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Climate effects of electricity production fuelled by coal, forest slash and municipal solid waste with and without carbon capture

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A B S T R A C T

We analyse the climate implications of producing electricity in large-scale conversion plants using coal, forest slash and municipal solid waste with and without carbon capture and storage (CCS). We calculate the primary energy, carbon dioxide (CO_2) and methane (CH_4) emission profiles, and the cumulative radiative forcing (CRF) of different systems that produce the same amount of electricity. We find that using slash or waste for electricity production instead of coal somewhat increases the instantaneous CO_2 emission from the power plant, but avoids significant subsequent emissions from decaying slash in forests or waste in landfills. For slash used instead of coal, we find robust near- and long-term reductions in total emissions and CRF. Climate effects of using waste instead of coal are more ambiguous: CRF is reduced when CCS is used, but without CCS there is little or no climate benefits of using waste directly for energy, assuming that landfill gas is recovered and used for electricity production. The application of CCS requires more fuel, but strongly reduces the CO_2 emissions. The use of slash or waste together with CCS results in negative net emissions and CRF, i.e. global cooling.

1. Introduction

Globally, we are heavily dependent on fossil fuel for electricity, heat and transportation. Fossil fuels including coal, oil and fossil gas supplied about 81% of global primary energy in 2013 [1], and their use is expected to increase in the future even if policy measures are implemented to reduce fossil fuel use [2] (Fig. 1). The largest use of fossil energy is for electricity production, both globally and in the European Union (EU). Electricity production is dominated by fossil fuel-based stand-alone power plants, through policy measures are being implemented to increase the use of combined heat and power (CHP) plants [3] as such plants have a higher system efficiency. Coal contributes about 40% of total global anthropogenic carbon dioxide (CO_2) emissions, and about 70% of the CO_2 emissions from the global electricity sector [4]. While coal is the most important fuel for electricity and heat production, oil is used more for transportation, contributing about 93% of transport energy globally and in the EU [5].

Forest biomass residues and municipal solid waste could play an increasing role as fuels for the electricity production sector [6]. These material flows are by-products of existing activities, and if not used as fuel they would decay partially or fully through natural processes, emitting CO_2 and methane (CH_4). Material flows associated with forest products industries typically involve many different biomass fractions. Of the total biomass of a mature spruce tree, about 50% is contained in the tree-top, branches, foliage, stump and roots of the tree [7], which has conventionally remained in the forest after harvest. When left in the forest, they decay naturally over time and emit stored carbon as CO_2. Forest slash (comprising branches, foliage and tree-tops) is increasingly recovered and used for energy purposes. For example, currently 20% of all harvestable residues in Sweden are used for bioenergy [8,9], and there is a large potential for increasing the extraction of forest residues [10]. Forest residues can be used in various ways for climate change mitigation, by substituting fossil fuels in the electricity, heat and transport sectors [11].

Municipal solid waste, commonly known as “garbage” or “refuse”, includes a diverse range of materials discarded by households and commercial establishments. It is typically deposited in landfills, where it partially decays into CO_2 and CH_4 [12]. It could, however, be managed for energy recovery, as occurs in several countries including Denmark, Sweden, and the Netherlands [13]. Thermal conversion and anaerobic digestion are the most common practices to convert waste to energy. However, while

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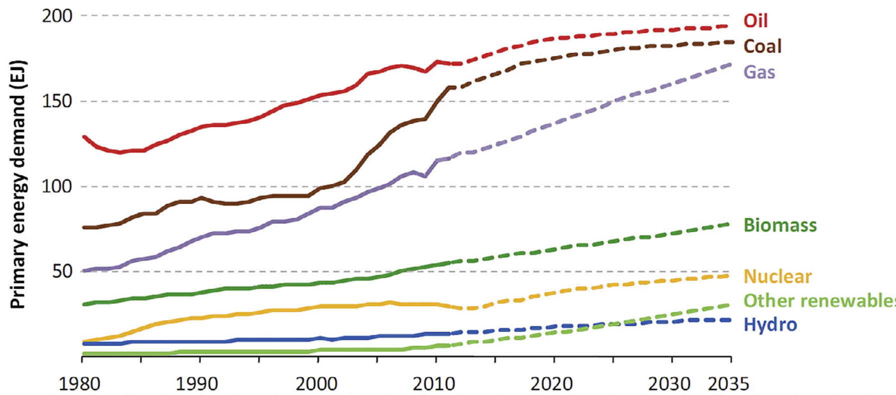

Fig. 1. Historical and projected trends of global primary energy use through 2035 with policy measures implemented for reducing the use of fossil fuel (IEA New Policies Scenario) [2].

organic fractions can be digested in an anaerobic reactor, non-organic fractions may only be converted to energy through incineration or gasification. However, the conversion process of waste to energy can be complicated by the heterogeneous nature of municipal solid waste and the need for gas cleaning equipment. If the waste is landfilled appropriately, most of the generated CH_4 can be collected and used for energy.

Carbon capture and storage (CCS) is a potential technology for large-scale carbon emission abatement from stationary sources [14,15]. In this approach, carbon is separated from fuel either before or after combustion, and is compressed and injected into geological formations for long-term storage. CCS technologies are commercially available, but are costly and require more fuel, and will require suitable policy instruments to promote their deployment for climate mitigation [16,17]. Coal-fired power plants are suitable candidates for CCS due to their typical large scale, and because coal remains the leading source of global electricity generation [18,19], is more abundant than other fossil fuels [20], and emits more CO_2 per delivered energy than other fossil fuels. CCS can also potentially be used with power plants fired by forest slash and municipal solid waste [21].

If forest slash and municipal solid waste are used for energy to replace fossil fuel without CCS, the carbon in the fuel is emitted immediately to the atmosphere as CO_2. If residues are left in the forest and waste is landfilled, and not used as fuel, a corresponding amount of fossil fuel will likely be used instead resulting in immediate fossil emissions. This will be followed by gradual emission of biogenic CO_2 from the decaying forest residues and landfilled waste. CH_4 is also typically emitted as a decay product of landfilled waste. If CCS is employed, the CO_2 emissions from fuel conversion will be substantially reduced, though emissions of CO_2 and CH_4 from forest and landfill decay will not be affected.

The variation of carbon flows over time can significantly affect the climate impact of forest residues and municipal solid waste used for energy. Within any finite time period, the climate effect depends on how much CO_2 and CH_4 are emitted, as well as when they are emitted. Cumulative radiative forcing (CRF, also called integrated radiative forcing or absolute global warming potential) is a metric that estimates the time-dependent climate effects of dynamic systems [37]. The analytical procedure requires information on time profiles of atmospheric emissions and removals of greenhouse gases (GHG) [22].

Radiative forcing has been used by various authors to analyse climate effects over time. To date, however, there have been few comparative analyses of CRF caused by the use of coal, forest slash and municipal solid waste for energy including what would happen with the fuels if not used for energy, i.e. the avoided baseline emissions. Several previous studies have analysed the radiative forcing implications of using biomass to replace fossil fuels [23–30]. Corresponding analysis of municipal solid waste, and comprehensive consideration of the potential benefits of CCS, have not heretofore taken place.

The aim of this study is to analyse the climate effects of producing electricity in large-scale conversion plants fuelled by coal, forest slash and municipal solid waste, with and without CCS. We analyse the primary energy, CO_2 and CH_4 emission profiles, and CRF of the different systems to produce the same amount of electricity. We also conduct a sensitivity analysis to determine important sources of uncertainty and variability.

