CO₂ emission mitigation through fuel transition on Danish CHP and district heating plants

Anders Taeroe Nielsen | Thomas Nord-Larsen © | Niclas Scott Bentsen ©

Abstract

The study analysed how carbon dynamics 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. For 10 plants, we calculated the cumulative net carbon emissions over time (t) from the fuel transition (CCE(t)) and carbon payback 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 cumulative net carbon emissions (RCCE(t)), as a measure of the carbon emission savings/costs induced by the fuel transition. 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 to 13 years indicating that carbon emission benefits were achieved at the latest after 13 years. Relative cumulative net carbon emissions 30 years after the fuel transition (RCCE(30)) ranged from 0.29 to 0.85 corresponding to emission savings of 15–71% relative to continued use of coal. For fuel transitions from natural gas to biomass, CPT ranged from 9 to 34 years and RCCE(30) from 0.81 to 1.03. Sensitivity analyses showed that the use of truly residual biomass (harvest residues or industrial residues with no alternative use), biomass harvest from productive forests and short transport distances are instrumental in achieving a short carbon payback time and large emission savings. The quantification of indirect or market mediated GHG emissions is controversial and uncertain. 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.

Abbreviations: CCE(t), cumulative net carbon emission assessed t years after initiation of the fuel transition; CHP, combined heat and power; CPT, carbon payback time. Estimated as the time it takes the CCE(t) for the biomass supply chain to fall permanently below the CCE(t) for a hypothetical continuation of the fossil supply chain. Equivalently estimated as the time it takes the RCCE(t) to fall permanently below 1; DH, district heating; GHG, greenhouse gases; iFUC, indirect fuel use change; iLUC, indirect land use change; iWUC, indirect wood use change; NDC, nationally determined contributions to the Paris Agreement; RCCE(t), relative cumulative net carbon emissions assessed t years after initiation of the fuel transition. Calculated as the sum of CO₂ emissions of the biomass life cycle relative to the sum of CO₂ emissions of the replaced fossil fuel life cycle.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. GCB Bioenergy Published by John Wiley & Sons Ltd
INTRODUCTION

The long-term goal of the Paris Agreement is to keep anthropogenic global warming well below a 2°C increase from pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C in recognition that this would substantially reduce the risk of severe climate change and impacts to society (UNFCCC, 2015). Denmark has ratified the Paris Agreement and through the EU NDCs committed to reduce GHG emissions by at least 40% below 1990 levels by 2030 (UNFCCC, 2015). Meeting the 1.5°C target requires significant society-wide transitions. The IPCC report on the 1.5°C target (IPCC, 2018) depicts four illustrative pathways to limit global warming to 1.5°C by the end of the 21st century. In all pathways, the energy sector plays a leading role. The share of renewables in electricity production must increase to between 66 and 86% by 2050 and bioenergy production may increase by 123–261% between 2010 and 2050.

The use of biomass in the energy sector in Denmark has been on the political agenda since the mid-1980s (Bentsen et al., 2018) while more recently, EU strategies and legislation have increasingly shaped the use of solid biomass. Specifically, the 2001 Directive (2001/77/EC) (European Parliament and the Council, 2001) promoting electricity production from renewable resources recognized biomass as renewable and the EU Biomass Action Plan from 2005 identified a number of initiatives to boost bioenergy (Mansoor et al., 2016). District heat and electricity production in Denmark have seen a significant transition in fuel use over the last 30 years (Figure 1), from predominantly coal in the 1990s to increased use of natural gas in the 2000s, and now to the current dominance of biomass with wind power and coal as large contributors. The increased use of biomass included a substantial expansion of wood in the biomass supply, which increased in share of the biomass used from 25% in 1990 to 67% in 2018 (Energistyrelsen, 2019).

In response to the increased demand for renewable energy, domestic production of wood chips has increased from 1.7 PJ in 1990 to 22.4 PJ in 2018, while import has increased from 0 PJ in 1990 to 6.3 PJ in 2018, currently constituting 22% of the supply (Energistyrelsen, 2019). Domestic production of wood pellets has remained constant around 2.5 PJ annually, while import has increased from 0 PJ in 1990 to 53 PJ in 2018 (Energistyrelsen, 2019).

The rapid growth of biomass use and resulting worldwide trade has spurred scientific, public and political concern in Denmark and elsewhere. In particularly, questions have been raised about the climate benefits of forest biomass for energy (Booth, 2018; Brack, 2017; Norton et al., 2019; Schlesinger, 2018; Sterman et al., 2018), the sustainability and sustainability verification of wood use (Jørgensen & Andersen, 2012) and the GHG accounting of bioenergy as carbon neutral for the energy sector (Schulze et al., 2012). These concerns have led to a demand for sustainability criteria for biomass use that ensure actual emission reductions and the protection of species and vulnerable habitats. In 2010, the EU issued recommendations which encouraged Member States to establish national sustainability criteria for solid and gaseous biomass.
transitions of heat and power plants from fossil fuel to bioenergy. In one example, Madsen and Bentsen (2018) analysed the fuel transition of a specific combined heat and power plant shifting from coal to biomass and reported carbon payback times of around one year.

The purpose of our study was to expand on the work by Madsen and Bentsen (2018) and analyse how emissions dynamics were influenced by a number of historical heat and power plant transitions from coal or natural gas to wood pellets or wood chips, including indirect effects of such transitions. This study updated results by Nielsen et al. (2020), adding more process data to the analysis and thereby increasing the robustness of the findings. By calculating carbon debt and payback time for the individual transition cases, we synthesized findings across supply chains and operational configurations with the aim to: (a) inform the scientific, public and policy debate on the effects of a fuel change from fossil to biomass fuels and (b) inform utilities on the effects of future fuel sourcing. In contrast to the majority of earlier studies, this analysis builds on data from actual supply chains and plant operations rather than relying on hypothetical modelling alone. We believe that the restricted use of models and their in-built assumptions ensure a strong foundation for the analysis and lead to conclusions that are more robust.

