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Time-dependent climate impact of biomass use in a fourth generation district heating system, including BECCS

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ABSTRACT

Changes to energy systems are needed in order to reduce greenhouse gas emissions and mitigate climate change. This study assessed the climate change mitigation potential, in terms of temperature change over time, of a new combined heat and power (CHP) plant, including the dynamic effect on an existing fourth generation district heating system. The climate impact of combusting forest residues (tops and branches) was compared with combusting municipal solid waste (MSW), waste wood or hard coal. A scenario with wood chip combustion and carbon capture and storage (BECCS) was also assessed. The district heating system in Stockholm, Sweden, was used as a case study for the assessment. The results clearly show climate change mitigation potential of combusting wood chips, compared with hard coal and MSW, with this climate benefit increasing further with BECCS. The results also demonstrate the importance of time dynamic effects in the energy system and temperature response, highlighting the importance of not postponing implementation of climate change mitigation options if agreed climate targets are to be met on time.

1. Introduction

In order to meet climate targets under the Paris Agreement [1], extensive conversion of the world's energy system is required, with fossil fuels replaced by renewable energy sources. Bioenergy is one alternative with potential to contribute to this conversion [2]. Sweden has a long tradition of forestry and increasing the use of forest residues for bioenergy is one option to meet future energy demands [3].

A future strategy to mitigate climate change is to capture carbon dioxide (CO_2) directly after fuel combustion, after which the CO_2 is compressed and transported to reservoirs under the seabed for storage. By combining carbon capture and storage (CCS) with biomass combustion (bio-CCS or BECCS), negative emissions can be achieved while, at the same time, heat and power are produced [4]. To assess the climate effects of such a system, greenhouse gas fluxes from the whole life cycle should be considered.

Life cycle assessment (LCA) is a standardised method for evaluating environmental impacts from a system perspective [5,6], with global warming potential (GWP) being the most commonly used method to assess climate impact [7]. However, in the GWP method all greenhouse gas emissions are converted into carbon dioxide equivalents (CO_2-eq) and summarised over the studied timeframe, which means that the timing of greenhouse gas fluxes is overlooked. Furthermore, biogenic carbon fluxes in bioenergy systems are commonly counted as zero, *i.e.* considered carbon-neutral, since emissions during combustion are assumed to be equal to uptake during biomass growth.

This carbon neutrality assumption is a simplification, since biomass use can lead to land use changes that alter carbon stocks in both soil and standing biomass [8,9]. Furthermore, carbon-neutral is not necessarily the same as climate-neutral, since the atmospheric concentration is temporarily altered when biomass is used for energy purposes. This is particularly relevant for forest biomass, which has longer timeframes.

Previous studies have shown that increasing the outtake of forest residues for energy purposes gives a warming impact, since biogenic CO_2 is released earlier in time than in the slower process of decomposition which occurs if the biomass remains in the forest [10–12]. To account for the biogenic carbon dynamic, a time-dependent LCA can be performed where yearly fluxes of greenhouse gases are considered [13, 14].

In Sweden, forest biomass is used in the sawmill industry and in the pulp and paper industry, but also to a large extent for producing district heating, which meets around 60% of the heat demand in Swedish

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buildings [15]. In well-developed district heating systems, so-called fourth generation district heating (4GDH), various energy carriers such as electricity, heating and cooling are integrated [16]. The 4GDH systems are flexible, as electricity can be produced in combined heat and power (CHP) plants when the supply from other weather-dependent renewable energy types is poor, and electricity can be consumed in heat pumps and electric boilers when there is surplus of renewable electricity (power to heat). Biomass thus contributes to robust 4GDH systems that can support expanding use of intermittent renewable energy sources [17,18].

Changes in energy systems occur dynamically and the climate effect of introducing a new biomass CHP plant into an existing district heating system will change over time. There are also dynamic effects between interconnected energy systems. Previous LCA studies on biomass have neglected or simplified such dynamic relationships, while studies on energy systems have neglected the dynamic relationships within and between the biosphere and atmosphere. The aim of this study was thus to assess the climate impact of introducing a new CHP plant into an existing energy system, considering these dynamic effects. Specific objectives were to evaluate:

1 the climate impact of combusting wood chips, in comparison with other types of fuels, in a new CHP plant.
2 the climate impact of combining wood chip combustion with carbon capture and storage (BECCS) in a new CHP plant.
3 the climate impact of a fourth generation district heating system when introducing a new CHP plant, and the effect of combusting different types of fuels.

The new CHP plant KVV8 in Stockholm's district heating system was used as a case study. Dynamic changes in the energy system and the time-dependent climate impact were both considered.

2. Method

2.1. Goal and scope

The goal of the study was to assess the time-dependent climate impact of dynamical changes in an energy system. The LCA was limited to climate impact and no other environmental impacts were considered. To capture the effect of time, a time-dependent climate metric was used where the impact is expressed in terms of temperature change over time (Absolute Global Temperature change Potential, AGTP). The climate metric considers the yearly fluxes of the well-mixed greenhouse gases CO_2, methane (CH_4) and nitrous oxide (N_2O). The climate impact of near-term climate forcers were not considered in this assessment.

The scope of the study included the climate impact of a new CHP plant that substitute marginal power and heat production, and the climate impact of the whole district heating system, with and without introducing the new CHP plant. The result of this study thus displays the climate impact in relation to a reference scenario, *i.e.* when no new CHP is introduced in the existing energy system. A scenario analysis was furthermore performed to evaluate the effect of combusting different fuels in the new CHP plant. Two functional units were used for the assessment; (1) total GWh fuel used and (2) average GWh heat produced per year.

The system boundaries included greenhouse gas emissions from production, distribution and combustion of fuels and biogenic carbon fluxes from direct land use change. Indirect land use changes were not considered in the assessment. Upstream emissions for residuals and waste fuels were allocated to the main product and excluded from the assessment.

The district heating system in Stockholm was used as a case study and is thoroughly described in Levihn [18]. The time perspective for the assessment was district heating produced between 2016 and 2041, and the climate effect for a 50-year time period was evaluated. This since the focus of the assessment, the KVV8 plant, was commissioned in 2016 (Fig. 1).

2.2. Scenario description

Five scenarios in which different fuels were combusted in the KVV8 plant, one in combination with CCS, were analysed (Table 1). A reference scenario without introducing the new CHP plant was also assessed.