2. Methodology

2.1. Analytical approach

We compare the climate effects of a unit of electricity produced by several different supply systems. We consider three different fuels: fossil coal, forest slash, and municipal solid waste. Each fuel is considered both with and without CCS technology. For conversion of each fuel, we consider large-scale average and state-of-the-art technologies, as well as emerging technologies for gasification. For each system, we calculate the primary energy use, the annual emissions of CO_2 and CH_4, and the CRF. Each system produces 1 MWh of electricity in Year 0, and we track the indicators over a 200-year period. We account for the direct emissions from fuel conversion as well as indirect emissions from fuel supply and logistics. We consider the emissions that would have occurred due to natural decay if forest slash and municipal solid waste had been left on forest floors or in landfills, respectively, and not been used for electricity. The analysed systems are summarized in Table 1.

2.2. Fuels

2.2.1. Fossil coal

Fossil fuels are expected to continue to dominate primary energy use globally. Forecasts from the International Energy Agency [2] suggest that in 2035 the global and European energy systems will still heavily depend on fossil fuels, under the current and New Policy scenarios. Table 2 shows the primary energy use of fossil coal, oil and gas for each sector of electricity, industry, buildings, and transportation for 2011 and 2035 (projected) globally and in EU with policy measures implemented for reducing the use of fossil fuel. Of the fossil fuels, coal is expected to play an important role in electricity production [2]. Therefore, we analyse the climate effects of producing electricity in large scale plants without and with CCS using coal, compared to using forest slash or municipal solid waste.

Fossil coal used at energy conversion plants is typically deployed from distant places, which requires extraction, transportation, processing and distribution. All these processes use energy which increases the total primary energy use per each unit of fuel used at conversion plants. In our study we consider the life cycle primary energy use and full fuel cycle CO_2 emission factors for hard coal, based on Gode et al. [31]. CH_4 is also released during coal mining, in quantities that depend on the local geology and the type of mine. Underground mines typically release more CH_4 than surface mines. In our main analysis we assume 0.5 kg of CH_4 is released per ton of mined coal, and in a sensitivity analysis assume 15 kg per ton, based on a survey of studies on coal mine methane emissions [32].

2.2.2. Forest slash

Forest slash is the residue from timber harvest, and comprises branches, foliage/needles and tree-tops that remain after stem-wood harvest. When slash is harvested, typically about 70% of the slash is removed from the forest, though the amount of tree needles harvested with the slash may vary. The Swedish Forest Agency [33] recommends leaving most needles in the forest to avoid nutrient depletion, except in nitrogen-rich regions where the needles should be removed. We assume that 20% of tree needles are harvested with slash, and the remaining needles fall off the dry branches and remain in the forest. We assume a carbon content of 50% by dry weight of the slash, and that a corresponding quantity of CO_2 is emitted in Year 0 when the slash is recovered and utilized for energy.

The forest slash supply system requires some fossil energy to collect, process and deliver the fuel to the end-user. The amount depends on several factors including recovery method, processing method, transport mode and transport distance. After collection of slash at a clear-cut site and forwarding it to the roadside, the slash is typically chipped or crushed immediately at the roadside landing. Once the biomass has been chipped it is transported to the end-user within a few days to reduce dry-matter losses from biological activity. The chipped biomass is here assumed to be transported 100 km by truck to a terminal, then 250 km by train to the coast, then 1100 km by ship to an international end-user. Dry matter loss during forwarding, chipping and transport may be between 2 and 15% [34]. We assume a dry matter loss of 10%.

Details on fossil fuel consumption for recovery, chipping and transport of slash used in this study are given in Table 3. The resulting CO_2 emissions were calculated based on a carbon intensity of diesel fuel of 76.9 $gCO_2e\ MJ^{-1}$ [31]. Once delivered, the biomass is assumed to provide 16.8 GJ of heating value per dry ton. The data in Table 3 are based on several recent studies that have analysed the fossil energy inputs for recovering and transporting slash [53–56]. We do not consider the energy use and emissions from forest establishment, management, and primary harvest, because we focus on the use of forest slash which is typically considered a by-product of forestry activities where the main product is timber.

Ash recirculation is typically prescribed in Sweden when slash is removed from forests, to ensure nutrient cycling for sustainable regrowth [33]. Conventional methods for ash handling and recirculation have been calculated to have negligible effect on energy balances and GHG emissions [34]. The energy input for the ash recirculation process is less than 0.1% of the energy content of the chipped and delivered biomass, and is therefore not considered here. For forest slash to be a viable long-term energy source, there is need for sustainable long-term management of forest resources. The post-harvest regrowth of forests is outside the system boundaries of this study, but is highly likely given Sweden's emphasis on sustainable forestry [39].

If the slash is left in the forest, it will be decomposed by macro- and micro-organisms and release biogenic carbon as CO_2 to the atmosphere. The decay rate of the slash varies in time because the initial quality changes to lower qualities which decompose more slowly. Studies [40] show that modelled decomposition rates vary with the assumptions made. We use the process-based Q model [41,42] to analyse the decomposition of forest slash. Parameter values for the model set-up are found in Table 4, and are taken from Ref. [42]. The climate data is a mean 70-year value for central Sweden, and include mean annual temperature of 2 °C, a temperature amplitude of 25 °C, and annual precipitation of 711 mm [43].

Table 2
Primary energy use (EJ) of fossil coal, oil and gas by the sectors of electricity, industry, buildings and transportation in 2011 and 2035 (projected) globally and in EU under the New Policies Scenario [2].

Region & sector	2011			Projection 2035		
	Coal	Oil	Gas	Coal	Oil	Gas
World						
Total	158	172	117	185	195	172
Electricity generation	99	12	47	119	6.2	67
Industry	30	14	21	34	15	21
Buildings	4.9	14	25	4.0	11	25
Transport	–	95	–	–	120	–
EU						
Total	12	23	17	6.1	15	19
Electricity generation	9.1	0.9	5.7	4.0	0.3	6.7
Industry	1.1	1.3	3.5	0.8	0.8	3.1
Buildings	0.5	2.4	6.2	0.3	1.3	7.6
Transport	–	12	–		8.9	–

Table 3
Specific fossil fuel use for slash collection and transport (MJ fossil energy per dry ton of delivered biomass).

Activity	Specific fossil fuel use	Reference
Recovery and forwarding	189	[34–37]
Roadside chipping	77	[34,36]
Truck transport (100 km) to terminal	145	[37,38]
Train transport (250 km) to port	19	[37]
Ship transport (1100 km) to end user	56	[37]
Total	**486**	

Table 1
Summary of systems modelled. Each system produces 1 MWh of electricity.

System name	Energy system emissions	Emissions from decaying feedstock
Coal	Coal mining, logistics, combustion/gasification	Natural decay of slash and waste in forest and landfills, respectively
Coal CCS	Coal mining, logistics, combustion/gasification with CCS	Natural decay of slash and waste in forest and landfills, respectively
Slash	Slash recovery, logistics, combustion/gasification	–
Slash CCS	Slash recovery, logistics, combustion/gasification with CCS	–
Waste	Waste logistics, combustion/gasification	–
Waste CCS	Waste logistics, combustion/gasification with CCS	–

In the Q model the harvest slash decomposes continuously at specific rates in time that depend on the quality of the litter. We use the version that includes the invasion time of woody litter [44] and variable temperature [43]. The model has been described in several papers, and has a proven capability to estimate soil organic carbon (SOC) changes at stand level and regional and national scales in Sweden [42,43].