2 | MATERIALS AND METHODS

2.1 | Model overview

For modelling carbon debt and payback times, we set up a modelling framework that assessed carbon pools and fluxes linked to each transition case and its supply chain (Figure 2). The modelling framework included direct product chain emissions from forest biomass growth and forest operations necessary for generating forest products such as wood products and energy. Further into the product chain, the model included direct emissions from wood processing, transport and from energy production in district heat and CHP plants. Biomass is a scarce resource and the transition from fossil fuels to bioenergy is implicitly associated with indirect changes in the area used to procure the resource, in the fuel use of the considered system and the use of wood and other materials. Accordingly, in addition to the direct emissions from the product chain, we modelled indirect emissions resulting from market mediated changes in land use (iLUC), wood use (iWUC) and fuel use (iFUC). The mapping of carbon flows included carbon in products and CO₂. Methane (CH₄) and other climate forcers, for example, nitrous oxide (N₂O), were disregarded. The model framework is documented by Taeroe et al. (2017).

We used this approach to calculate the cumulative net carbon emissions (CCE(t)), over 40 years of time series starting
5 years prior to the initiation of the fuel transition to include the fossil baseline and covering 35 years of post-conversion period. From CCE(t), we derived the relative cumulative net carbon emissions (RCCE(t)) as the CCE(t) for the biomass life cycle relative to the CCE(t) for the replaced fossil fuel life cycle. To assess the point in time where the fuel transition starts to contribute positively to climate change mitigation, we calculated a carbon payback time (CPT). The CPT is reached when the CCE(t) for the biomass supply chain falls permanently below the CCE(t) for a hypothetical continuation of the fossil supply chain. We further calculated the relative cumulative net carbon emissions 30 years after initiation of the fuel transition (RCCE(30)) as an indicator of emission savings or additions over the typical technical lifetime of a CHP or DH facility.

The CCEi(t) for plant (i) at time (t) was calculated as:

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

where \( \sum_{j=1}^{T} ED_{i,j} \) is the cumulative carbon emissions from decomposition of dead biomass, \( \sum_{j=1}^{T} EB_{i,j} \) is the cumulative carbon emissions from direct combustion of biomass, \( \sum_{j=1}^{T} EF_{i,j} \) is the cumulative carbon emissions from combustion of fossil fuels (coal, oil or natural gas), \( \sum_{j=1}^{T} EP_{i,j} \) is the cumulative supply chain carbon emissions from extraction, production, transportation and processing of biomass or fossil fuels (j), \( \sum_{j=1}^{T} EiWUC_{i,j} \) is the additional cumulative carbon emissions along the whole supply chain from the amount of fossil fuel intensive products (such as steel, concrete or aluminium) needed to reach the same material output, if wood suited for wood products is instead used for energy, \( \sum_{j=1}^{T} EiLUC_{i,j} \) is the additional cumulative carbon emissions along the whole supply chain from the amount of land that is indirectly intensified or converted as a consequence of increased use of biomass, \( \sum_{j=1}^{T} EiFUC_{i,j} \) is the additional cumulative carbon emissions incurred when the use of biomass on a transitioned plant affects the fuel use of other plants in the same district heating network or in the electricity grid, and \( \sum_{j=1}^{T} EdLUC_{i,j} \) is the cumulative net carbon uptake in both above- and belowground living biomass.

2.2 | Data from utilities

To provide data for the analysis, a number of utilities were selected in collaboration with Danish Energy and the Danish District Heating Association. Data are characterized in Table 1. The 10 plants were selected to cover a broad range of configurations, for example, combined heat and power production or district heat production; 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. The plants covered biofuel capacities ranging from 18 to 852 MW. Fuel transitions took place between 1985 and
2017. Data providers were asked to supply data for a time series beginning 5 years prior to initiation of the fuel transition and ending 5 or more years after completion of the transition.

Data received from the utilities exhibited large variation with respect to the details provided, length of time series and temporal resolution. The type and detail of data requested were clearly challenging for the data providers as only within the last few years, where utilities have had to document sustainability compliance against the Industry Agreement to ensure Sustainable Biomass, these data have been collected regularly (Larsen et al., 2019).

Not all utilities provided complete time series as requested. Where necessary, we extrapolated backwards in time to 5 years prior to initiation of the fuel transition from the first data point in the time series received. Likewise, we extrapolated forward in time using the last data point in the time series to construct 40 years of time series for each plant.

### 2.3 Data from other sources

For data not provided by the utilities, assumptions were made based on scientific literature regarding, for example, substitution factors of forest products, emissions related to the alternative fate of wood and forest growth (Table 2).

### 2.4 Forest operations, harvest and processing of biomass

Our data primarily included two types of biomass: wood chips and wood pellets. Wood chips are wood that is chipped 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, for example, sawdust, stems or other residues from lumber production. Processes involved include grinding of wood inputs into smaller particles, drying and pressing into pellets. Emission data for specific operations are provided in Table 2.

### 2.5 Transport

Our data did not contain detailed information about the location of harvest of biomass or extraction of coal; only the country of origin and, if shipped, the harbour from which it was shipped. For each country, we estimated internal transport distances of fuel prior to export. Assuming that the fuel (biomass or coal) was procured uniformly across the region, we used the distance from the centroid of the region to the shipping harbour. Furthermore, we assumed that the fuel was shipped directly to the harbour in Denmark closest to the CHP or district heating plant (Table 3). The shipping distance (rounded to nearest 100 km) was measured on Garmin nautical charts.

### 2.6 Forest carbon uptake

The rate at which carbon is sequestered by forests depends on the growth rate of the forests from which the biomass is harvested. Lacking specific information on where the biomass was harvested, local growing conditions could not be assessed. Instead, we applied national and regional forest growth models for the most common tree species in the individual
countries to estimate mean annual forest growth and carbon sequestration (Table 4). Forest growth data formed the basis for calibration of a standard forest growth model for conifer and broad-leaved forests. The growth model for a single stand included 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, assuming a uniform age-class distribution.