2.3. Minerva

The output from the district heating system was determined based on calculations in a program called Minerva used by Stockholm Exergi for investments and changes to the district heating system. Simplified Minerva optimises production on a least-cost basis for a load duration for each consecutive year in the calculation period. The program also takes limits in distribution between subnetworks into account and has a high degree of technical detail in relation to different plants in the Stockholm district heating system. The program has previously been used in calculating system effects of LCA emissions of large-scale biochar [19], technoeconomics of BECCS [20] and data-driven strategic planning of building energy retrofits [21].

2.4. Fuel use in the district heating system

Fuel use in the district heating system in the reference scenario, *i.e.* without introducing the new CHP plant, varied over time (Fig. 2). Hard coal was phased out during the first decade and different types of wastes composed the largest fuel share (see Fig. S1 in Supplementary Material for fuel use in all scenarios).

Wood chips and pellets were assumed to be produced from Norway spruce forest residues (tops and branches), eucalyptus imported from Brazil, olive seeds from Tunisia and sawmill residues from Spain. Biodiesel was assumed to be produced from rapeseed oil (rapeseed methyl ester, RME) imported from the USA and France and tall oil from Sweden (Fig. 3).

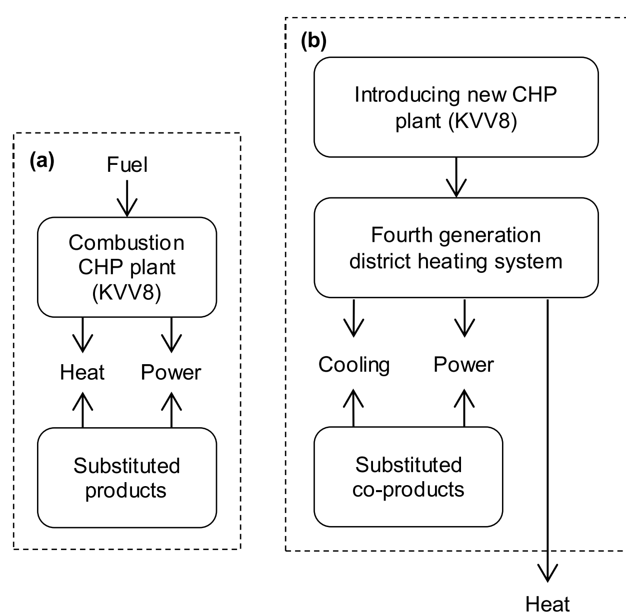

Fig. 1. System boundaries of (a) the new combined heat and power (CHP) plant KVV8 and (b) the effect on the existing fourth generation district heating system in Stockholm of introducing the new CHP plant.

Table 1
Scenarios in which different fuels were combusted in the studied combined heat and power plant KVV8 (S1–S5) and a reference scenario (S6).

Scenario no.	Name	Description
S1	Wood chips	Wood chips from forest residues (tops and branches) harvested at final felling in Sweden.
S2	Hard coal	Hard coal from Russia.
S3	MSW	Municipal solid waste (MSW) with 60% biogenic material. Landfill alternative banned.
S4	Waste wood	Waste wood transported 100 km.
S5	BECCS	Same as scenario 1, with carbon capture and storage (CCS).
S6	Reference (without KVV8)	Baseline scenario without introducing the studied combined heat and power plant (KVV8).

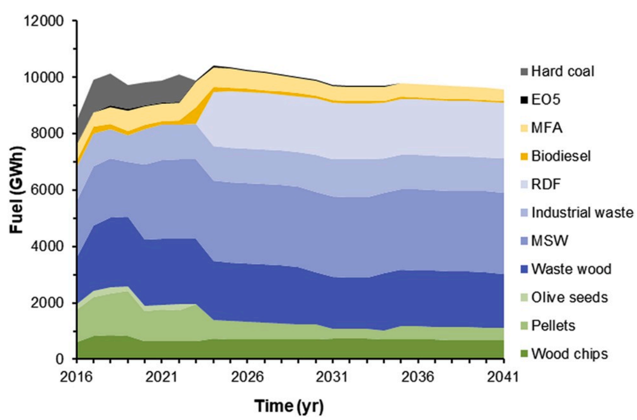

Fig. 2. Fuel consumption in Stockholm district heating system in the reference scenario, *i.e.* without introducing the new combined heat and power plant KVV8 (MFA = mixed fatty acids, MSW = municipal solid waste, RDF = refuse-derived fuel, EO5 = heating oil).

2.5. Data collection

2.5.1. Transport

Transport distances for the different fuels used in the district heating system were calculated with NTM [22] or retrieved from previous studies (Table 2).

Emission factors for transport were retrieved from Ecoinvent (Table 3).

2.5.2. Fossil greenhouse gas emissions

Data on fossil greenhouse gas emissions from the production, distribution and combustion of the different fuels were retrieved from previous studies [23,24] (Table 4).

2.5.3. Biogenic carbon

Biogenic carbon fluxes from harvesting and combusting forest residues (tops and branches) from Norway spruce stands were included in the assessment, based on previous studies. As reference land use, a forestry without forest residues harvesting at final felling was

Table 2
Transport distances (km) for the different fuels used in Stockholm district heating system (MFA = mixed fatty acids, MSW = municipal solid waste, RDF = refuse-derived fuel, EO5 = heating oil).

Fuel	Country of origin	Distance (one-way)		
		Train	Truck	Ship
Wood chips	SE	317[a]	96[a]	
	EE		100[b]	400[c]
	LV		100[b]	450[c]
	FI		100[b]	300[c]
	NO	317[b]	96[b]	
	BR	240[d]	10[d]	13000[c]
	ES		10[b]	4500[c]
Pellets	RU		100[b]	600[c]
Olive seeds	TN		10[b]	6000[c]
Waste wood	SE		100[b]	
MSW	SE		10[b]	
	FI		10[b]	300[c]
	NO	500[c]	10[b]	
	GB		10[b]	2000[c]
Industrial waste	SE		100[b]	
RDF	SE		100[b]	
Biodiesel	SE	450[c]		
	FR			2000[c]
	US			7800[c]
MFA	BE		100[b]	1800[c]
	NL		100[b]	1800[c]
EO5	RU	450[c]		600[c]
Hard coal	RU	2000[c]		600[c]

[a] Skogsindustrierna [40].
[b] Assumed.
[c] calculated with NTM [17].
[d] Porsö, Hammar, Nilsson and Hansson [39].