2.2.3. Municipal solid waste

In the EU-27, approximately 240 million tons of municipal solid waste was generated in 2014 [45], with a calorific energy content of about 2.4 EJ. Techniques to efficiently handle municipal solid waste are being developed, and waste is increasingly considered as a potential resource to enlarge the energy supply [46]. As a result, approximately 27% of the total municipal solid waste in Europe was treated in waste-to-energy facilities in 2014. Still, about 28% of municipal solid waste was landfilled [45], though the actual portion varies significantly between countries. Sweden is among several countries more advanced in diverting municipal solid waste from landfills to energy recovery, with over 50% of the total municipal solid waste being incinerated for energy purpose [47]. For over a decade in Sweden, over 2 million tons of municipal solid waste (about 20 PJ) is used annually for energy, corresponding to about 220 kg per person in 2014 [48].

The composition of municipal solid waste varies over place and time. We consider two different Swedish samples of waste. Sample 1 is from the Fortum's facility in Stockholm, while Sample 2 is from the Tekniska Verken's facility in Linköping [49]. Characteristics of both municipal solid waste samples are detailed in Table 5. The municipal solid waste considered here is left over after removal of recyclable components from a much larger overall waste stream. Although Table 5 shows some percentage of potentially recyclable materials in the waste samples, it is not considered feasible to separate them at this stage. The plastic portion of Sample 2 is about a half of Sample 1 while the degradable organic carbon is about the same for both samples. A change of biological and fossil carbon composition of municipal solid waste could influence the climate effects of using waste to replace fossil fuels. In our main analysis, we base our calculations on the composition of Sample 1. In a sensitivity analysis we consider Sample 2. We do not consider the energy use and emissions from the collection and local transportation of municipal solid waste, because we assume the same would occur if the waste were landfilled. However, when waste is used for energy instead of landfilled, we consider the longer transportation to a power plant, assuming the same distance and transport modes described above for slash, i.e. 100 km by truck to a terminal, then 250 km by train to a port, then 1100 km by ship to an international end-user.

If municipal solid waste is not incinerated, it is typically deposited in a landfill. There is significant uncertainty regarding the fate of landfilled waste over time and the resulting GHG emissions and climate effect [51]. Typically, both CO_2 and CH_4 are expected to be generated, due to the anaerobic nature of the decomposition. We model landfill dynamics using the IPCC first-order decay model [52]. This approach assumes that landfill gas generation is proportional to the degradation of organic matter following first-order kinetics. We calculate CH_4 emissions as the CH_4 generated by waste decomposition, minus CH_4 recovered for combustion, minus CH_4 oxidized in the soil cover. We calculate CO_2 emissions as the CO_2 generated by waste decomposition, plus the corresponding CO_2 produced by CH_4 combustion and soil oxidation.

We use default IPCC parameter values for Northern Europe for landfill emission modelling [52]. All parameter values are listed in Table 6. We use a CH_4 correction factor (MCF) of 1.0, corresponding to managed anaerobic landfill sites. We assume that 80% of the generated CH_4 is recovered and used in a gas engine for electricity production. In our carbon accounting, electricity from landfill gas is assumed to substitute coal-fired electricity during the year the gas is captured, and the avoided coal CO_2 emission partially offsets the landfill CO_2 emission of that year. We limit electricity production to the first 50 years following landfilling, during which time 99% of all CH_4 is produced, and the subsequent 1% of CH_4 is captured and simply flared. In a sensitivity analysis we also consider flaring all recovered CH_4 without electricity generation, as well as zero recovery of landfill gas. The rate constant of biodegradation (k) determines how fast the waste is decomposed. IPCC default values for boreal and temperate areas distinguish between wet and dry regions, based on whether the ratio of mean annual precipitation to potential evapotranspiration is greater than or less than one. This ratio is roughly one in Swedish conditions, thus there is no clear wet or dry condition. In our main analysis we use the IPCC wet default value of 0.09, which is also supported by Borjesson et al. [53] who used a value of 0.092 in an analysis of Swedish landfill emissions. In a sensitivity analysis we also consider the IPCC dry default value of 0.05. The degradable organic carbon (DOC) content of waste will depend on its composition. Our main analysis uses waste Sample 1, with a DOC content of 0.218 by wet weight basis (see Table 5). In a sensitivity analysis we also consider Sample 2 with a DOC content of 0.213. Of the total DOC, only a fraction of the carbon (termed DOC_f) is ultimately degraded and released by decay organisms. The default value for DOC_f was 0.77 prior to 2006, but was then revised to 0.5–0.6 based on updated information [52]. We use a DOC_f value of 0.5 in our main analysis, and use a value of 0.77 in a sensitivity analysis to understand the significance of such model and parameter uncertainties.

2.3. Energy conversion technologies

A range of technologies are currently used to convert primary energy resources to convenient intermediate energy carriers. Direct combustion to produce heat is the most common use for both fossil and biomass fuels including municipal solid waste [54].

Table 4
Parameter information for soil carbon modelling with the Q model. Based on [42].

Parameter	Description	Value
q_{0n}	Initial quality of needles and fine roots	1.01
q_{0w}	Initial quality of woody litter	1.0
ε_{11}	Parameter determining how rapidly substrate quality decreases as substrate is used by decomposers	0.36
B	Shape parameter determining how steeply decomposer growth rate changes with substrate quality	7
e_0	Microbial decomposer growth efficiency	0.25
u_{00}	Parameter for decomposer growth rate	0.0855
u_{01}	Parameter for decomposer growth rate	0.0157
fC	Carbon concentration in decomposer biomass	0.5
$t_{maxbr+tops}$	Time for total invasion of branches and tops	13
$t_{maxcoarseroots+stumps}$	Time for total invasion of coarse roots and stumps	60

Table 5
Composition of two samples of municipal solid waste used in existing waste-to-energy facilities in Sweden [49,50].

Parameter	Sample 1	Sample 2
Sample as received		
Moisture content (% by weight)	45.4	43.1
Calorific value (MJ_{LHV} kg^{-1})	9.44	9.67
Total carbon (%)	25.2	26.4
Share of fossil carbon in total carbon (%)	32.7	28.8
Share of degradable organic carbon in total carbon (%)	21.8	21.3
Sample composition (% by dry mass)		
Biological waste	14.6	31.4
Paper	37.6	23.2
Plastic	25.7	13.8
Glass, metal, inorganic, etc.	7.0	7.1
Wood, textile, absorbent hygienic products, etc.	15.1	24.5

Table 6
Parameter information for landfill emission modelling. Values in parentheses are considered in a sensitivity analysis.

Parameter	Description	Value
DOC	Fraction of degradable organic carbon (by wet weight basis)	0.218 (0.213)
DOC_f	Fraction of DOC that is degraded	0.5 (0.77)
MCF	CH_4 correction factor	1.0
F	Fraction of CH_4 in landfill gas	0.5
k	Rate constant of biodegradation	0.09 (0.05)
R	Fraction of landfill gas that is recovered	0.8 (0.0)
OX	Fraction of CH_4 that is oxidized in soil cover	0.1

Combustion applications for forest slash range from simple small-scale systems for heating to complex modern industrial steam boilers that produce steam for industrial processes or electricity. Waste incineration is normally conducted in medium-to-large facilities with capabilities of handling different hazardous components. Waste incineration can be conducted in conventional moving grate furnaces. In a waste-to-energy facility, heat from the combustion gases is recovered for power generation through conventional steam turbines to produce electricity. Exhaust steam can be used for district heating applications, though in this study only electricity production is considered.