Via biomass expansion factors, we estimated the number of stems and amounts of harvest residues produced at thinning or final harvest using standard allometric factors (IPCC, 2006a). As the analysis covered a period of time where the demand for biomass was increasing, we assumed that all biomass used for energy represented an additional demand, which affected the forest carbon pools (dead or alive). Harvest of residues affects the dead wood carbon pool, as the input to this pool is reduced when harvest residues are not left in the forest. Furthermore, we assumed that additional harvesting as a response to increased demand for bioenergy drives the living forest carbon stock from a no-bioenergy equilibrium to a lower with-bioenergy equilibrium.

**TABLE 2** Basic assumptions for calculation of the cumulative net carbon emissions (CCE) and carbon payback time (CPT)

| No. | Assumption                                                                 | Source                                                                 |
|-----|---------------------------------------------------------------------------|-----------------------------------------------------------------------|
| 1   | Above- and below-ground biomass and dead wood carbon pools in unmanaged  | IPCC (2006a)                                                          |
|     | forest are set as the default IPCC values                                 |                                                                       |
| 2   | Soil carbon pools (including the forest floor) in unmanaged forests are   | Callesen et al., (2015), Vesterdal and Christensen (2007)              |
|     | in steady state during the whole projection period and are unchanged by  |                                                                       |
|     | use of bioenergy throughout the projection period                        |                                                                       |
| 3   | We assume that establishment of forests and growth after intervention    | Möller (1933), Nord-Larsen and Johannsen (2007), Taeroe et al. (2016) |
|     | follows existing yield tables and models for the most common tree species |                                                                       |
|     | in the region                                                            |                                                                       |
| 4   | Below-ground biomass of all forest management alternatives is 20% of     | Nord-Larsen, Meilby, et al. (2017)                                     |
|     | the above-ground biomass                                                 |                                                                       |
| 5   | The half-life of harvest and industrial residues left for decay is 5      | Hérault et al. (2010), Krankina and Harmon (1995), Russell et al. (2014) |
|     | years for tropical regions, 10 years in temperate regions and 15 years   |                                                                       |
|     | in boreal regions respectively. For biomass burned, we assumed a         |                                                                       |
|     | a half-life of 1 year                                                     |                                                                       |
| 6   | All biomass contains 50% carbon                                            | Huntington (1995)                                                     |
| 7   | Carbon emissions per unit of heat and electricity produced for each plant | IPCC (2006a)                                                          |
|     | and each year were calculated directly from the data by using standard   |                                                                       |
|     | emissions factors for coal, oil, natural gas and biomass                  |                                                                       |
| 8   | There are no significant emissions along the production chains of other  | Assumption for simplicity                                              |
|     | greenhouse gasses than carbon dioxide                                     |                                                                       |
| 9   | For forest site operations, we used 2.29 l diesel t⁻¹ biomass. For       | Börjesson (1996), Röder et al. (2015), Spinelli and De Arruda Moura   |
|     | harvest, forwarding and chipping, we used emissions factors of 2.31 and   | (2019)                                                                |
|     | 0.87 Kg C m⁻³ harvested wood, and for chipping, we used 1.85 l diesel   |                                                                       |
|     | t⁻¹ biomass. For processing, we used emissions (fossil) equivalent to    | Börjesson (1996)                                                     |
|     | 15% of combustion emissions                                               |                                                                       |
| 10  | For transport (of both biomass and coal), we used fuel consumption       | Wihersaari (1996), Yu et al. (2014)                                    |
|     | emissions of 1.3, 0.68 and 0.22 MJ Mg⁻¹ km⁻¹ for truck, train and ship    |                                                                       |
|     | transport, respectively                                                  |                                                                       |
| 11  | Mining emissions for coal were set to 5% of combustion emissions. Production| IPCC (2006b), Schou et al. (2015)                                     |
|     | chain and transport emissions for oil and natural gas were assumed to be  |                                                                       |
|     | 10 and 14%, respectively, of the emissions from their combustion         |                                                                       |
| 12  | The half-life of the wood product pool is 35 years for sawn timber, 25   | Leskinen et al. (2018)                                                |
|     | for wood-based panels and 2 for paper                                     |                                                                       |
| 13  | The wood product substitution factor (SF) is set to 1.4 for timber, 1.2   | Energistyrelsen (2020)                                               |
|     | for panels and 1 for other products                                       |                                                                       |
| 14  | Indirect emissions related to a changes in electricity production in    |                                                                       |
|     | conversion to biomass were based on calculations and projection by the    |                                                                       |
|     | Danish Energy Agency                                                      |                                                                       |
2.7 | Biomass counterfactuals

Based on the data supplied by the utilities, we characterized biomass into six source categories: harvest residues, stems, bioenergy crops, industrial residues, non-forest wood and unknown biomass origin.

Residue biomass is harvested biomass not otherwise being utilized for wood products but left to decay or potentially available for bioenergy. Here, we included residues from harvesting, decayed or low quality stems and processing residues such as sawdust or shavings not suitable for other uses, defining them as ‘true residues’. Modelling counterfactuals for true residues, we assumed two possible options: (a) the residues were burned on site or (b) left to decay naturally. We assumed that burning on site or decay of forest biomass left on the forest floor followed a first-order exponential decay function using the half-lives described in Table 2.

When the demand for biomass for energy exceeds the supply of residues, the prices may increase and influence GHG emissions from adjacent sectors. This may lead to expansion of the forest area from which biomass is harvested to meet the demand for other products, for example, pulp and paper (Schmidt et al., 2015). Such expansion is named indirect land use change (here denoted forest iLUC). Forest iLUC was treated as an expansion of managed forest into primary or secondary forests implying additional harvesting in these areas. Such expansion affects carbon storage across several parameters: (a) For a period, the carbon pool in living biomass is smaller in managed forest after intervention, (b) input to the dead wood carbon pool is reduced, as part of the biomass is extracted for energy and (c) in some cases, the soil carbon pool is affected by lower input resulting from increased extraction. We modelled forest management expansion into previously unmanaged forests according to the method developed by Schmidt et al. (2015).

For the forest carbon pool, we used region-specific yield tables and the forest growth model to determine the living and dead forest carbon stocks. Forest iLUC emissions were modelled as the difference between the carbon stock (living and dead biomass) of the unmanaged reference and that of the managed forest.

