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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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ABSTRACT

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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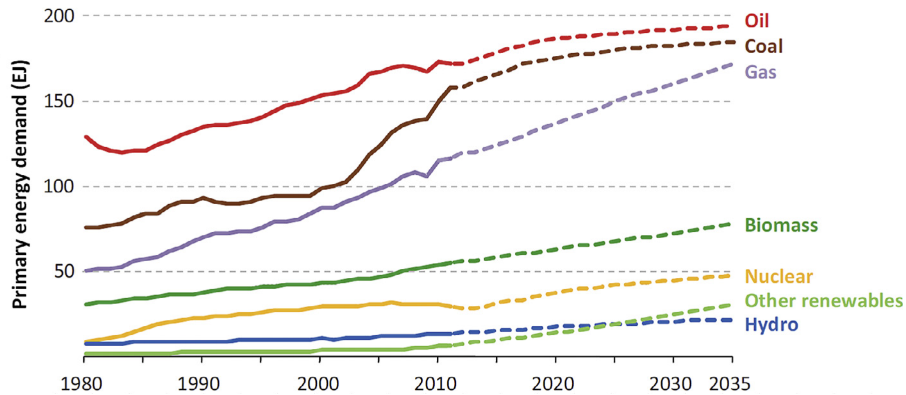

Fig. 1. Historical and projected trends of global primary energy use through 2035 with policy measures implemented for reducing the use of fossil fuel (IEA New Policies Scenario) [2].

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