Biomass gasification is an emerging technology that converts solid fuels to gaseous fuels for various purposes. Gasification may become a key pathway for efficient use of woody biomass and municipal solid waste [55,56]. This technology potentially increases the conversion efficiency of standalone power plants [57] and the electricity-to-heat ratio of CHP plants [58,59]. Moreover, gasification is a technically viable option for the conversion of municipal solid waste to energy [61]. Biomass-based motor fuel production via gasification has received increasing attention as a potential fuel in the transport sector [11,60]. The gaseous fuel produced from gasification can be upgraded to various types of biomotor fuels such as biomethane, dimethyl-ether and methanol [62–67]. However, these processes are still being developed, thus the available data varies significantly between different sources, influenced by scale of plant as well as the targeted products. We chose to study large-scale biomass conversion plants for stand-alone production of electricity based on average and state-of-the-art steam turbine technology as well as emerging gasification technology.

Table 7 shows conversion efficiencies of selected fuels and stand-alone power production technologies used in our analysis, representing current average used technology, current state-of-the-art technology, and emerging technology. Fuel use and CO_2 emission from the conversion plants are based on the efficiencies given in Table 7. We focus on state-of-the-art technology in our main analysis, and we consider average and emerging technologies in a sensitivity analysis.

2.4. Carbon capture and storage technologies

CO_2 capture is generally considered suitable for stationary sources that emit at least 0.1 $MtCO_2$ per year. Stationary sources smaller than this emit a small fraction of total global emissions [76], and CO_2 capture from smaller sources may be cost prohibitive [14]. Globally, such large stationary sources together emit about 13.8 $GtCO_2$ annually [77], roughly half of all fossil fuel CO_2 emissions and a quarter of all anthropogenic GHG emissions. Among large stationary sources, coal-fired electric power plants contribute about 60% of CO_2 emissions.

Three main strategies can be used to capture CO_2 from power plants: post-combustion, pre-combustion, and oxy-fuel. In post-combustion capture the fuel is burned in air, and CO_2 is separated from nitrogen and other components of the flue gas. Pre-combustion capture converts the fuel into CO_2 and hydrogen, and separates the CO_2 prior to combustion of the hydrogen. In an oxy-fuel process air is separated into nitrogen and oxygen and the fuel is burned in nearly pure oxygen, resulting in a flue gas of mainly CO_2 and water vapour, from which the CO_2 is separated. All of these CO_2 capture processes involve some form of gas separation. Major categories of separation media include physical and chemical solvents, solid adsorbents, and membranes. Presently, post-combustion capture using chemical solvents such as monoethanolamine (MEA) is the most mature capture technology [78]. However, many promising technologies are currently under development such as ionic liquids, zeolites, and metal-organic frameworks [79].

After the CO_2 is captured, it is compressed to a “supercritical” fluid with properties between those of a gas and a liquid. It is then transported to a location suitable for long-term storage. Although CO_2 may be transported by truck, rail, or ship, the most likely method for large-scale transport is pipeline [14]. CO_2 is then injected deep below the surface in geologic formations including deep saline aquifers, oil and gas reservoirs, un-mineable coal seams, and possibly organic-rich shale and basalt formations [80]. Sustained climate benefit of CCS systems requires long-term storage of CO_2. IPCC suggests that CO_2 leakage from appropriately selected and managed geological reservoirs will likely be less than

Table 7
Efficiencies of stand-alone electricity production using selected fuels and technology levels. State-of-the-art technologies are used in main analysis, and others are considered in a sensitivity analysis.

Fuel	Conversion efficiency (%)	Reference
Average used technology		
Coal	35	Average used in EU-27 [2]
Forest slash	27	Average used in EU-27 [2]
Municipal solid waste	22	Average for existing plants [68]
Landfill gas	34	[69–71]
State-of-the-art technology		
Coal	48	[72]
Forest slash	46	[72]
Municipal solid waste	30	[72]
Landfill gas	44	[72]
Emerging technology		
Coal	52	Projection for 2030 [73,74]
Forest slash	50	Projection for 2030 [73,74]
Municipal solid waste	36	[75]
Landfill gas	49	Projection for 2030 [72]

1% over 1000 years, due to a combination of physical and geochemical trapping mechanisms that become more secure over longer time periods [14]. Other potential impacts from underground CO_2 storage, such as groundwater contamination and induced seismicity, merit further study. Instead of injecting it underground, a part of the captured CO_2 could also be used as a feedstock for industrial synthesis of various chemical products [81].

CCS is an energy intensive process and generally uses both heat and electricity. For example, heat is needed to regenerate MEA and is provided by steam which could otherwise have been used to produce electricity. Additional electrical power is used for operating pumps and fans and for compressing CO_2. The energy penalty associated with CCS applied to an electric power plant is often expressed as either the increase in fuel input per unit of delivered electricity, or as the decrease in electricity output for a given fuel input [14]. A review of life cycle assessments showed that the increase in fuel energy required per unit of electricity output associated with CCS ranges from about 16% to 65% [82]. About 90% of the carbon in the burned fuel is typically captured in the form of CO_2, though additional fuel is burned to produce a unit of electricity, thus the net reduction of flue gas CO_2 emissions is less than 90%. The net life-cycle CO_2 emission reduction between cases with and without CCS is even lower due to increased CO_2 emissions from mining and transporting the additional fuel, and emissions from manufacturing CCS infrastructure. The net life-cycle GHG emission reduction is still lower, averaging 74%, due to increased CH_4 emissions from coal mines (for coal-fired plants) and fossil gas leakage (for fossil gas-fired plants).

There is a thermodynamic minimum energy required for gas separation and compression, which provides an absolute limit for efficiency improvements [83]. The minimum energy penalty varies for different types of power plants and capture systems due to their different thermodynamic processes [84]. For example, post-combustion capture requires separating CO_2 from nitrogen, while pre-combustion capture processes separate CO_2 from hydrogen. Since CO_2 is relatively easier to separate from hydrogen than from nitrogen, the energy penalty of pre-combustion capture is potentially lower than that of post-combustion capture [79]. Another difference is that between fuels, e.g. coal- and fossil gas-fired plants. Since coal combustion produces more CO_2 per unit of thermal energy than fossil gas combustion, CCS at coal-fired plants will capture more CO_2 per unit of electricity generation but still will emit more CO_2 than fossil gas-fired plants with CCS. Other factors that influence the energy penalty include the higher pressures associated with pre-combustion capture, which are more favourable for CO_2 separation than the low-pressure flue gas conditions associated with post-combustion capture. The development of novel capture technologies may increase the efficiency of future CCS systems, but will not eliminate the energy penalty. Using low-grade waste heat from a power plant for regenerating capture media can increase the efficiency of the systems. However, using waste heat for CCS may conflict with other energy efficiency and climate mitigation measures such as CHP production or combined cycle electricity production. Regardless of efficiency improvements in the CO_2 capture process, energy will still be needed for CO_2 compression to allow transport and storage. Table 8 shows net electricity production and capture efficiency of the selected stand-alone power production technologies with CCS used in our analysis. The estimated efficiency penalty was based on the assumption that the same quantity of electricity is used for a unit of captured CO_2, and is expressed as a percentage-point decrease in conversion efficiency. In this study coal is used to cover the energy penalty of CCS processes. Hence, the same amount of forest slash and municipal solid waste is used in systems with or without CCS. We do not consider use of CCS for electricity produced from landfill gas, due to the relatively small size of the plant, for which CO_2 capture is cost prohibitive [14].