Agricultural iLUC occurs when prices for bioenergy exceed food prices and farmers switch from food crops to dedicated bioenergy crops. This leads to increased pressure on the food market, which may lead to agricultural iLUC, that is, expansion of agriculture into forest areas. For more comprehensive introduction to and illustration of the iLUC concept, we refer to Schmidt et al. (2015). Here, we used the same approach to quantifying GHG emissions related to iLUC as described by Schmidt et al. (2015).

Conceptually, the only difference in estimation of forest iLUC and agricultural iLUC is what happens after iLUC occurrence. Where only stems are removed in forest iLUC and a managed forest is regenerated after forest iLUC, the entire forest carbon stock is removed in agricultural iLUC and no regeneration takes place.

When the supply of timber for wood products decreases due to increased bioenergy consumption, the price of wood may increase, leading to decreasing consumption of industrial wood. To meet demand, for example, for building

### Table 3: Distances and modes for transport of biomass and coal from different regions to Denmark.

| Country     | Fuel     | Truck | Train | Ship  |
|-------------|----------|-------|-------|-------|
|             | Transport distance (km) |       |       |       |
| Denmark     | Biomass  | 150   | 0     | 0     |
| Australia   | Coal     | 500   | 100   | 24,000|
| Baltic states| Biomass | 250   | 0     | 1,000 |
| Belarus     | Biomass  | 400   | 0     | 1,000 |
| Colombia    | Coal     | 500   | 100   | 9,000 |
| Europe      | Biomass  | 500   | 0     | 1,000 |
| Ghana       | Biomass  | 200   | 0     | 5,000 |
| Germany     | Biomass  | 500   | 0     |       |
| Kazakhstan  | Coal     | 700   | 100   | 9,000 |
| Norway      | Biomass  | 300   | 0     | 600   |
| Norway      | Coal     | 300   | 100   | 600   |
| Poland      | Coal     | 500   | 100   | 300   |
| Russia      | Biomass  | 500   | 0     | 1,300 |
| South Africa| Coal     | 500   | 100   | 12,000|
| Sweden      | Biomass  | 300   | 0     | 200   |
| USA/Canada  | Biomass  | 500   | 0     | 5,000 |
| USA/Canada  | Coal     | 500   | 100   | 5,000 |

### Table 4: Average annual carbon sequestration for sourcing countries/regions

| Country    | Broadleaves | Conifers |
|------------|-------------|----------|
| tC ha⁻¹ year⁻¹ |              |          |
| Denmark    | 4.6         | 5.7      |
| Estonia    | 1.9         | 1.8      |
| Lithuania  | 1.9         | 1.4      |
| Latvia     | 1.9         | 1.4      |
| Belarus    | 1.9         | 1.3      |
| USA        | 3.0         | 4.8      |
| SE         | 3.0         | 4.8      |
| USA/Canada | 5.0         | 5.0      |
| SE/USA     | 3.0         | 4.8      |
material or furniture, producers may, depending on price elasticities, shift a part of the demand to other products. This shift is called indirect wood-use change (iWUC). Here, we assumed that all additional demand not provided for by ‘true’ residues or iLUC was replaced with other products such as steel, concrete or plastic. Commonly GHG emissions from such shifts are expressed as a substitution factor that gives the carbon emissions as a factor of the carbon in the wood used for energy instead of wood products (Table 2).

As the counterfactual for harvest residues, we assumed that 30% were burned directly on the forest floor and 70% were left in the forest for natural decay. For stem biomass not extracted for wood products, we assumed that 90% was felled and left on site following harvest. The remaining 10% was assumed to lead to indirect emissions, with 5% attributed to iLUC and 5% to iWUC. Similarly, for industrial residues (sawdust, bark, slabs, edgings, off-cuts, veneer clippings, sawmill and particleboard trimmings, planer shavings and sander dust), the counterfactual can range from burning or decay on site to energy or wood material production off site. We made the same assumptions for indirect emissions for industrial residues as for stems with 5% leading to iLUC and 5% leading to iWUC. The counterfactual for non-forest wood (municipal park waste, wood from removal of invasive species in nature areas, harvesting of shelterbelts etc.) was treated as stem biomass left for decay. The unknown biomass origin category was treated as 50% stem biomass and 50% industrial residues. The choice of 10% of the biomass with indirect emissions is arbitrary, as no data was available to determine this. However, we do not see any indications that Danish biomass utilization is causing large-scale iLUC within Europe, from where 75% of the data originate.

The direct fuel displacement at the energy plants treated here was quantified directly in the data supplied by the utilities. However, the production at an individual CHP or district heating unit is potentially linked to the production at other units through trade and connection to the same district heating network or the electricity grid (Rajagopal et al., 2011). If the fuel transition in the cases included here led to a change in the production of heat and electricity, this may have led to compensatory actions at other plants supplying the same district heating network or the electricity grid. Such market-mediated ripple effects are considered as indirect fuel use change (iFUC), and the GHG emissions attributable to iFUC were added to 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 based on production data from the Danish Energy Agency (Energiproducenttællingen, confidential data). We found that fuel changes at suppliers to a district heating network other than the plants treated here could not unambiguously be attributed to the introduction of wood fuels at the plants (Nielsen et al., 2020). Consequently, in this analysis, we assumed that there were no iFUC GHG emissions with reference to district heat production. For electricity delivery to the grid, changes following a switch in fuel were assumed to be compensated by electricity production elsewhere in the grid, leading to changes in GHG emissions. We used current and projected average GHG emissions related to electricity production from the Danish Energy Agency to estimate iFUC emission following changes in electricity production (Energistyrelsen, 2020).

### 2.8 Basic analyses

The basic analyses relied on assumptions listed in Table 2 and inputs described above to calculate CCE(t), CPT and RCCE(30), for each plant. Subsequently, we developed a ‘typical plant’, corresponding to a hypothetical transition case of average size, with a weighted average conversion efficiency, fuel mix and sourcing strategy (Table 5).