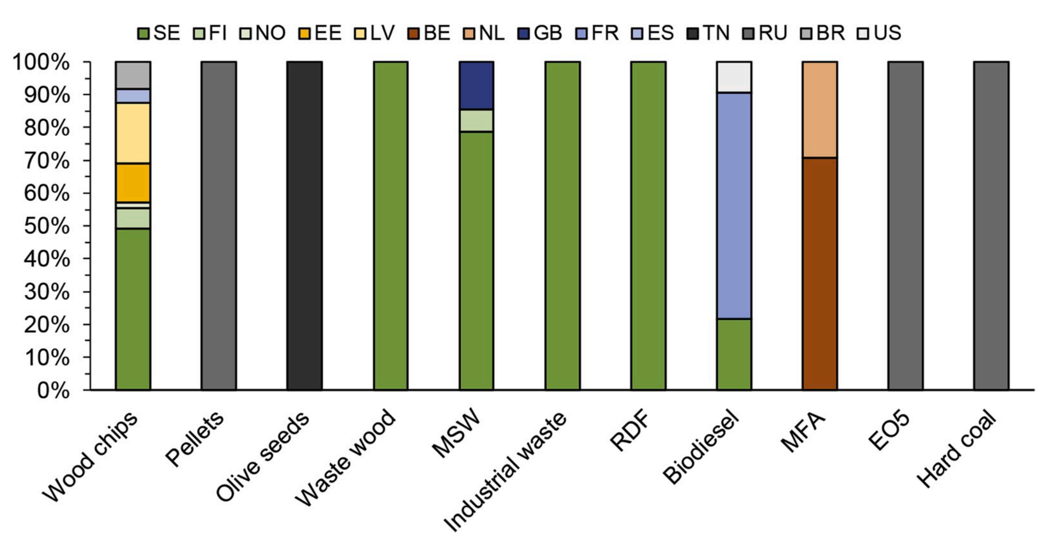

Fig. 3. Fuel origin (for country abbreviations, see Table S1) in the reference scenario, *i.e.* without introducing the new combined heat and power plant KVV8 (MFA = mixed fatty acids, MSW = municipal solid waste, RDF = refuse-derived fuel, EO5 = heating oil).

Table 3
Emission factors (g Mg^{-1} km^{-1}) for different types of transport [20].

	N_2O	CH_4	Fossil CO_2
Train (electricity Europe)	0.001	0.07	37.3
Train (electricity & diesel Europe)	0.001	0.06	44.7
Truck	0.003	0.10	126.4
Liquefied natural gas (LNG) tanker	0.0001	0.04	17.9
Tanker	0.0002	0.01	5.7

considered. Harvesting forest residues releases biogenic CO_2 emissions earlier in time than the slower process of decomposition (Fig. 4a). The net effect of harvesting forest residues was calculated as the yearly difference between the reference land use (*i.e.* decomposition of tops and branches) and harvest of forest residues at final felling (*i.e.* combustion of tops and branches). No impact on future forest productivity was assumed, which means that biogenic carbon fluxes for the next forest rotation (*i.e.* planting and growing of new trees) was equal in both cases, and the net effect was thus zero. To meet the yearly energy demand for forest biomass, new forest stands need to be harvested each year. To simulate the effect of continuous outtake of forest residues, a theoretical forest landscape was modelled based on the forest carbon dynamics of a forest stand in central Sweden [25] (Fig. 4b).

Harvesting rates and biomass decomposition data were retrieved from Hammar et al. [25]; where the forest system was simulated by the Heureka forestry decision support system and biogenic carbon fluxes from decomposition of forest residues were modelled using the Q model [26,28]. Biogenic carbon fluxes for forest residues harvested in the Baltic countries, Norway, Finland and Russia were assumed to be the same as for forest residues harvested in Sweden. Wood chips imported from Spain were assumed to be produced from sawmill residues (sawdust and wood shavings).

Biogenic carbon fluxes in standing biomass for eucalyptus plantations were included based on Porsö et al. [29]; while soil organic carbon changes were assumed to be zero based on findings by Fialho and Zinn [30] that eucalyptus plantations in Brazil on average have no net effect on soil carbon stocks. The net carbon effect of growing eucalyptus

Table 4
Greenhouse gas emissions (kg GWh^{-1}) from the production, distribution and combustion of different fuels (MFA = mixed fatty acids, MSW = municipal solid waste, RDF = refuse-derived fuel, EO5 = heating oil).

Fuel	Origin	Production			Distribution			Combustion			Total		
		N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2
Wood chips	SE	0.1	1.5	3300	0.1	5.9	4490	0	0	0	0.3	7.4	7800
	EE	0.1	1.5	3300	0.1	2.2	2800	0	0	0	0.2	3.7	6100
	LV	0.1	1.5	3300	0.1	2.2	2850	0	0	0	0.2	3.8	6160
	FI	0.1	1.5	3300	0.1	2.1	2690	0	0	0	0.2	3.6	6000
	NO	0.1	1.5	3300	0.1	5.9	4490	0	0	0	0.3	7.4	7800
	BR	11.9	49.7	13100	0.5	16.2	16400	0	0	0	12.3	65.9	29500
	ES	5.0	56.8	25300	0.1	4.8	5130	0	0	0	5.1	61.6	30400
Pellets	RU	0.1	1.5	3300	0.1	2.4	3020	0	0	0	0.2	3.9	6320
Olive seeds	TN	0	0	0	0.3	8.5	9150	0	0	0	0.3	8.5	9150
Waste wood	SE	0	0	0	0.0	1.7	2270	0	0	0	0.0	1.7	2270
MSW	SE	0	0	0	0.0	0.3	389	14.9	11.8	156000	14.9	12.1	156000
	FI	0	0	0	0.0	0.8	918	14.9	11.8	156000	14.9	12.6	156000
	NO	0	0	0	0.2	11.1	6140	14.9	11.8	156000	15.1	22.9	162000
	GB	0	0	0	0.1	3.6	3920	14.9	11.8	156000	15.0	15.4	159000
Industrial waste	SE	0	0	0	0.1	3.4	4510	0	0	0	0.1	3.4	4510
RDF	SE	0	0	0	0.1	2.8	3700	0	0	0	0.1	2.8	3700
Biodiesel	SE	0	0	0	0.1	3.0	1590	2.2	7.2	0	2.2	10.2	1590
	FR	75.6	43.6	61900	0.0	1.0	1090	0	0	0	75.6	44.6	63000
	US	75.6	43.6	61900	0.1	4.0	4240	0	0	0	75.7	47.5	66200
MFA	BE	0	0	0	0.2	6.9	8270	0	0	0	0.2	6.9	8270
	NL	0	0	0	0.2	6.9	8270	0	0	0	0.2	6.9	8270
EO5	SE	0.2	104	18700	0.1	5.6	2770	18.0	7.2	274000	18.3	117	296000
Hard coal	RU	2.0	877	10400	0.4	16.4	12300	4.6	49.0	382000	7.0	942	404000