2.5. Cumulative radiative forcing

Based on the life cycle modelling described above, we calculate the net annual emissions of CH_4 and biogenic and fossil CO_2 over a 200-year time period following the generation of electricity. We then make temporally explicit estimates of the atmospheric concentration of the gases, using the simple climate models described by Zetterberg [86], with updated parameter values from IPCC [87–89]. The atmospheric decay of each annual emission is estimated using Equations (1) and (2) describing the removal of CO_2 and CH_4, respectively, from the atmosphere by natural processes at varying time rates [87–89]:

$$(CO_2)_t = (CO_2)_0 \times \left[0.217 + 0.224e^{\frac{-t}{394.4}} + 0.282e^{\frac{-t}{36.54}} + 0.276e^{\frac{-t}{4.304}}\right] \quad (1)$$

$$(CH_4)_t = (CH_4)_0 \times \left[e^{\frac{-t}{12}}\right] \quad (2)$$

where t is the number of years since the emission, $(CO_2)_0$ and $(CH_4)_0$ are the masses of CO_2 and CH_4 initially emitted, and $(CO_2)_t$ and $(CH_4)_t$ are the masses of CO_2 and CH_4 remaining in the atmosphere at year t. The total atmospheric mass of each GHG during

Table 8
Characteristics of stand-alone electricity production with CCS, using selected fuels and technology levels. State-of-the-art technologies are used in main analysis, and others are considered in a sensitivity analysis.

Fuel	Conversion efficiency (%)	CO_2 capture efficiency (%)	Reference
Average used technology			
Coal	25	90	CCS efficiency penalty of 10% [85]
Forest slash	17	90	CCS efficiency penalty of 10% [85]
Municipal solid waste	12	90	CCS efficiency penalty of 10% [85]
State-of-the-art technology			
Coal	38	90	CCS efficiency penalty of 10% [85]
Forest slash	36	90	CCS efficiency penalty of 10% [85]
Municipal soil waste	20	90	CCS efficiency penalty of 10% [85]
Emerging technology			
Coal	45	90	[73,74]
Forest slash	43	90	[73,74]
Municipal solid waste	29	90	CCS efficiency penalty of 7% [85]

each year of the simulation period is then determined by summing the emissions occurring during that year plus the emissions of all previous years minus their decay during the intervening years.

The change in atmospheric mass of each GHG is then converted to change in atmospheric concentration, based on the molecular mass of each GHG, the molecular mass of air, and the total mass of the atmosphere [90]. We estimate marginal changes in instantaneous radiative forcing due to the CO_2 concentration changes using Equation (3) [87–89]:

$$F_{CO_2} = \frac{3.7}{\ln(2)} \times \ln\left\{1 + \frac{\Delta CO_2}{CO_{2ref}}\right\} \tag{3}$$

where F_{CO2} is instantaneous radiative forcing in W m^{-2}, ΔCO_2 is the change in atmospheric concentration of CO_2 in units of ppmv, and CO_{2ref} is 400 ppmv. We estimate marginal changes in instantaneous radiative forcing due to the CH_4 concentration changes using Equation (4) [87–89]:

$$F_{CH_4} = 0.036 \times \left(\sqrt{\Delta CH_4 + CH_{4ref}} - \sqrt{CH_{4ref}}\right) - f(M,N) \tag{4}$$

where F_{CH4} is instantaneous radiative forcing in W m^{-2}, ΔCH_4 is the change in atmospheric concentration of CH_4 in units of ppbv, CH_{4ref} is 1800 ppbv, and *f(M,N)* is a function to compensate for the spectral absorption overlap between N_2O and CH_4 [87–89]. In this analysis we assume minor marginal changes in GHG concentrations.

The estimated values of instantaneous radiative forcing are annual and global averages, in units of Watts of radiative imbalance per m^2 of surface area of the earth's troposphere. We then integrate across time and area to determine aggregate impacts [91]. Integrating over time, we convert the power (in units of W) of radiative imbalance into energy (in units of MWh of heat accumulated per year). Integrating over the surface area of the tropopause, we estimate the total heat accumulated within the earth system. We extend the analysis over a 200-year period, and we present results as MWh of heat accumulated over time, per MWh of electricity produced in Year 0.

3. Results and discussion

3.1. Primary energy use and instantaneous CO_2 emission

Table 9 shows fuel use and instantaneous CO_2 emission at the conversion plant when generating a MWh of electricity using state-of-the-art conversion technology. Municipal solid waste has the highest fuel use and instantaneous emission, followed by slash and coal. Using CCS technologies increases the fuel use but significantly decreases the CO_2 emissions.

Table 10 shows the primary energy use and CO_2 emissions for fuel supply and combustion at the power plant. The logistics of supplying fuel is responsible for about 9% of total primary energy use for coal, but only 3% for slash and less than 1% for waste, without CCS. The relative significance of fuel supply emissions increases when CCS is used, because the emissions from combustion are strongly reduced and the fuel supply emission is increased. When CCS is used, fuel supply accounts for half of total emissions for coal, 26% of emissions for slash, and 19% of emissions for waste.

3.2. Time profiles of baseline GHG emissions

If forest slash and municipal solid waste are not used as fuel, they will decay naturally on forest floors and in landfills. Fig. 2 shows the CO_2 emission profile if 932 wet kg of forest slash, which would be needed to produce 1 MWh of electricity, is left in the forest to decay. Fig. 3 shows the emission profiles of CO_2 and CH_4 if 1270 wet kg of municipal solid waste, which would be needed to produce 1 MWh of electricity, is instead landfilled. The CO_2 and CH_4 emissions from landfilled waste was calculated with the assumption that 80% of the gross CH_4 production is captured and combusted to CO_2, and 10% of the remaining CH_4 is oxidized to CO_2 by natural soil processes. Also shown in Fig. 3 is the avoided coal-based CO_2 emission that is avoided when captured CH_4 is used to generate electricity that substitutes coal-fired power.

3.3. Time profiles of total CO_2 emissions

Fig. 4 show cumulative CO_2 emissions per produced MWh of electricity from systems without and with CCS, using state-of-the-art conversion technologies, including the actual emissions in Year 0 when the electricity is produced, plus emissions from decaying forest slash and municipal solid waste. The use of coal for electricity production instead of slash or waste causes lower instantaneous CO_2 emission without CCS. However, the decay of forest slash and landfilled waste causes emissions, gradually increasing the

Table 9
Fuel use and instantaneous CO_2 emission at the conversion plant for generation of 1 MWh of electricity using state-of-the-art conversion technology.

Fuel	Fuel use (MWh_{LHV})			CO_2 emissions (kg)		
	Coal	Slash	Waste	Biogenic	Fossil	Total
Coal	2.08	–	–	–	710	710
Coal CCS	2.63	–	–	–	90	90
Slash	–	2.17	–	875	–	875
Slash CCS	0.57	2.17	–	88	19	107
Waste	–	–	3.33	790	384	1175
Waste CCS	0.88	–	3.33	79	68	147

Table 10
Primary energy use and CO_2 emissions for fuel supply and fuel combustion at the power plant using state-of-the-art conversion technology to produce one MWh of electricity.

	Primary energy use (MWh_{LHV})			CO_2 emissions (kg)		
	Fuel	Fuel supply	Total	Fuel	Fuel supply	Total
Coal	2.08	0.21	2.29	710	71	781
Coal CCS	2.63	0.26	2.89	90	90	179
Slash	2.17	0.06	2.23	875	18	893
Slash CCS	2.75	0.12	2.86	107	37	144
Waste	3.33	0.02	3.35	1175	5	1180
Waste CCS	4.21	0.11	4.32	147	35	182

cumulative emissions associated with coal use. After less than 10 years, CO_2 emissions from coal use plus slash decay become greater than CO_2 emissions of slash use. Cumulative CO_2 emissions from coal use plus waste decay are lower, due to the offsetting effect of power production from landfill gas. For brevity, we do not show figures of cumulative CH_4 emissions, though such emissions are included in calculations of CRF, and are distinguished in Fig. 6.

