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Lifecycle Climate Impact of Cars and Trucks Powered by Bioelectricity, Biofuels or Fossil Fuels[a]

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ABSTRACT

Here we compare the biomass feedstock use, net CO_2 emission, and cumulative radiative forcing of passenger cars and cargo trucks powered by different energy pathways. We consider the full lifecycle of the vehicles, including manufacture and operation. Our system boundaries include all fossil and biogenic emissions from technical systems, and the avoided decay emissions from harvest residue left in the forest. We find that the pathways using bioelectricity to power battery electric vehicles have strongly lower climate impacts, compared to the liquid-fuelled internal combustion pathways using biomethanol, DME, gasoline or diesel. The pathways using bioelectricity with carbon capture and storage (CCS) result in negative emissions leading to global cooling. These findings suggest that accelerating the current trend toward vehicle electrification, together with scaling up renewable electricity generation, is a wise strategy for climate-adapted transport.

Keywords: biomethanol; dimethyl-ether; battery electric vehicles; climate change; woody biomass; BECCS

1. INTRODUCTION

Mitigation of, and adaptation to, climate change requires a strategic evolution and transformation of several technical sectors including building, energy, industrial and transportation systems [1,2]. Fossil fuels now provide more than 80% of global primary energy supply [3], and this dependence is difficult to change, particularly in some sectors including transportation. Massive introduction of high efficiency renewable energy systems is needed, as well as sustainable management and use of land including forest resources. Also, it is increasingly evident that avoiding climate disruption will require negative emission technologies, such as bioenergy with carbon capture and storage (BECCS) [4].

Sweden has abundant forest resources, and an active debate over how the resources may best be managed. A point of current discussion in Sweden is how renewable forest bioenergy resources may be used in a sustainable and climate-adapted transport sector. Passenger cars contributed 61% of Swedish domestic transport greenhouse gas (GHG) emissions in 2018, and 19% of total GHG emissions [5]. Emissions from heavy duty vehicles (those with total vehicle mass greater that 3.5 t) in Sweden in 2020 contributed 7% of total Swedish GHG emissions, and 20% of total domestic transport emissions [6].

To better understand the opportunities and challenges of climate adapted transport systems, we develop and employ a bottom-up system model of passenger car and cargo truck transport considering different energy pathways. The pathways include internal combustion vehicles (ICV) as well as battery electric vehicles (BEV), and each pathway is considered with and without carbon capture and sequestration (CCS). The bioelectricity and liquid biofuel pathways are fueled by forest harvest residues obtained from sustainable forestry. We analyse biomass usage, net CO_2 emissions, and cumulative radiative forcing (CRF) of each pathway.

Our goal is to identify energy-efficient pathways with lasting opportunities to use forest residues to mitigate climate change impacts of car and truck transport, to enable wise decisions about the various alternatives.

2. METHODOLOGY

We compare BEV and liquid-fuel ICV cars and trucks that provide equivalent transport service. BEVs are powered by electricity generated from forest harvest residues (slash) in stand-alone power plants and CHP plants, or from a mix of 70% wind and 30% forest residues. ICV cars are powered by gasoline, or by biomethanol produced from slash. ICV trucks are powered by diesel, or by dimethyl ether (DME) produced from slash. We include the manufacturing processes that produce the vehicles and batteries, and the operating energy use and CO_2 emissions of the vehicles over their lifespans. We take a forward-looking approach and consider the likely conditions during the coming decade. Our modelling of biomethanol and DME production is based on data from Nguyen & Gustavsson [7] and we use the average of the 2 most efficient of the 6 plants they studied. We consider biomass integrated gasification combined cycle (BIGCC) technology for converting woody biomass to electricity [7,8]. For the CCS technology we assume an energy penalty of 20% with capture and permanent storage of 90% of the CO_2 [9]. CCS is impractical for tailpipe emissions from ICVs.

For cars, we consider medium-size vehicles with a mass of about 1600 kg, such as the VW Passat or Toyota Corolla. We assume a lifespan of 15 years, and an annual driving distance of 15,000 km. Electric cars are fitted with a 40 kWh battery, which last the full lifespan of the car. We assume a final operational energy use of 0.70 MJ/km for electric cars, and 2.1 MJ/km for internal combustion cars, based on data from [7,10,11].

For trucks, we consider medium-size vehicles with a gross vehicle mass of about 20,000 kg. We assume a lifespan of 7 years, and an annual driving distance of 60,000 km [12,13]. Electric trucks are fitted with a 280 kWh battery, which is replaced midway through the lifespan of the truck. We assume a final operational energy use of 4.0 MJ/km for electric trucks, and 9.3 MJ/km for internal combustion trucks, based on data from [14,15,16,17,18,19].