The typical plant may be interpreted as a proxy for the Danish transition from fossil to biomass fuels in the period 2002–2018. This typical plant was analysed for transition to biomass from both coal and natural gas and was used to conduct sensitivity analyses.

**Table 5** Characteristics of the ‘typical’ fuel transition. Based on the weighted average of contributing CHP and district heating plants

| Parameter                      | Value   |
|--------------------------------|---------|
| Production (heat + electricity) | 2.6 GJ/year |
| Conversion efficiency          | 85%     |
| Composition of biomass         |         |
| Residues                       | 24%     |
| Stems                          | 34%     |
| Industrial residues            | 36%     |
| Non-forest biomass             | 2.8%    |
| Dedicated bioenergy             | 0.17%   |
| Origin of biomass              |         |
| Denmark                        | 32%     |
| Baltic states                  | 40%     |
| Belarus                        | 3.5%    |
| Germany                        | 2.0%    |
| Ghana                          | 1.0%    |
| Norway                         | 1.7%    |
| Other European                 | 3.0%    |
| Russia                         | 3.5%    |
| Sweden                         | 0.3%    |
| USA/Canada                     | 6.5%    |
| Unspecified                    | 5.5%    |
2.9 Sensitivity analyses

To assess the robustness of the estimated CCE(t), CPT and RCCE(30), we changed several assumptions one at a time and recalculated CCE(t), CPT and RCCE(30) for the typical plant (Table 6).

3 RESULTS

The CPT was 6 years for the typical plant transitioned from coal to biomass and ranged from 0 to 13 years for the individual plants (Figure 3a). For these transitions, RCCE(30) of the typical plant was 0.69 corresponding to an emission saving of 31%, with a range between 0.29 and 0.85, corresponding to emission savings between 15% and 71%, 30 years after the transition, compared to the continuation of coal use. The plants with short CPTs and low RCCE(30) were the plants that had low or negative iFUC emissions and low iWUC and/or iLUC emissions, that is, plants with continued high electricity production after the fuel transition and a higher than average proportion of true residues in the fuel mix. Plants with reduced electricity production subsequent to the fuel transition and a large proportion of stems and industrial residues in their fuel source, leading to large iFUC and iWUC and/or iLUC emissions, had longer CPTs and higher RCCE(30).

For the transitions from natural gas, CPTs of individual plants ranged between 9 and 34 years with 24 years for the typical plant (Figure 3b). The typical transition from natural gas resulted in an RCCE(30) of 0.93, while RCCE(30) of individual plants ranged from 0.81 to 1.03. The case with the longest CPT and highest RCCE(30) had very high iFUC emissions, but also iLUC and iWUC emissions.

3.1 Efficiency

The total fuel efficiency (the efficiency with which fossil or biomass fuels are converted into electricity and district heat) did not change significantly because of the fuel transition. Cases transitioned from coal had a mean fuel efficiency of 84% prior to the transition and 83% after the transition. Correspondingly, for the natural gas transitions, the efficiency before and after the fuel transition was 88% and 89%, respectively.

| Parameter                                  | Biomass type in focus | Basic assumption | Alternative assumptions |
|--------------------------------------------|-----------------------|------------------|-------------------------|
| Biomass origin                             | All types             | Table 5          | Denmark or USA          |
| Wood chips/wood pellets distribution        | All types             | 40%/60%          | 100%/0% or 0%/100%     |
| Decay rate of residues (half-life)          | Harvest residues      | 10 years         | 5 or 25 years           |
| iWUC/iLUC for stem biomass                 | Stems                 | 5%/5%            | 5%/0% or 20%/0%        |
| iWUC/iLUC for industrial residues          | Industrial residues   | 5%/5%            | 0%/5% or 0%/20%        |
| Fuel for drying wood for pellets            | All types             | Natural gas      | Hog fuel                |

TABLE 6 Overview and assumptions changed for sensitivity analyses

FIGURE 3 Relative cumulative net carbon emissions (RCCE(t)) and carbon payback time (CPT) of the plants included in the study. The CPT is reached when the lines for the individual or typical plants cross the line for the fossil reference (1.0 on the y-axis) and permanently stays below the line. Plants with transition from coal are illustrated in panel (a) and from natural gas panel (b). The line exceeding the response axis in panel B reached RCCE(t) of 1.65 two years after transition from natural gas.
3.2 | Upstream emissions

For biomass supply chains, upstream emissions (forest operations, transport and processing) represented up to 11% of the direct emissions. In coal supply chains, mining and transport emissions were responsible for 9% of the direct emissions. For natural gas, extraction and transport made up 13% of the direct emissions (Figure 4). Although coal has higher energy content per ton than biomass, the transport emissions were higher for coal than for biomass due to much longer transport distances for coal, on average. 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 approx. 30% lower for coal than for wood pellets per unit of heat and electricity produced. For wood chips, the upstream emissions were approx. 3% (Figure 4).

The influence of the basic assumption that wood for pellets was dried burning natural gas was tested alternatively assuming that wood was dried burning hog fuel as also assumed by, for example, Jonker et al. (2014). For transitions from coal, burning hog fuel reduced the CPT for the typical plant from 6 to 4 years and RCCE(30) from 0.69 to 0.64. The corresponding changes for the typical natural gas transition were a reduction of CPT from 24 to 19 years and of RCCE(30) from 0.93 to 0.85.

3.3 | Transport modes and distances

Transportation by truck had almost six times higher emissions per ton and km than transportation by ship. For the typical plant, sourcing from Denmark, upstream emissions were 60% of the upstream emissions for cases sourcing from the USA. The typical plant that shifted from coal to biomass and sourced biomass from Denmark had a CPT of 5 years and RCCE(30) of 0.67. For a similar case sourcing from the USA, the corresponding figures were 9 years and 0.75.