3.4. Cumulative radiative forcing

Fig. 5 shows CRF (MWh of accumulated heat per MWh of electricity produced in Year 0) without and with CCS, using state-of-the-art conversion technologies. Without CCS, CRF is highest when coal is used for electricity and slash decays, and is lowest when slash is used for electricity. Using municipal solid waste for electricity gives about the same CRF as using coal for electricity and letting the waste decay. Variation over time between these two options is due to the CH_4 emission from decaying waste, which has high climate impact but short atmospheric residence time. When CCS is used the CRF is reduced for all options, and is lowest for using slash and waste for electricity. CCS strongly reduces emissions from power plants, but does not reduce decay or gas engine emissions. Fig. 6 distinguishes between the CRF impacts of CO_2 and CH_4 emissions, if municipal solid waste is used without and with CCS. CRF from landfill CH_4 emissions is not affected by CCS use, but CRF from CO_2 emissions from waste combustion is much lower when CCS is deployed.

By subtracting the avoided coal and decay CRF from the actual slash and waste CRF, we calculate the change in CRF if slash or waste is used instead of coal (Fig. 7). When CCS is used, CRF is substantially reduced if slash and waste are used instead of coal.

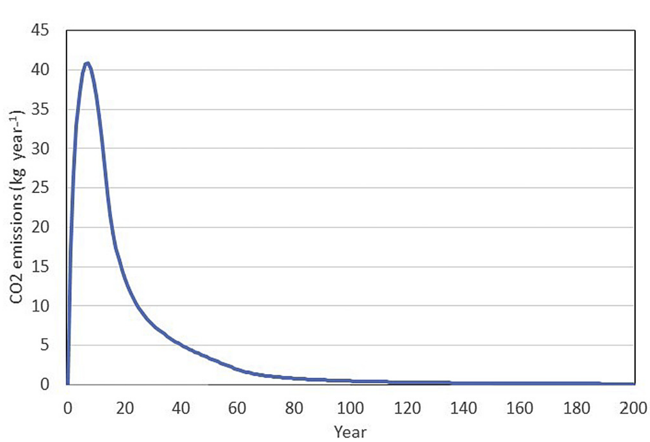

Fig. 2. Emissions of CO_2 from natural decay of 932 wet kg of forest slash that is left in the forest in Year 0.

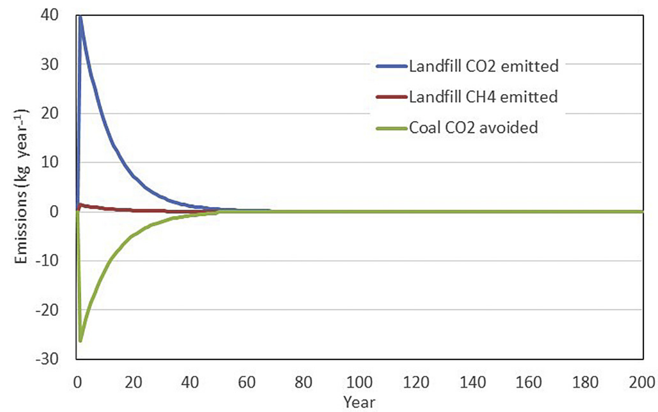

Fig. 3. Emissions of CO_2 and CH_4 from natural decay of 1270 wet kg of municipal solid waste that is landfilled in Year 0, and avoided coal CO_2 emissions if captured CH_4 is used instead of coal to produce electricity using state-of-the-art conversion technology.

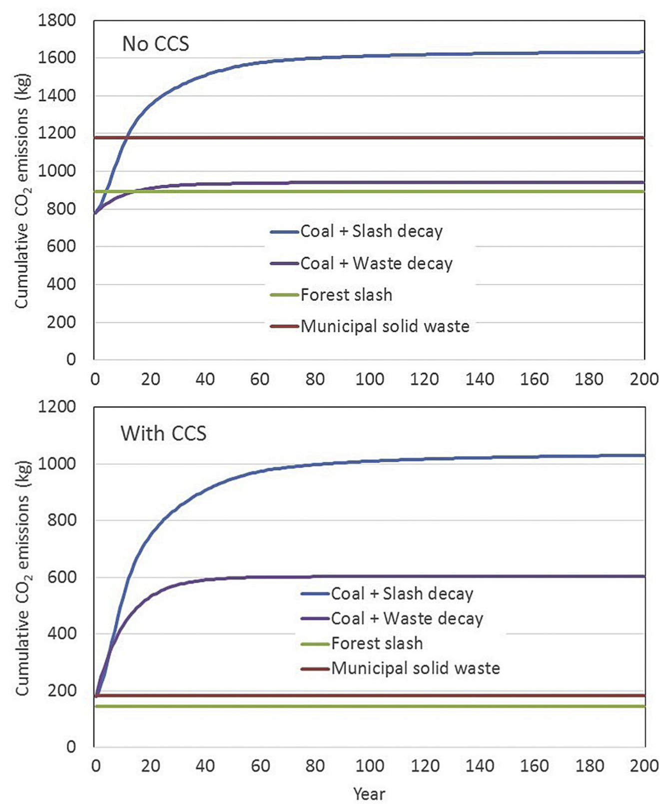

Fig. 4. Cumulative CO_2 emissions per MWh of electricity produced without CCS (top) and with CCS (bottom) using state-of-the-art conversion technology. CH_4 emissions from landfilled waste and coal mining is not shown.

Without CCS, electricity production with slash instead of coal gives consistent climate benefits. The climate effects of using waste instead of coal are less clear, with an initial reduction in CRF for about 120 years, followed by increased CRF. This variation is due to the CH_4 emission from decaying waste, which has higher climate impact but shorter atmospheric residence time compared to the CO_2 emissions from combusting waste.

3.5. Sensitivity analysis

As several of the model parameters are uncertain or variable, here we vary selected parameters individually from their base-case values, to determine the sensitivity of the results. The base-case and adjusted values of the parameters are shown in Table 11. Results are shown in Fig. 8 when forest slash is used instead of coal, and in Fig. 9 when municipal solid waste is used instead of coal. In general, uncertainly is lower for slash used instead of coal, which robustly results in reduced CRF. There is greater uncertainty of the climate effects of using waste instead of coal, regarding both the extent and sign (positive or negative) of the CRF change.

Using forest stumps as fuel instead of forest slash increases CRF, because extracting stumps requires more energy than recovering slash and the stumps decay more slowly than slash. Still, using stumps for energy instead of coal gives substantial climate benefits. Variations of climate condition for decaying forest slash give small variations in CRF. Variations of transport distance of both slash and waste give very small variations in CRF and are not visible in Figs. 8–9. When waste is used, the most sensitive parameters involve the management of landfill gas. If no landfill gas were recovered, which is not likely in managed Swedish landfills, the climate benefit of using waste for energy would increase, because the avoided CH_4 emissions from decaying waste in landfills would be much higher. Similarly, if landfill gas were flared instead of used for electricity production, there would be greater climate benefits of using the waste for energy instead of landfilling. The next most sensitive parameter is DOC_f, the fraction of total DOC that is ultimately degraded during the biological decay process. The recommended default value for this parameter had been 0.77 prior to 2006, but was then revised to 0.5–0.6 [52]. Change of this parameter value causes significant variation in results, suggesting that landfill process modelling is an important source of uncertainty in this analysis. Using waste Sample 2 instead of Sample 1 (see Table 5) modestly increases CRF of using waste for energy, due