Forest slash that is removed from the forest and used for bioenergy releases CO_2 into the atmosphere immediately when burned or gasified. If the slash is left in the forest it decomposes naturally and slowly releases CO_2 over decades. In this analysis, we consider all biogenic CO_2 emissions from the bioenergy pathways, as well as the avoided CO_2 emissions from the biological decay of slash if slash is harvested. We estimate CO_2 emissions from the biological decay with the Q model [20], using parameter values specific to central Sweden [21].

Cumulative radiative forcing (CRF) measures the total amount of energy added to or reduced from the earth system, and is a proxy for surface temperature change. CRF is a better metric of climate impacts than net CO_2 emissions, because it considers the temporal patterns of CO_2 emissions and uptakes and their cumulative effects on the earth system. We calculate CRF using the method proposed by Zetterberg [22], with updated parameter values from IPCC [23]. CRF is based on time profiles of CO_2 emissions to the atmosphere, and accounts for the various natural processes that remove CO_2 from the atmosphere.

The analytical methodology is described in more detail by Sathre and Gustavsson [24].

3. RESULTS

3.1 Vehicle specific analysis

Table 1 shows the total amount of biomass feedstock (forest slash) used to power a car and a truck during their 15- and 7-year service lives, respectively. The total driving distance of the car and truck is 225,000 and 420,000 km, respectively. DME and Biomethanol pathways used the greatest amount of feedstock. Wind+Bioelectricity and Wind+CHP-Bioelectricity pathways use the least amount. Pathways including CCS use more feedstock than those without CCS, to power the CO_2 capture processes.

Table 1. Total biomass feedstock used during the full service life of a passenger car and a cargo truck powered by different energy pathways.

Bioenergy pathway	Biomass use (TJ)
Car: Biomethanol CCS	0.905
Car: Biomethanol	0.754
Car: Bioelectricity CCS	0.378
Car: Bioelectricity	0.315
Car: Wind+Bioelectricity CCS	0.113
Car: Wind+Bioelectricity	0.095
Truck: DME CCS	7.09
Truck: DME	5.91
Truck: Bioelectricity CCS	3.99
Truck: Bioelectricity	3.33
Truck: CHP Bioelectricity CCS	3.11
Truck: CHP Bioelectricity	2.59
Truck: Wind+Bioelectricity CCS	1.20
Truck: Wind+Bioelectricity	1.00
Truck: Wind+CHP Bioelectricity CCS	0.93
Truck: Wind+CHP Bioelectricity	0.78

Figure 1 shows the cumulative CO_2 emissions including avoided CO_2 emissions from decay of forest slash, over the life cycle of a car using either of 4 energy pathways without and with CCS. The avoided decay emissions of each year's biomass feedstock are tracked over 100 years. For the three pathways that use biomass, their cumulative CO_2 emissions peak at Year 15, the last year of car operation, and then begin to decline as avoided decay emissions gradually mount. Biomethanol peaks at 67 t CO_2, Bioelectricity peaks at 34 t CO_2, and Wind+Bioelectricity peaks at 16 t CO_2. After 100 years, the net cumulative emission of the three bioenergy pathways is near zero. In contrast, the Gasoline pathway rises linearly during the 15 years of operation, then remains constant at 42 t CO_2 for the duration. Bioenergy with carbon capture and storage results in net negative CO_2 emissions corresponding to global cooling. The greater biomass feedstock use of the Biomethanol pathway means greater quantities of CO_2 captured and sequestered. The cumulative emissions of the Gasoline pathway with CCS is slightly lower than without CCS due to minor CO_2 capture during the refining process.

Figure 2 shows the CRF for 4 energy pathways without and with CCS, corresponding to the CO_2 emissions shown in Figure 1. Without CCS, the Biomethanol pathway has the highest CRF, followed by Gasoline, showing that gasoline gives lower climate impact than biomethanol. This means that it is better to leave the harvest slash in the forest and instead use gasoline, rather than use the slash to produce biomethanol. The Wind+Bioelectricity pathway has the lowest CRF with a climate impact less than 30% of the Biomethanol path. The Bioelectricity CCS pathway has negative CRF after 100 years, giving global cooling, because the cumulative CO_2 emissions peak early and become significantly negative.