3.4 | Wood pellets versus wood chips

The lower heating value of wood chips and wood pellets differs, as the water content is typically 45% in wood chips and 10% in wood pellets. Hence, for plants without flue gas condensation, wood chips had higher combustion emissions per unit of energy than wood pellets as some of the energy is lost in evaporation of water. Moreover, pellets have lower transport emissions, as the energy density is higher. Conversely, wood pellet production uses energy, for the pelletizing process and for drying, where wood chips only undergo chipping before combustion. Hence, wood pellets had larger emissions from processing than wood chips (Figure 4). Resulting from the opposing effects of combustion and transport emissions, the typical plant using wood chips only had a CPT of 7 or 22 years (transition from coal or natural gas respectively) and RCCE(30) of 0.66 or 0.89 while the typical plant using wood pellets returned a CPT of 5 or 24 years with RCCE(30) increasing to 0.70 or 0.94. Had we assumed that the pellets were dried using wood as fuel, the payback time and RCCE(30) would have been similar to or lower than those obtained for plants using wood chips.

3.5 | Biomass counterfactuals

For the 10 plants studied here, we found positive as well as negative iFUC emissions. Some plants increased electricity production after the transition to biomass and consequently displaced other partly fossil-based electricity production. The inclusion of indirect (market mediated) effects (iLUC, iWUC and iFUC) generally extended payback time for transitions from both coal and natural gas to biomass (Figure 5). For the typical coal plant, iFUC added 1 year to CPT and 2 years to the typical natural gas plant, iLUC added 1 year to the typical coal to biomass transition and 4 years to the typical natural gas to biomass transition. iWUC added 1 year to the typical coal to biomass transition and 3 years to the typical natural gas to biomass transition.

Some plants sourced wood chips largely made from forest residues, where others relied on wood pellets produced from low quality stems and industrial residues. The transition of the typical coal plant based on true residues (tops and branches) only demonstrated a CPT of 2 years and RCCE(30) at 0.47. The corresponding figures for the typical natural gas plant were 8 years and 0.61 respectively. The

![Figure 4](image) Direct and up-stream GHG emissions of the fuel supply chains included in this analysis. ‘Biomass’ represents a data-driven average of the two main forest fuels ‘Wood chips’ and ‘Wood pellets’
above findings build on an assumption of residue half-lives of 10 years. If true residues were sourced from tropical regions with a residue half-life of 5 years, the CPT was reduced about 1 year. Similarly, sourcing residue wood from boreal regions with a residue half-life of 25 years increased the CPT about one year.

Stem wood used for heat and electricity production is in most cases rotten, deformed, damaged or of a non-merchantable tree species with no alternative use, and is treated as forest residues albeit with a slower decay rate. Part of the stem wood used may have had alternative uses, for example, for industrial timber or pulp and paper. Sourcing such wood fractions leads to indirect wood use emissions (iWUC) or to expansion of managed forest into unmanaged forests, that is, indirect land use change (iLUC).

For a plant sourcing only stem wood and assuming that 10% of the sourced stems would have had alternative uses, transition of the ‘typical’ coal plant returned a CPT of 10 years and an RCCE(30) of 0.77 (Figure 6). For a similar natural gas transition, the CPT was 33 years and RCCE(30) 1.04 (Figure 6). Increasing the amount of stem wood with alternative uses to 20% increased the CPT and RCCE(30) to 13 years and 0.81, respectively, for the coal plant and 44 years and 1.11, respectively, for the natural gas plant. Reducing the proportion of stem wood with alternative uses to 5% led to a CPT of 8 years and an RCCE(30) of 0.74 for the coal plant and 30 years and 1.00, respectively, for the natural gas plant (Figure 6).

Some plants sourced wood industry residues, which potentially could have been used for alternative products, for
example, wood panels. Assuming that 10% of the sourcing had alternative uses, CPT and RCCE(30) were 9 years and 0.73, respectively, for the typical coal plant and 28 years and 0.99, respectively, for the typical natural gas plant (Figure 6). The sensitivity analysis (5% and 20% industrial residue wood with alternative uses) returned a range of CPT and RCCE(30) of 7–9 years and 0.68–0.83, respectively, for the typical coal plant and 24–45 years and 0.92–1.12, respectively, for the typical natural gas plant.

4 | DISCUSSION

For most transitions, the CPT was reached within 13 years after the fuel transition from coal to biomass. The CPT was reached within 22 years for transition from natural gas to biomass, except for one plant with a CPT of 34 years. Cases with up to 50% stem wood and industrial residues in the fuel mix and sourcing within Europe achieved CPTs below 10 years for coal to biomass transitions and 20 years for natural gas to biomass transitions. CPTs for natural gas transitions were more sensitive to sourcing strategy and indirect emissions, in line with earlier studies identifying the fossil fuel reference and leakage as among the key parameters determining CPT (Lamers & Junginger, 2013; Timmons et al., 2015).

Based on our analyses of the DH and CHP data, we assumed that 90% of the biomass sourced for energy were real residues with no alternative use. Consequently, CPTs reported here were comparable to those obtained for sourcing strategies based on residues (see e.g., Pingoud et al., 2012; Repo et al., 2012). Building bioenergy supply chains on true residues generally leads to short CPTs and rapid climate benefits (Agostini et al., 2013; Bentsen, 2017; Buchholz et al., 2016; Lamers & Junginger, 2013; Madsen & Bentsen, 2018; Mitchell et al., 2012). Oppositely, studies assuming that the biomass originates from harvest dedicated to bioenergy production, or from sources, where the supply is already equal to the demand before using biomass for energy commonly result in much longer CPTs (Cherubini et al., 2013; Holtsmark, 2015; Mitchell et al., 2012; Zanchi et al., 2012). The latter assumptions would also result in longer CPT for the cases presented in our study.

The transitions analysed here were either for DH plants or CHP plants with a large proportion of heat production. Such plants are more efficient than plants producing electricity only and the CPTs found in the literature are correspondingly smaller for studies that analyse cases with heat production (Lamers & Junginger, 2013; Madsen & Bentsen, 2018; Timmons et al., 2015) compared to studies analysing cases solely with production of electricity (Colnes et al., 2012; Walker et al., 2013).