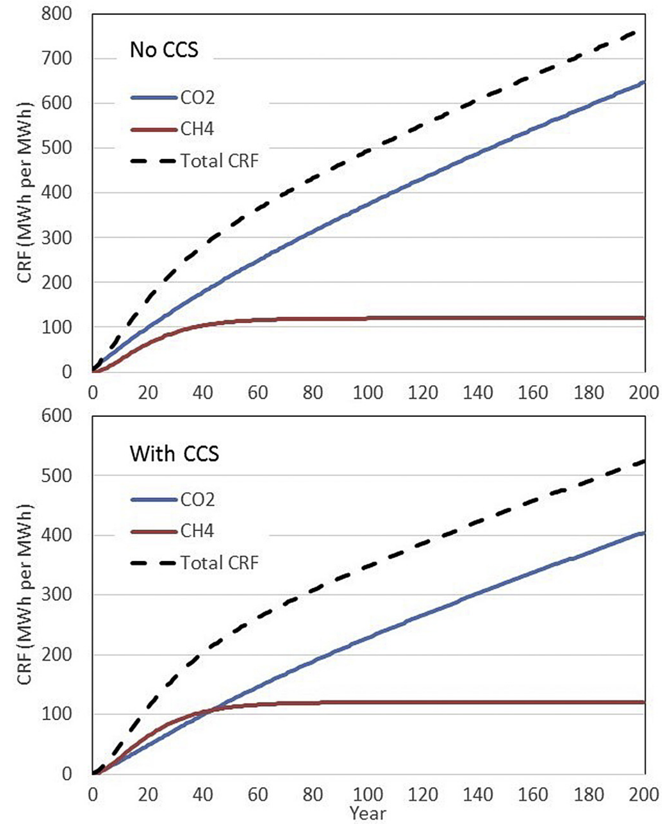

Fig. 6. CRF of municipal solid waste decay plus coal used for energy without CCS (top) and with CCS (bottom) to produce 1 MWh of electricity using state-of-the-art conversion technology. CRF contributions from CO_2 and CH_4 emissions are distinguished.

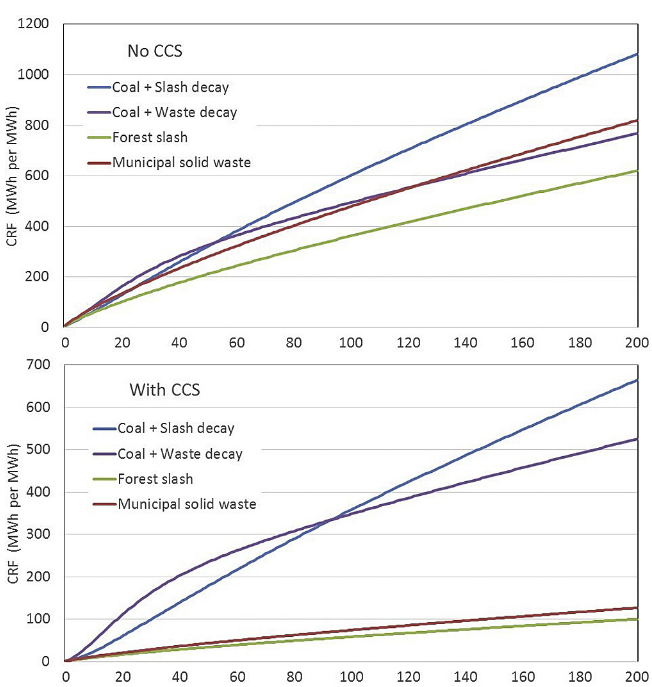

Fig. 5. CRF per MWh of electricity produced in Year 0 without CCS (top) and with CCS (bottom) using state-of-the-art conversion technology.

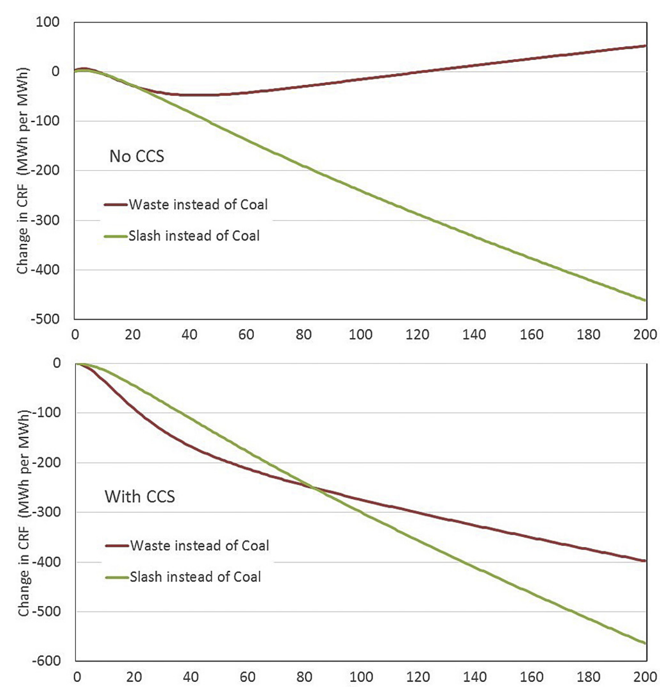

Fig. 7. Change in CRF when slash or waste is used for energy instead of coal without CCS (top) and with CCS (bottom) to produce 1 MWh of electricity using state-of-the-art conversion technology.

Table 11
Base-case values and adjusted values of selected parameters.

Parameter	Base case value	Adjusted value
Coal		
Coal mine CH_4	0.5 kg per ton	15 kg per ton
Forest slash		
Biomass type	Slash	Stumps
Biomass decay climate	Central Sweden	South Sweden
Transport distance	International	Local
Municipal solid waste		
Landfill gas recovery (R)	80%	0%
Recovered landfill gas	Electricity	Flared
DOC degraded (DOC_f)	0.50	0.77
Waste sample[a]	Sample 1	Sample 2
Waste decay constant (k)	0.09	0.05

[a] See Table 5.

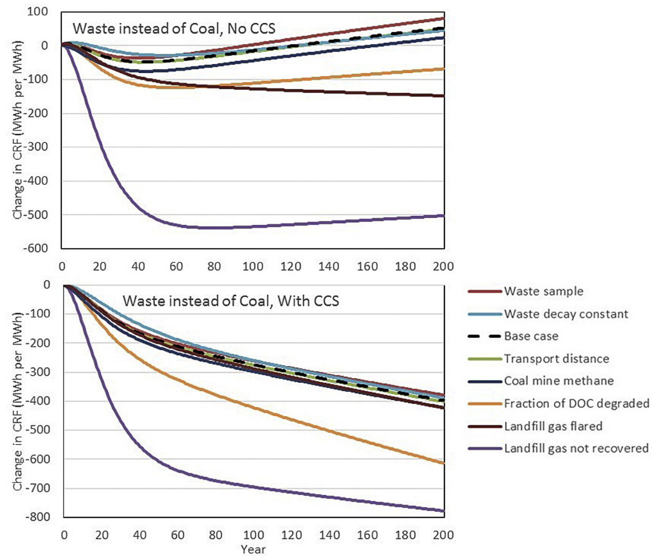

Fig. 9. Effect of variation of selected parameter values on the change of CRF when municipal solid waste is used instead of coal to produce 1 MWh of electricity using state-of-the-art conversion technology.

to both its higher calorific value and lower DOC content. Variation of the biodegradation rate constant (k) results in a minor increase in CRF of using waste for energy. Increased emissions of CH_4 from coal mines has a minor impact on CRF.