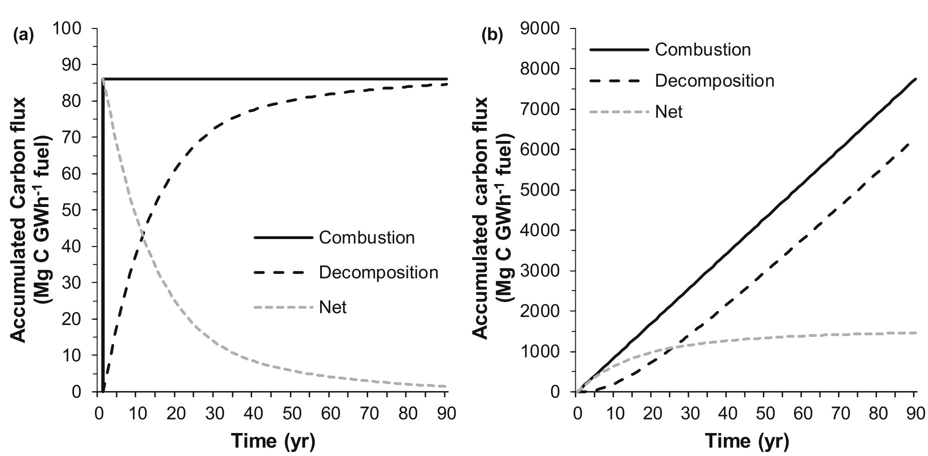

Fig. 4. Accumulated biogenic carbon fluxes of forest residues (tops and branches) when either harvested (combustion) or not harvested (decomposition) from (a) a forest stand and (b) a theoretical forest landscape in central Sweden, based on Hammar, Ortiz, Stendahl, Ahlgren and Hansson [22]. The net effect is the yearly difference between combustion and decomposition, *i.e.* the consequence of harvesting forest residues for energy purposes.

depends on initial carbon content in soil and reference land use, *i.e.* the carbon content in soil and biomass for an alternative land use.

The biodiesel produced from dedicated energy crops was assumed to be produced from rapeseed crops where biogenic carbon fluxes in standing biomass were taken up and released annually, and the net effect was thus zero during one year. Soil organic carbon (SOC) changes from direct land use can vary with different initial SOC content, reference land use, management practice, soil texture and geographical location, and previous studies of rapeseed cultivated for biodiesel production have shown potential to both increase and decrease SOC [31, 32]. Due to this variability, SOC changes were assumed to be zero in this assessment.

No biogenic CO_2 emissions were included for the combustion of industrial waste or residues (waste wood, municipal solid waste (MSW), mixed fatty acids (MFA), crude tall oil), since the environmental burden of production of the material was allocated to the primary use of the biomass. Furthermore, no alternative waste management other than incineration was considered an option for the wastes, since landfill is not an alternative under Swedish waste regulations.

2.5.4. Carbon capture and storage (CCS)

The BECCS scenario (S5) was based on calculations presented in Levihn et al. [20]. It was assumed that 95% of the CO_2 released from biomass combustion at KVV8 was captured using hot potassium carbonate, which corresponds to approximately 300 Mg CO_2 GWh^{-1} fuel. The CO_2 was assumed to be compressed and transported by LNG ships to the coast of Norway and then transported by pipeline to the North Sea for permanent storage in reservoirs under the seabed. No leakage during transport and storage was considered. Electricity consumed in the CCS unit and fuel use in transport were included in the assessment.

2.5.5. Power substitution

Changes in net electric power output are caused both by the CHP plant itself and by other components in the energy system. This includes changes in production in other CHP plants and in electricity-consuming technologies such as heat pumps. The net electricity produced in the different scenarios was assumed to replace dynamic marginal electricity, calculated based on dynamic modelling work by Hagberg et al. (2017, pp 27–35) based on a TIMES/Markal model developed by the International Energy Agency (IEA). The data of the models and scenarios are based on the Nordic Energy Technology Perspectives report [27]. The model and data accounts for the Swedish power system as part of the Nordic and European power systems. Hagberg et al. [33] applied a complex marginal perspective whereby decisions made today have a short-term impact on operation of the system and a long-term impact on both operation and the composition of the electric power system. Hagberg et al. [33] also report seasonal differences in changes in supply or demand for electric power and present several scenarios for future electricity production. The output of the model is not separated into different greenhouse gases, and all emissions were therefore calculated as CO_2.

2.6. Climate impact assessment

Greenhouse gases have different radiative efficiencies, which means that they are unequally strong climate agents. They also remain in the atmosphere for varying timeframes when emitted, *e.g.* CH_4 and N_2O decay through chemical reactions in the atmosphere, while CO_2 is partly taken up by the ocean and biosphere, while a fraction will stay airborne. The atmospheric lifetime of CH_4 and N_2O is modelled by first-order exponential decay functions, with mean lifetime of 12.4 and 121.0 years, respectively. The atmospheric lifetime of CO_2 can be modelled using the Bern carbon cycle model [34].

Several climate metrics and timeframes can be used to assess climate impact in an LCA [35]. In addition to the most common climate metric global warming potential (GWP), a time-dependent climate metric that displays the impact in terms of temperature response over time was used for the present assessment. Both metrics are based on radiative forcing (RF), which measures a change in the radiative balance of the atmosphere in Wm^{-2}. GWP expresses the cumulative radiative forcing (CRF) of a greenhouse gas (x) emission relative to the CRF of CO_2 during a specific timeframe (H):

$$\mathrm{GWP_x(H)} = \frac{\mathrm{CRF_x(H)}}{\mathrm{CRF_{CO_2}(H)}} \left(kg\ CO_2 - eq\ kg^{-1}\ gas\right) \quad (1)$$

Using GWP emission factors, greenhouse gas emissions are converted into CO_2-eq. According to the IPCC AR5 report, the GWP_{100} factor (including climate-carbon feedbacks) for CO_2, biogenic/fossil CH_4 and N_2O is 1, 34/36 and 298, respectively [36]. Although the GWP approach has benefits, *e.g.* is easier to use and enables comparisons with previous studies, it also has the disadvantage of ignoring the timing of greenhouse gas fluxes within the studied timeframe. Therefore the time-dependent climate metric absolute global temperature change potential (AGTP) was also used here:

$$\mathrm{AGTP_x(H)} = \int_0^H \mathrm{RF_x(t) R_T(H-t) dt} \left(\mathrm{K\ \ kg^{-1}}\ gas\right) \quad (2)$$

This metric considers the temperature impulse response (R_T) of a unit change in RF from a pulse emission of the specific greenhouse gas (x). The overall temperature response is the sum of the AGTP of all greenhouse gas emissions (E) during the studied timeframe (H) (measured in degrees K):

$$\mathrm{Temperature\ \ response\ \ (H)} = \sum_x \int_0^H \mathrm{E_x(t) AGTP_x(H-t) dt\ (K)} \quad (3)$$

where t is the time of emission or uptake of the specific gas (x).

