.9133	**3.4595**	**<0.0001**
Waste heat	Wood use			0.0189	0.5931				
	Fuel capacity			-0.3185	0.3253				
	Heat production			0.0441	0.2760				
	Electricity production			-6306.0	0.6126				

Plant		E		F		G		H		I	
Fuel	Factor	Estimate	P value	Estimate	P value	Estimate	P value	Estimate	P value	Estimate	P value
Coal	Wood use	-0.2891	0.1322	-0.1107	0.9460	22.474	0.1073				
	Fuel capacity	**-5.1686**	**0.0268**	1.1684	0.7701	**-73.230**	**0.0399**				
	Heat production	0.0776	0.8428	0.0670	0.8742	4.0499	0.0836				
	Electricity production	0.5395	0.0563	**1.0791**	**0.0067**	0.6950	0.3960				
Fuel oil	Wood use	-0.0897	0.1417								
	Fuel capacity	-0.9343	0.1783								
	Heat production	-0.0152	0.9027								
	Electricity production	-0.0792	0.3595								
Natural gas	Wood use	-0.1754	0.2094	0.4907	0.6889			**1.0983**	**0.0236**		
	Fuel capacity	1.0062	0.4110	-0.6977	0.8153			**-5.1528**	**0.0080**		
	Heat production	**0.5631**	**0.0030**	-0.0072	0.9819			0.2601	0.3039		
	Electricity production	-0.1078	0.3666	**0.8094**	**0.0065**			**1.8108**	**<0.0001**		
Gas oil	Wood use										
	Fuel capacity										
	Heat production										
	Electricity production										
Biogas	Wood use										
	Fuel capacity										
	Heat production										
	Electricity production										
Straw	Wood use					**-4.6813**	**0.0116**				
	Fuel capacity					**3.1113**	**0.0262**				
	Heat production					**-0.7180**	**0.0147**				
	Electricity production					**0.2457**	**0.0224**				
Wood chips	Wood use							-0.7355	0.1101		
	Fuel capacity							0.3740	0.8986		
	Heat production							0.4941	0.0648		
	Electricity production							-0.3744	0.1646		
Wood and biomass waste	Wood use										
	Fuel capacity										
	Heat production										
	Electricity production										
Wood pellets	Wood use	0.1536	0.3718	-1.2654	0.3472	-16.892	0.1092				
	Fuel capacity	-0.8391	0.5807	-1.6734	0.6066	**59.650**	**0.0322**				
	Heat production	-0.0257	0.8949	0.5155	0.1481	-3.1261	0.0797				
	Electricity production	0.0098	0.9465	-0.1803	0.5221	1.2290	0.0907				
Waste	Wood use	0.0844	0.2209	0.1733	0.6203	0.8600	0.2036				
	Fuel capacity	-0.0155	0.9856	-1.3158	0.1376	-1.7122	0.2523				
	Heat production	-0.1529	0.2302	**-0.2745**	**0.0078**	0.1806	0.1218				
	Electricity production	0.0105	0.9096	0.1242	0.1075	-0.0586	0.1996				
Waste heat	Wood use									-5.8e-8	0.7320
	Fuel capacity									-	
	Heat production									**1.0000**	**<0.0001**
	Electricity production									-	

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