The efficiency of converting fuels to electricity is a sensitive parameter, and can by varied according to the technical design of the conversion plant. Emerging technologies are being developed that are expected to enable higher conversion efficiencies in future power plants. Our base case analysis considers the conversion efficiencies of state-of-the-art technology, and here we consider both the lower efficiencies of averaged used technology and the higher efficiencies of emerging technology (see Tables 7 and 8). The amount of slash and waste available to each system is held constant, as they are limited resources, based on the amounts needed to produce 1 MWh of electricity using state-of-the-art conversion technology. When lower efficiency technologies are used, more fuel is needed to produce 1 MWh of electricity, and we assume coal is used to fill this gap. When higher efficiency technologies are used, less fuel is needed to produce the electricity and we assume the surplus slash or waste is used elsewhere to replace coal. Fuels used in each case are shown in Table 12. For each scenario (average used, state-of-the-art and emerging technologies), different conversion efficiencies are used consistently for all three fuels as well as for landfill gas used to produce electricity. The resulting changes in CRF are shown in Fig. 10. In general, higher conversion efficiencies of emerging technologies lead to slightly greater climate benefits when slash or waste is used instead of coal.

4. Conclusions

In this study, we have analysed a set of options for producing dispatchable electricity, each of current interest in Europe and globally. We examined 3 fuels—coal, forest slash and municipal solid waste—that are currently used for electricity production at

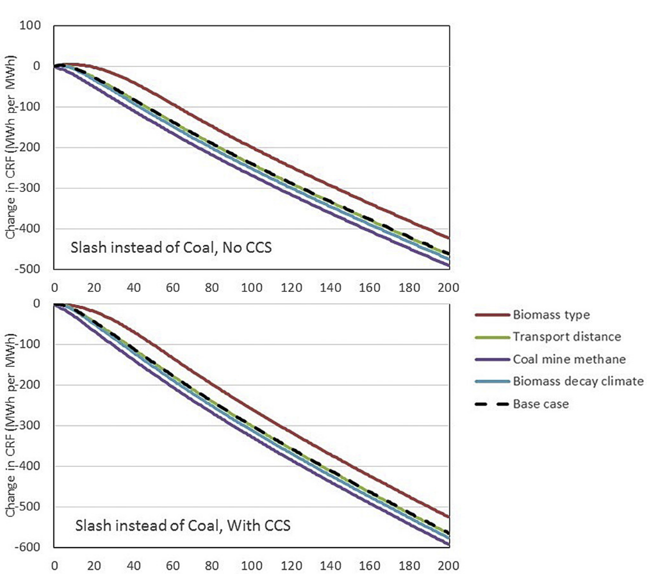

Fig. 8. Effect of variation of selected parameter values on the change of CRF when forest slash is used instead of coal to produce 1 MWh of electricity using state-of-the-art conversion technology.

Table 12
Fuel use at the conversion plant for generation of 1 MWh of electricity using different technologies, when amount of slash and waste available to each system is held constant. Negative coal use by emerging technologies is due to surplus slash and waste used to substitute coal-fired electricity.

Fuel	Fuel use (MWh_{LHV})		
	Coal	Biomass	Waste
Average used technology			
Coal	2.86	–	–
Coal CCS	4.00	–	–
Slash	1.18	2.17	–
Slash CCS	2.52	2.17	–
Waste	0.76	–	3.33
Waste CCS	2.40	–	3.33
State-of-the-art technology			
Coal	2.08	–	–
Coal CCS	2.63	–	–
Slash	–	2.17	–
Slash CCS	0.57	2.17	–
Waste	–	–	3.33
Waste CCS	0.88	–	3.33
Emerging technology			
Coal	1.92	–	–
Coal CCS	2.22	–	–
Slash	−0.17	2.17	–
Slash CCS	0.14	2.17	–
Waste	−0.38	–	3.33
Waste CCS	0.07	–	3.33

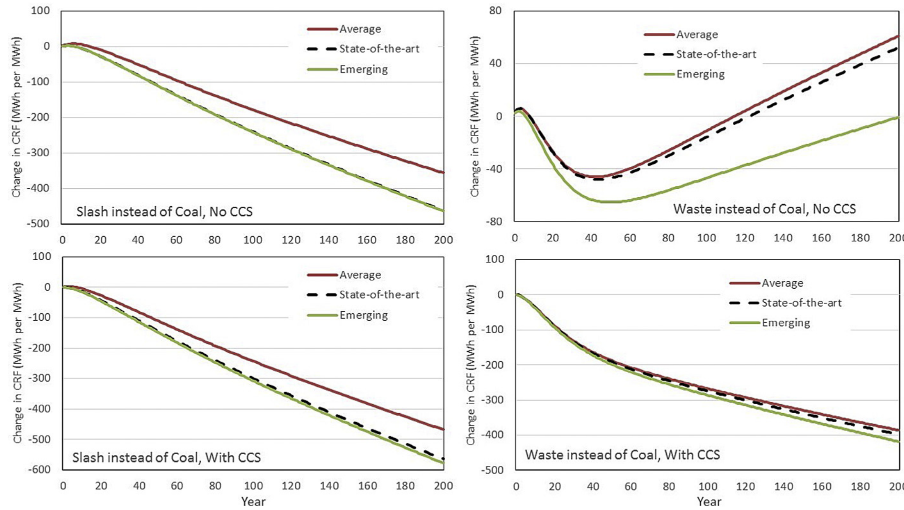

Fig. 10. Effect of using average, state-of-the-art and emerging conversion technologies on the change of CRF when forest slash and municipal solid waste is used instead of coal to produce 1 MWh of electricity, with and without CCS.

varying scales, and are likely to play non-trivial roles in future electricity supply. We considered each fuel with and without CCS, a potential technology for climate change mitigation. Other energy sources and conversion technologies, such as wind and solar photovoltaic, will undoubtedly play important roles in the future electricity landscape [92]. However, given the still prominent place of coal in electricity production globally and in Europe, and credible projections of its future continued use, it is highly likely there will be ample opportunities to substitute coal, within the service life span of a new power plant.

We have found that using forest slash to replace coal for electricity production gives significant climate benefits. Using slash instead of coal increases slightly the CO_2 emissions emitted from a power plant that produces a unit of electricity. However, the avoided CO_2 emissions from the natural decay of slash result in significantly lower net emissions and global cooling when slash is used to produce electricity instead of coal. When CCS technology is used, CO_2 emissions from the electricity production plant are sharply reduced, while the avoided emissions from natural decay are unaffected, resulting in strong climate benefits when slash is used for electricity production in combination with CCS. However, the use of CCS increases the use of fuel to produce the same quantity of electricity.

We have also found that using municipal solid waste to replace coal for electricity production without CCS brings more ambiguous climate benefits, if landfill gas is collected and used to produce electricity. Conversion efficiency of directly converting waste to electricity is relatively low, and using the waste as fuel foregoes partial sequestration of the waste's carbon content in landfill, as well as the opportunity to recover and use landfill CH_4 as fuel. The substantial uncertainties regarding landfill decay processes cast further questions on the climate benefits of using waste for electricity. Emerging gasification technologies slightly improve the conversion efficiency of producing electricity, and facilitate the use of difficult-to-handle fuels including municipal solid waste [93].

There remain uncertainties in parts of this analysis, in particular the emissions from landfilled municipal solid waste. Nevertheless, the overall results appear robust: Using forest residues to replace coal gives substantial climate benefits, while using municipal solid waste to replace coal gives questionable climate benefits unless accompanied by CCS. CCS requires more energy, but strongly reduces the CO_2 emissions from conversion plants. Efficiently using forest residues as fuel, with or without CCS technology, should be considered as suitable for electricity production in a carbon-constrained future.

Acknowledgements

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