4.1 | Conversion efficiency

A common assumption in the scientific literature is that the transition from fossil to biomass fuel leads to a decline in the plant efficiency; see, for example, Mitchell et al. (2012) and Sterman et al. (2018). Madsen and Bentsen (2018) demonstrated that a fuel transition on a CHP plant from coal to biomass is possible without loss of efficiency and this study corroborates that for most transitions. The high efficiencies reported here stem from utilities 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 in our study experienced a change in electricity production after the fuel transition relative to the period leading up to the transition. In this analysis, such changes were attributed to the fuel transition in the form of increased or decreased marginal electricity production from other operators in the grid, resulting in iFUC emissions. However, other factors influence the role of large centralized CHP plants over time. Together with the build-up of electricity generation capacity from intermittent renewables, such as wind and solar power, increased electricity trading capacity leads to a reduction in the price of electricity. Reduced electricity prices favour the production of district heat over electricity production and by shifting the ratio between heat and electricity production, CHP plants can accommodate to intermittent electricity production. Hence, temporal changes in the mix of heat and electricity production may not solely be attributed to iFUC emissions. In our study, we used projections of the capacity to accommodate such changes in the energy demand, but the subject may be studied in greater detail.

4.2 | Indirect emissions/leakage

Biomass is a scarce resource and the transition from fossil fuels to bioenergy is implicitly associated with a reduction in alternative biomass use, for example, in the power (co-firing in coal condensing power plants) and transport sector (production of biogas, bioethanol, FT-diesel etc.) or expansion of the area affected by the procurement of biomass. Such indirect emissions or leakage cover GHG emissions derived from market mediated effects (Axelsson & Harvey, 2010) or telecoupling (Fang et al., 2016; Liu et al., 2015). Often indirect effects contribute substantially to the bioenergy supply chain GHG emissions (Lapola et al., 2010; Plevin et al., 2010; Repo et al., 2011), but are the effects that build on the weakest scientific foundation (Djuric Ilic et al., 2014; Kim &
Dale, 2011; Wicke et al., 2012). While there is scientific consensus on the existence of indirect GHG emissions related to bioenergy production, the quantification of indirect GHG emissions remains controversial.

In this study, we included iLUC, iWUC and iFUC in an attempt to capture the dynamics of indirect emissions. Even with the 10% of biomass associated with indirect emissions assumed here, the CPT was much longer for plants using stem wood and industrial residues than for those using true residues. In the sensitivity analysis, we increased the 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 (Buchholz et al., 2016; Timmons et al., 2015).

Buchholz et al. (2016) and Bentsen (2017) report that differences in model choice and inclusion of leakage are among the main cause of the observed large differences in carbon CPT across various studies, which points to the importance of analytical transparency, model calibration and consensus on model choices. The model we present here is such an attempt as it includes all leakage effects, but reports their contribution separately.

There is little empirical evidence to support assumptions on what fraction of a specific biomass assortment or a specific supply chain creates 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 (Lotze-Campen et al., 2010). Locally, competition and price elasticities may differ from the global market. The 10% assumed in this study represents quality timber, with a product half-life of 35 years (IPCC, 2006b) and a substitution factor of 1.4 (Leskinen et al., 2018). The net prices of pulp, paper and wood fuel assortments are often similar and may with increased pressure on the bioenergy market favour the sale of wood in pulp and paper quality for fuel purposes. However, the half-life of paper and cardboard is 2 years (IPCC, 2006b), meaning that from a carbon debt and CPT perspective using pulp and paper wood for energy has lesser influence on the CPT than had it been sawn timber. The net price difference between wood fuel assortment and timber assortments remains large, and hence, there is little risk that increased bioenergy demand will affect the market for sawn timber severely.

When processing round wood, 40–50% of the biomass in timber logs is lost at sawmills in the production of sawn timber (Schou et al., 2015), meaning that there is an equal amount of timber and industrial residues available for the market. Production of wood-based panels (the main product from industrial residues) only corresponds to approx. 10% of the amount of sawn timber in Denmark (Nord-Larsen, Johanssen, et al., 2017), and possibly also in other countries, making large quantities of industrial residues available for other products such as energy. However, with increasing use of biomass for various products through innovative use of forest resources, the proportion of industrial residues that may be burdened with iLUC or iWUC will grow along with increased market pressure.

Greater demand for bioenergy may also lead to harvest of biomass in forests with poor timber quality, especially in countries where forests are managed extensively, relying on natural regeneration with no tending after harvest. Such forestry practices reduce post-felling costs and may make it profitable to harvest low quality/price assortments, which will increase the risk of iLUC through additional harvest. Conversely, in intensively managed forests with higher costs (planting and tending) after interventions, the low price of bioenergy compared with other assortments may make it less profitable to harvest low quality compartments and reduce the risk of iLUC. In our data, most of the biomass originates from northern European countries, for example, Scandinavia, the Baltic countries and Germany, where most forests are intensively managed. The carbon stock in most European forests has been increasing over several decades or centuries, but also over the latest decades where the demand for bioenergy has increased (Forest Europe, 2020; Nabuurs et al., 2013), indicating that overutilization of the forest resource is limited. Therefore, we believe that the risk of iLUC from additional harvest has been limited in most of Europe for the period in scope, and that our assumption that 10% (5–20%) of the stems and industrial residues are associated with iLUC emissions is reasonable. In other countries, with large extensively managed forest areas, where regulation is poor or absent, with high levels of corruption and poorly developed forest sectors, there is a much larger risk of iLUC, especially in the form of additional harvest. We recommend that the issues of iWUC and iLUC for bioenergy receive much more scientific attention in the future.

4.3 | Methodological issues

The analysis presented here was largely based on case-specific data on biomass sourcing, conversion efficiencies and production. Still, the analysis included uncertain parameters, especially concerning the fraction of biomass associated with indirect emissions. For parameters where quantification was based on incomplete information, we often conservatively chose 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 aboveground increment of conifers in the SE USA corresponds to 8.0 tonnes dry matter per hectare per year. Jonker et al. (2014) 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 the CPT in cases where forest iLUC occurs and increased yield leads to reduced iLUC emissions as recapture of released carbon is enhanced and hence to a shorter CPT.