3. Results and discussion

3.1. Heat and power production

The studied CHP plant (KVV8) produced about 10% of the total district heating in the energy system (Fig. 5). The drop in the hard coal scenario in 2020 was caused by an assumed switch to heat pumps in order of merit, due to a combination of expected market developments of the electric power price, coal price and price of emission allowances.

Power production varied over time and between scenarios (Fig. 6). Introducing the new CHP plant increased net power production in all future scenarios (S1–S5) compared with the reference scenario (S6), meaning that the new CHP plant replaced other power production. As seen for heat production (Fig. 5), the switch in year 2020, with heat pumps replacing coal CHP, had an obvious effect on power production in S2 (Fig. 6).

Over time, hard coal, wood chips and BECCS resulted in similar production of electrical energy. In the BECCS scenario (S5), the power output of KVV8 was reduced compared with in the scenarios with combustion of wood chips (S1) and hard coal (S2). The incentive to construct BECCS was assumed to be one carbon credit per Mg CO_2 captured. As such, the contribution margin would be required to at least cover both capital and operating costs (see Levihn et al. [20] for a further discussion). One result of the simulations was increased annual operation of the CHP, increasing the total electrical energy production even though electric power output was reduced.

3.2. Temperature response

3.2.1. CHP plant KVV8

Combusting wood chips in the new KVV8 plant resulted in a cooling climate impact when considering all emissions, *i.e.* fossil and biogenic greenhouse gas emissions and avoided emissions from substitution of heat and power (Fig. 7).

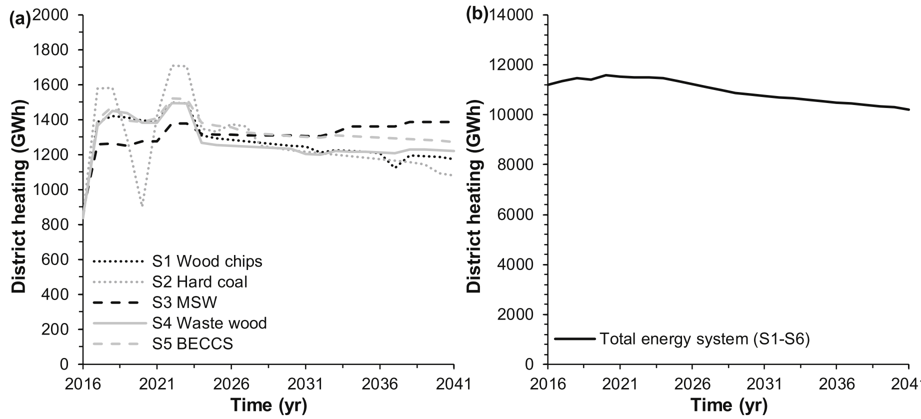

Fig. 5. Production of district heating at (a) the combined heat and power plant KVV8 and (b) the whole energy system in Stockholm, in all scenarios (S1–S6). Note scale difference.

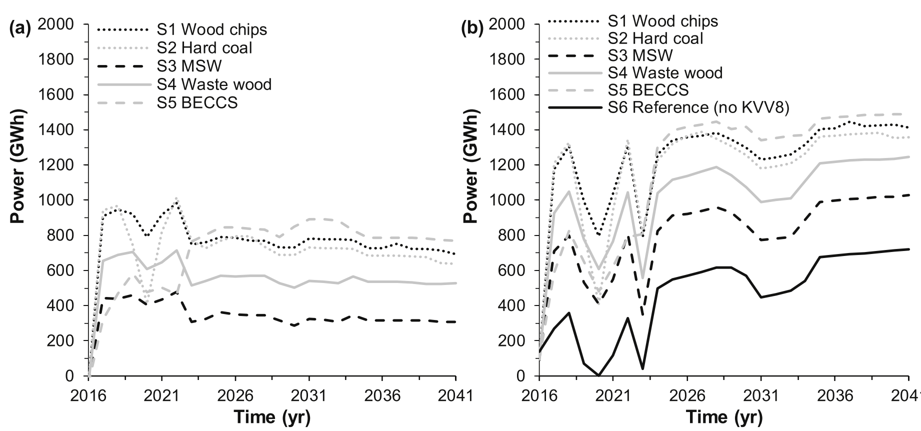

Fig. 6. Net power production of (a) the combined heat and power plant KVV8 and (b) the whole energy system in Stockholm, in all scenarios (S1–S6).

CO_2 emissions increased during the first decades of KVV8 operation, after which the curve stabilised at a new steady state (see Fig. 4b). However, since the emissions timeframe for fuel combustion was only the first 25 years (2016–2041), the curve showed a downturn when combustion of wood chips ended (Fig. 8b), while heating from fossil fuel combustion stabilise and only show marginal downturn after combustion ended (Fig. 8a). Combining wood chips combustion with CCS increased the cooling temperature effect by removing biogenic CO_2 emissions. After the first 25 years, the temperature response of the fuels generating large amounts of fossil greenhouse gas emissions remained high, while the climate impact of wood chips decreased due to the shorter perturbation lifetime of biogenic CO_2. The difference of substituting district heating production (Fig. 8c) compared to electric power production (Fig. 8d) is visible and based on that 4th generation district heating to a large extent is based on non-fossil fuels.

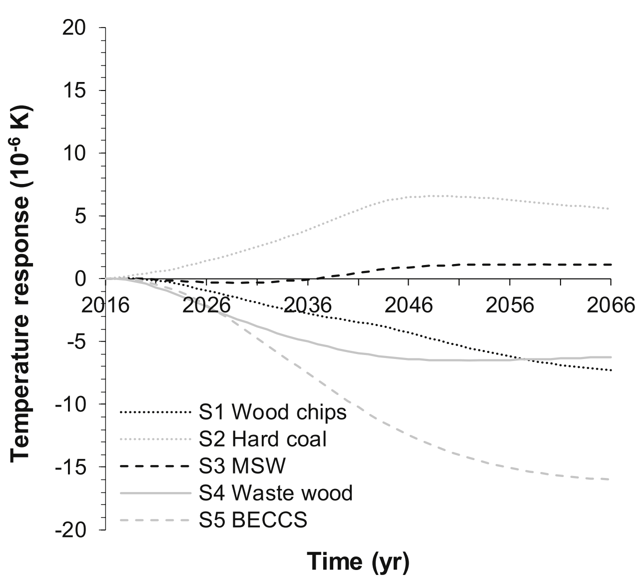

Fig. 7. Temperature response of the combined heat and power plant KVV8. Values represent total fuel use at KVV8 during 2016–2041, and the climate effect during the following 25 years.