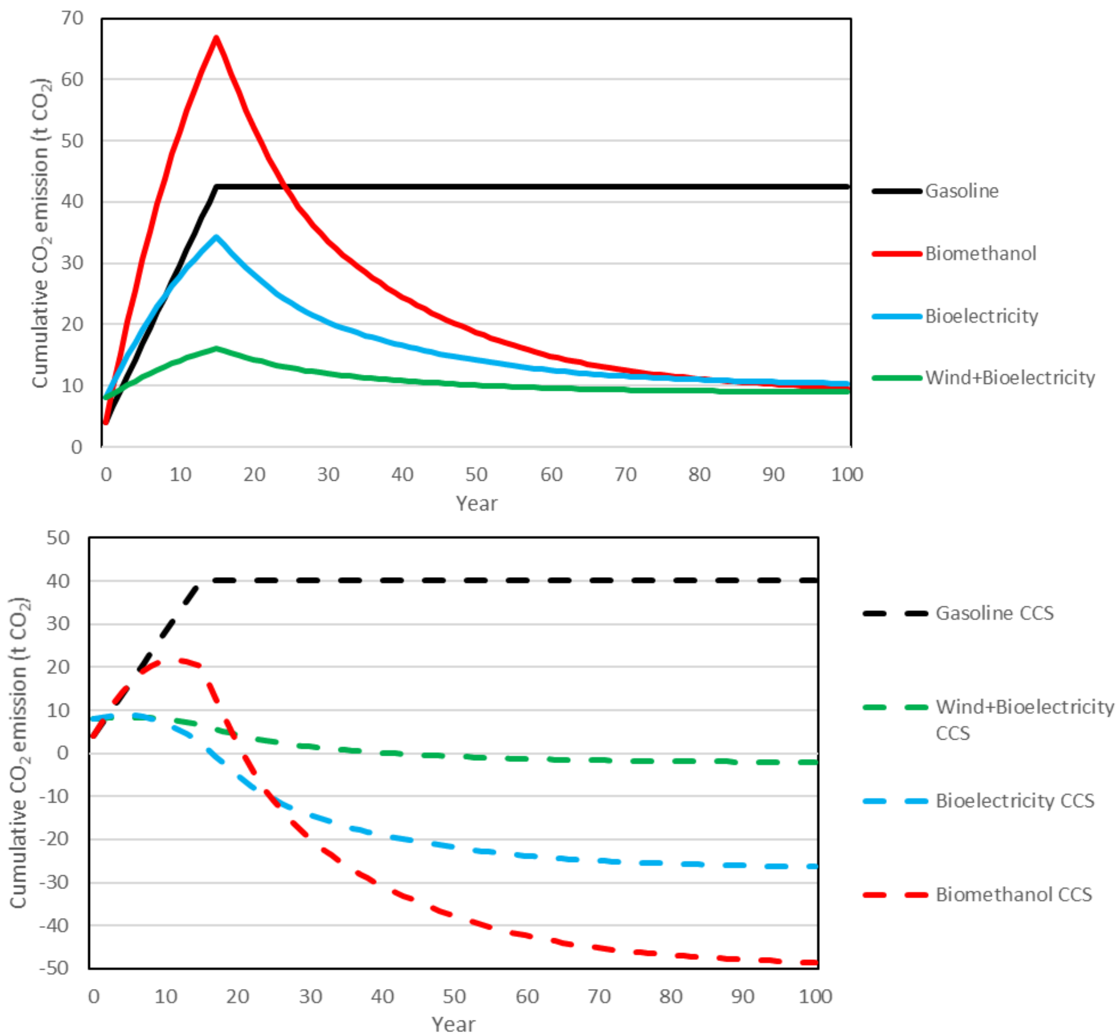


Fig. 1. Cumulative CO_2 emissions including avoided decay emissions from forest slash for energy pathways for cars without CCS (top) and with CCS (bottom).