As another example, we assumed that process energy for drying wood for wood pellets was supplied by fossil energy, which probably is rarely the case. The analysis by Jonker et al. (2014) assumed that energy for drying wood dust prior to pelletization was provided by burning bark and shavings (hog fuel). The assumption used in our analysis led to a worst-case scenario for the transition from fossil energy to biomass, and the sensitivity analysis found this assumption to have a large influence on CPTs and RCCE(30)s.

4.4 Future sourcing strategies

Sustainable sourcing strategies should consider the impact of biomass harvest on other ecosystem services. Producing and harvesting biomass in forests to mitigate climate change often exhibits trade-offs with other ecosystem services such as biodiversity protection, ground water protection and visual impacts (Duncker et al., 2012; Miller, 2010; Sántha & Bentsen, 2020). Many sustainability issues are addressed in the EU Renewable Energy Directive and by national initiatives in Denmark, United Kingdom, the Netherlands and Belgium (Larsen et al., 2019). Indirect effects, however, are only included in the Dutch sustainability verification and documentation framework that includes an assessment of iLUC (Larsen et al., 2019).

5 CONCLUSIONS

The aim of this study was, through the mapping of carbon dynamics of 10 bioenergy value chains, to: (a) inform the scientific, public and policy debate on GHG emission of a fuel switch from fossil to biomass fuels on CHP and district heating plants, and (b) inform utilities on the GHG emission effects of their fuel sourcing.

Based on the analysis, we conclude that over the typical life-time of a CHP or district heating plant, the transition from fossil fuels to forest biomass reduced GHG emissions to the atmosphere relative to continued use of fossil fuels. Our results further showed that the use of truly residual biomass (harvest residues or industrial residues with no alternative use), biomass harvest from productive forests and short transport distances are instrumental in achieving a short carbon payback time and emission savings.

While the conclusions are robust for the fuel transitions treated here, the results cannot be extrapolated to future fuel transitions. Increasingly, other renewable energy technologies, in Denmark mainly wind and solar, together with interlinks, trade, sector coupling and storage provide stable electricity production. For district heat production, heat pumps driven by renewable electricity and possibly in combination with smaller biomass boilers for peak load provide alternatives to fossil fuel use that will reduce the demand for biomass. The future role of biomass for energy is uncertain but the current focus on power-to-X, BECCS and negative emissions points to biomass as a carbon source for liquid and gaseous fuels, for advanced biomaterial and for long-term carbon storage.

This study points to a number of issues that must be considered in planning and documenting future biomass strategies. True residual biomass should be prioritized over biomass with other applications; shorter transport distances should be prioritized over longer (although transport contributes little to the total supply chain GHG emissions); displacement of coal with biomass should be prioritized over displacement of natural gas. In addition, the current and future role of electricity producing units should be taken in to consideration to address potential indirect effects in the form of iFUC.

ACKNOWLEDGEMENTS

This study was funded by Danish Energy, a non-commercial lobby organization for Danish energy producers; and the Danish District Heating Association, which organizes Danish district heating companies. The funding parties have had no influence on methodology or analysis applied, but have facilitated access to case-specific and confidential production and supply chain data.

DATA AVAILABILITY STATEMENT

The analyses presented here build partly on data publicly available in scientific literature and reports, and in online databases, and partly on commercially sensitive data from utility companies, which are not publicly available, but made available to the authors provided non-disclosure. A more elaborate description of data can be found in Nielsen et al. (2020).

ORCID

Thomas Nord-Larsen  https://orcid.org/0000-0002-5341-6435
Niclas Scott Bentsen  https://orcid.org/0000-0002-5130-0818

REFERENCES

Agostini, A., Giuntoli, J., Boulamanti, A., & Marelli, L. (2013). Carbon accounting of forest bioenergy: Conclusions and recommendations from a critical literature review. Publications Office of the European Union.

Axelsson, E., & Harvey, S. (2010). Scenarios for assessing profitability and carbon balances of energy investments in industry. AGS, The Alliance for Global Sustainability, 57 p.
The European Parliament and the Council of the European Union. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). (Text with EEA relevance).

Timmons, D. S., Buchholz, T., & Veeneman, C. H. (2015). Forest biomass energy: Assessing atmospheric carbon impacts by discounting future carbon flows. *GCB Bioenergy, 8*, 631–643. https://doi.org/10.1111/gcbb.12276

UNFCCC. (2015). Paris Agreement. United Nations, New York, USA

Vesterdal, L., & Christensen, M. (2007). The carbon pools in a Danish semi-natural forest. *Ecological Bulletins, 52*, 113–121.

Walker, T., Cardellichio, P., Gunn, J. S., Saah, D. S., & Hagan, J. M. (2013). Carbon accounting for woody biomass from Massachusetts (USA) managed forests: A framework for determining the temporal impacts of wood biomass energy on atmospheric greenhouse gas levels. *Journal of Sustainable Forestry, 32*(1–2), 130–158. https://doi.org/10.1080/10549811.2011.652019

Wicke, B., Verweij, P., van Meijl, H., van Vuuren, D. P., & Faaij, A. P. C. (2012). Indirect land use change: Review of existing models and strategies for mitigation. *Biofuels, 3*(1), 87–100. https://doi.org/10.4155/bfs.11.154

Wihersaari, M. (1996). Energy consumption and greenhouse gas emissions from biomass production chains. *Energy Conversion and Management, 37*(6–8), 1217–1221.

Yu, L., Ge, Y., Tan, J., He, C., Wang, X., Liu, H., Zhao, W., Guo, J., Fu, G., Feng, X., & Wang, X. (2014). Experimental investigation of the impact of biodiesel on the combustion and emission characteristics of a heavy duty diesel engine at various altitudes. *Fuel, 115*, 220–226. https://doi.org/10.1016/j.fuel.2013.06.056

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy, 4*(6), 761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x

How to cite this article: Nielsen AT, Nord-Larsen T, Bentsen NS. CO₂ emission mitigation through fuel transition on Danish CHP and district heating plants. *GCB Bioenergy*. 2021;13:1162–1178. https://doi.org/10.1111/gcbb.12836