No biogenic CO_2 fluxes were included for waste wood combustion and the climate impact was thus negative, since fossil emissions were low and heat and power substitution had the largest climate impact. Incineration of MSW was the second largest emitter of fossil greenhouse gases, after combustion of hard coal. However, these emissions were largely counteracted by the heat and power substitution.

3.2.2. District heating system

The effect of introducing the new CHP plant into the existing district heating system in Stockholm varied with type of fuel combusted (Fig. 9). The best option from a climate perspective was wood chips in combination with CCS (S5), followed by the waste wood and wood chips scenarios (S4 and S1). A negative climate impact of the CCS scenario was reached after about 15 years, where the delayed cooling effect was partly due to emissions from other plants within the district heating system and to delays due to the inertia of the climate system. Introducing the new CHP plant increased the power substitution in all

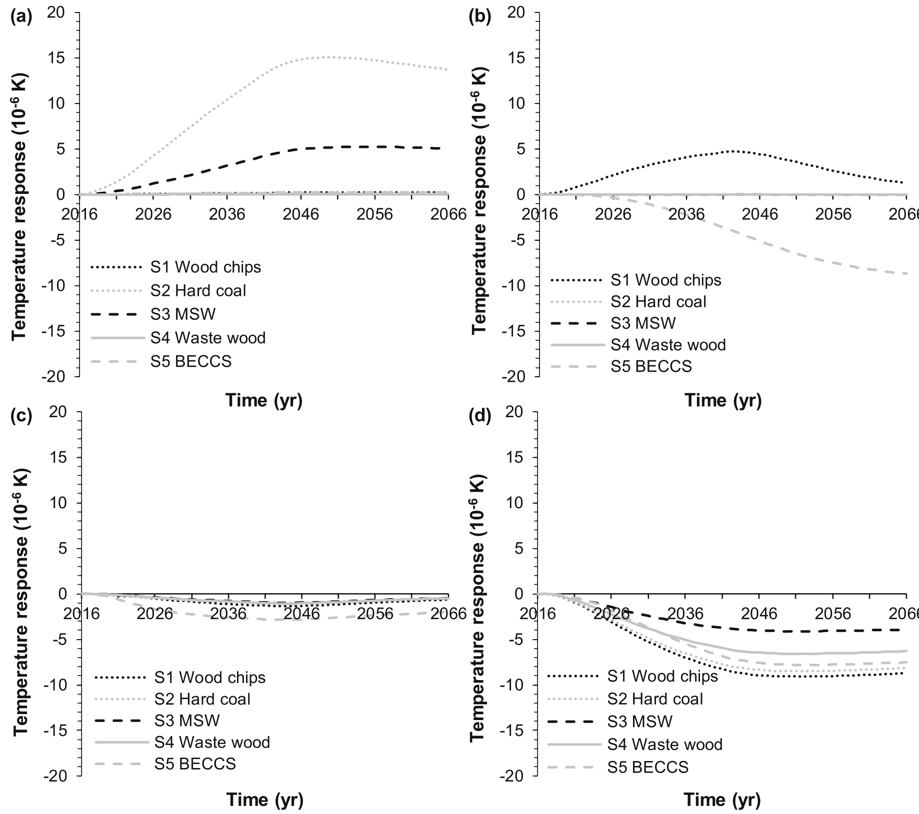

Fig. 8. Temperature response of the combined heat and power plant KVV8 including only (a) fossil emissions, (b) biogenic carbon emissions, (c) avoided emissions from heat substitution and (d) avoided emissions from power substitution. Values represent total fuel use at KVV8 during 2016–2041, and the climate effect during the following 25 years.

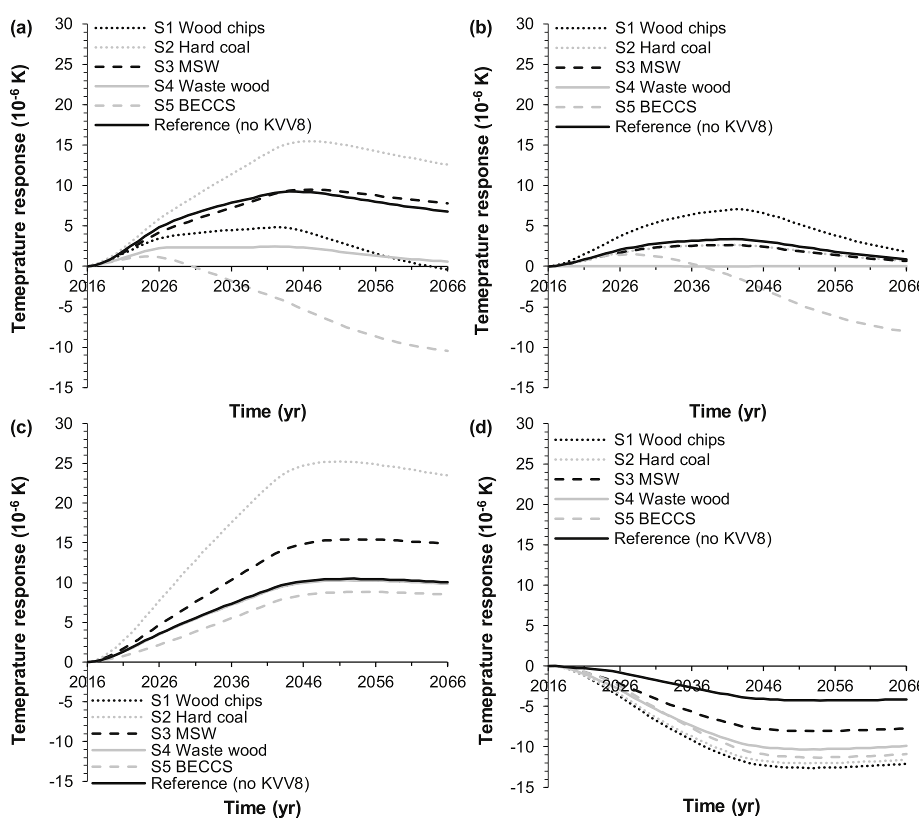

Fig. 9. Temperature response of Stockholm district heating system including (a) total emissions; (b) biogenic carbon emissions; (c) fossil emissions; and (d) avoided emissions from power substitution. Values represent total heat produced 2016–2041, and the climate effect during the following 25 years.

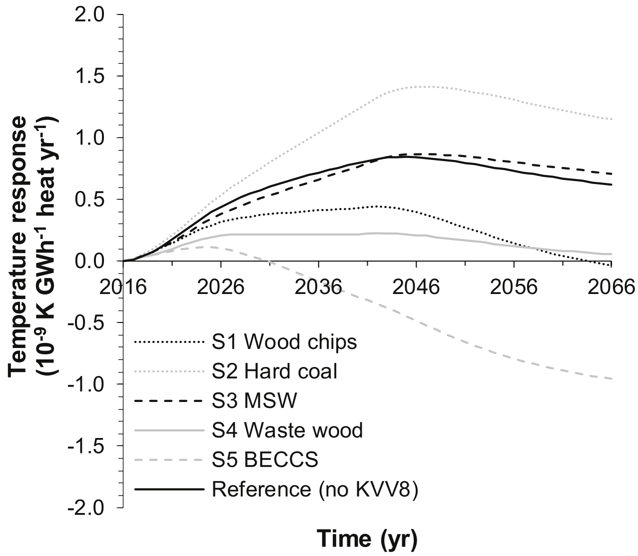

Fig. 10. Temperature response of the whole district heating system in Stockholm per average GWh heat produced per year, 2016–2041, and the climate effect during the following 25 years.

scenarios compared with the reference (Fig. 9d), with the climate benefit being highest in the wood chips scenario.

Incineration of MSW (S3) increased fossil greenhouse gas emissions from the district heating system (Fig. 9c), but the total climate impact was of the same magnitude as in the reference scenario (S6) due to the increased power substitution. The MSW scenario provides interesting insights, as the value of combusting MSW into electric power and district heating was similar to that in the do nothing reference scenario. Even though MSW incineration gives a relatively high climate impact, alternative waste management options, *e.g.* landfill, could give an even a higher climate impact by generating large CH_4 emissions. This issue was not covered in this study and should be investigated in future research. However, the results show the importance of efficient resource utilisation and waste prevention, *e.g.* by increasing recycling, reducing use of fossil products ending up as waste and, for what cannot be reduced, capturing the CO_2 from MSW incineration.

If the CHP plant studied here adopted BECCS, the whole district heating system in Stockholm would have a negative climate change impact after the year 2030. The negative emissions from BECCS would then counter emissions from the district heating system that would otherwise lead to global warming. This confirms the general results in Levihn et al. [20]; but adds the complication of delays in temperature response. Postponing adoption of BECCS delays this net zero point in time. Other abatement options not included in the scenarios could

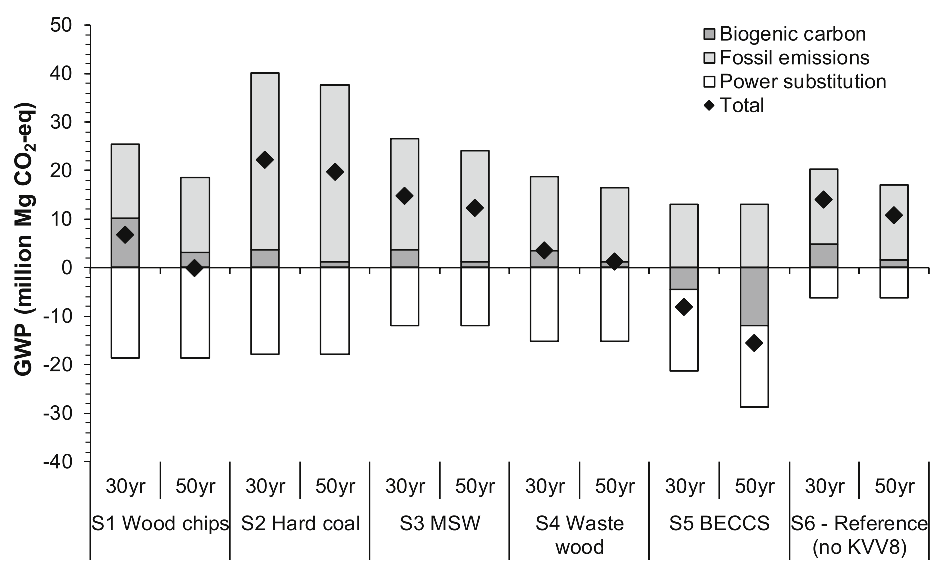

Fig. 11. Global warming potential (GWP_{100}) after 30 and 50 years (fuel combustion only the first 30 years) in the different scenarios (S1–S6). Values represent total GWh fuel used in the district heating system during 2016–2041.

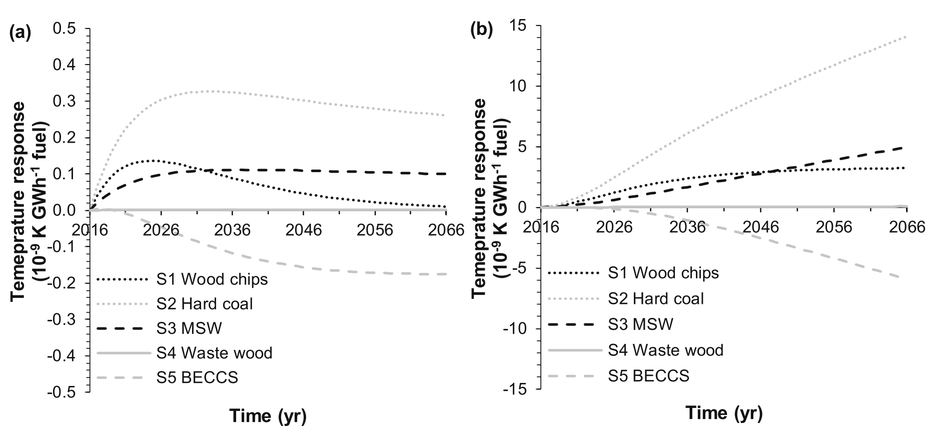

Fig. 12. Temperature response of the combined heat and power plant KVV8 in (a) one-year combustion (2016) and (b) 50-year combustion (2016–2066) per average GWh fuel combusted, excluding heat and power substitution. Note scale difference.

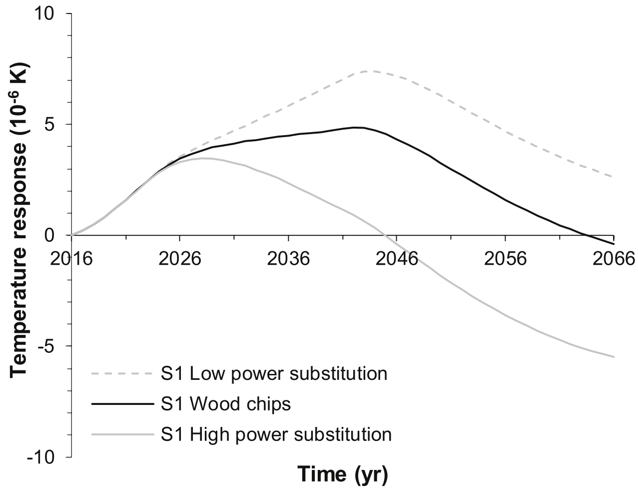

Fig. 13. Sensitivity analysis of power substitution with different fossil fuel intensities. Values represent total heat produced 2016–2041, and the climate effect during the following 25 years.

advance the net zero point by reducing the emissions counterbalanced by BECCS. One of the main sources of global warming is MSW, again pointing to the importance of increasing recycling and reducing waste generated.

Per GWh heat produced, the type of fuel combusted in the KVV8 plant had a large impact on the climate impact of the whole district heating system in Stockholm (Fig. 10). The difference in temperature response between biomass and coal was visible already after the first years of operation, and continued to increase over time.

Combusting waste wood gave the lowest climate impact of all scenarios examined in this study except BECCS, which was due to biogenic CO_2 not being included in the assessment. The environmental burden of harvesting the wood was allocated to its primary use and biogenic carbon fluxes from combustion were counted as zero, since no other option apart from combustion was considered an alternative. However, combusting waste wood emits CO_2 and prolonging the lifetime of the wood product could keep the carbon sequestered for a longer timeframe. Considering alternative uses of the waste wood could thereby affect the result.

When studying the climate impact of biomass use, a baseline or reference land use can be defined differently depending on the aim of the assessment, *e.g.* as natural regeneration (development without further human intervention), business as usual (continuing the current land use) or zero baseline (no development, which equals only including absolute emissions) [37]. In this study, the reference land use for the wood chips combustion scenarios (S1 and S5) was defined as forestry without harvesting of tops and branches at final felling, since the aim was to assess the impact of an increase in extraction.

No impact on future forest productivity was assumed, since the consequences of removing forest residues are uncertain. Previous studies have shown varying results, with some reporting negative effects on productivity due to nutrient removal and some reporting no effects and a few even positive effects on future productivity [38]. For scenarios with waste wood and wood chips from branches and tops, no effect on future forest growth was considered, *i.e.* replanting of new trees in place of the removed biomass. A requirement on replanting (or not) is a social construct and the overall economics of forestry are affected by extracting branches and tops. It would be of interest to address this issue in future research, *e.g.* the view on extracting residues as part of overall forest management.

Biogenic carbon fluxes from harvesting forest residues were based on simulations for central Sweden. However, the geographical location of the forest stand has an impact, since both productivity and decomposition vary with climate zone. Hammar et al. [25] showed that harvesting forest residues from forest stands in northern Sweden gives a somewhat higher climate impact than for forest stands in the south of the country, since biomass left *in situ* would have acted as a carbon sink longer in the colder northern region, due to slower decomposition. Spatial variability is thus an uncertain factor. However, the difference between the regions is relatively small compared with the difference between combustion of forest residues and fossil fuels.

3.3. Global warming potential

As seen for the temperature response curves, the GWP varied with choice of timeframe for the assessment (Fig. 11), since biogenic carbon changes are temporary while fossil greenhouse gases give a long-term climate impact.

3.4. Sensitivity analysis

3.4.1. Time perspective

To better understand the time dynamics of combusting different fuels in the CHP plant (KVV8), the climate effects of one-year combustion and 50-year fuel combustion were evaluated (Fig. 12). Removing forest residues for energy emits CO_2 earlier in time than in the slower process of decomposition that occurs if the biomass remains in the forest (see Fig. 4). The consequence of combusting wood chips for energy was calculated as the yearly difference between decomposition and combustion of the biomass. In the one-year combustion (stand) perspective, this meant that the climate impact was highest after around one decade, after which the temperature started to level off, since the biogenic carbon would have been released from the forest anyway through decomposition. In the continuous energy generation (landscape) perspective, yearly harvesting of a new forest stand resulted in a temperature increase during the first 2-3 decades, after which the temperature started to stabilise (Fig. 12). In the BECCS scenario, the cooling temperature response instead continued to increase over time, since more biogenic CO_2 was removed than would have been released through decomposition.

For fossil-source greenhouse gases, the temperature response of one-year combustion decreased slightly over time, mainly due to the shorter atmospheric lifetime of CH_4 and N_2O. In continuous fuel combustion, the temperature response continued to increase and the difference between the studied scenarios thus increased with a longer time perspective.

3.4.2. Power substitution

Power substitution has a large influence on the overall climate impact and therefore assumptions regarding future power production are important for the results of an assessment. In this study, dynamic marginal electricity from Hagberg et al. [33] was assumed. That report defines three different scenarios for future Swedish electricity, which were tested in a sensitivity analysis in the present study (Fig. 13). The differences between the power substitution scenarios were evident after about 25 years, when high power substitution, *i.e.* substitution of more fossil fuel-intensive power production, lowered the climate impact of the whole energy system over time. Conversely, low power substitution increased the total climate impact of the whole energy system.

One uncertainty with the climate scenarios is that the emissions are only available as CO_2-eq, which means that all emissions were counted as CO_2 and not divided between CH_4 and N_2O. In future studies, separating the emissions into the different climate gases would improve the robustness of the results.

4. Conclusions

Combusting biomass in a new CHP plant in Stockholm's 4GDH system resulted in a cooling climate impact when considering all emissions, *i.e.* fossil and biogenic greenhouse gas emissions and substitution of heat and power. The climate change mitigation potential was even higher with BECCS, where other emissions from the existing district heating system were counteracted after about 15 years.

In relation to general techno-economic studies of energy systems, adding the time dynamic perspective on greenhouse gas emissions and biomass revealed the value of considering the lag between adoption of a certain climate change mitigation option and the response in reducing global warming. The integrated approach adopted in this study also provided knowledge on the sustainability of biomass beyond simplified assumptions (*e.g.* climate change neutrality). The results of the study clearly show that biomass CHP in a 4GDH system contributes to reducing global warming compared to using hard coal or MSW, and that BECCS further increase this benefit. This finding was obtained without the general view on biomass growing by capturing atmospheric CO_2, *e.g.* only considering the decision to extract residues from forestry or not.

The results confirm the value and necessity of using more integrated models that take dynamic relationships into account and provide broader perspectives on different trajectories for transforming energy systems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2020.105606.

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