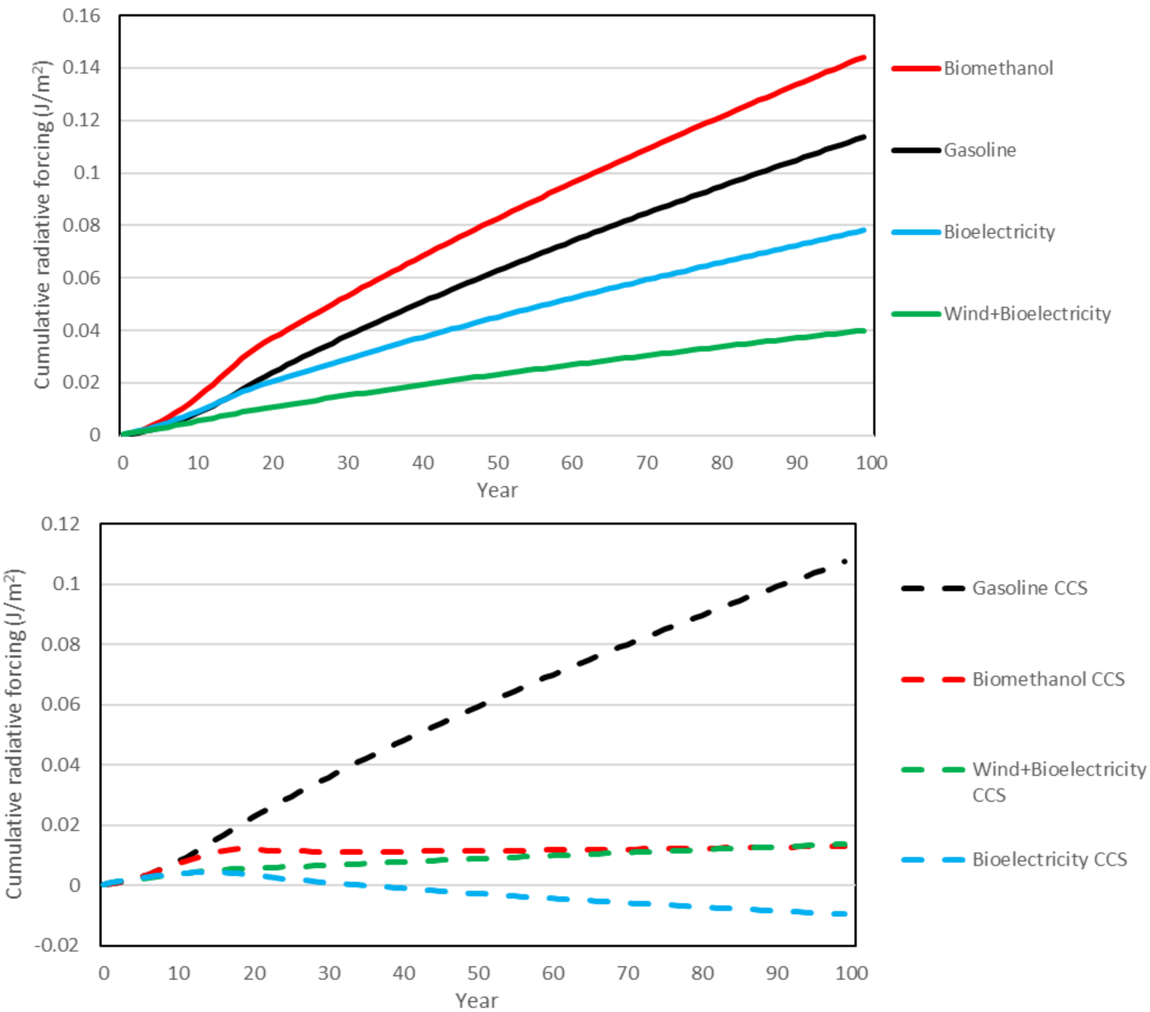


Fig. 2. Cumulative radiative forcing for energy pathways for cars corresponding to emissions shown in Figure 1.

Figure 3 shows the cumulative CO_2 emissions including avoided CO_2 emissions from decay of forest slash, over the life cycle of a truck using either of 6 energy pathways without and with CCS. For the 10 pathways that use biomass, their cumulative CO_2 emissions peak at Year 7, the last year of truck operation, and then begin to decline as avoided decay emissions gradually mount. Without CCS, DME peaks at 880 t CO_2, Bioelectricity peaks at 560 t CO_2, and Wind+Bioelectricity peaks at 230 t CO_2. After 100 years, the net cumulative emission of the 5 bioenergy pathways is near zero. In contrast, emissions from the Diesel pathway rises linearly during the 7 years of operation, then remain constant at 375 t CO_2 for the duration. Bioenergy with CCS results in net negative CO_2 emissions corresponding to global cooling. The greater biomass feedstock use of the DME pathway means greater quantities of CO_2 captured and sequestered. The cumulative emissions of the Diesel pathway rise linearly during the 7 years of operation, then remain constant at 355 t CO_2, slightly lower than without CCS.

Figure 4 shows the CRF for 12 energy pathways without and with CCS. Without CCS, The Diesel pathway has the highest CRF after 100 years, followed closely by the DME pathway. The Wind+Bioelectricity pathway has the lowest CRF with a climate impact less than 30% of the DME path. With CCS, the Diesel CCS pathway has clearly the highest CRF. The Bioelectricity CCS pathway has negative CRF after 100 years, causing global cooling, because the cumulative CO_2 emissions peaked early and became significantly negative.

Figure 5 compares the lifecycle biomass feedstock use and the CRF after 100 years, for cars (top) and trucks (bottom) powered by different energy pathways. The most desirable outcome is the lower left corners of the figures, with low biomass use and low CFR. The best energy pathways are those using wind and bioelectricity, particularly CHP-electricity, both with and without CCS.

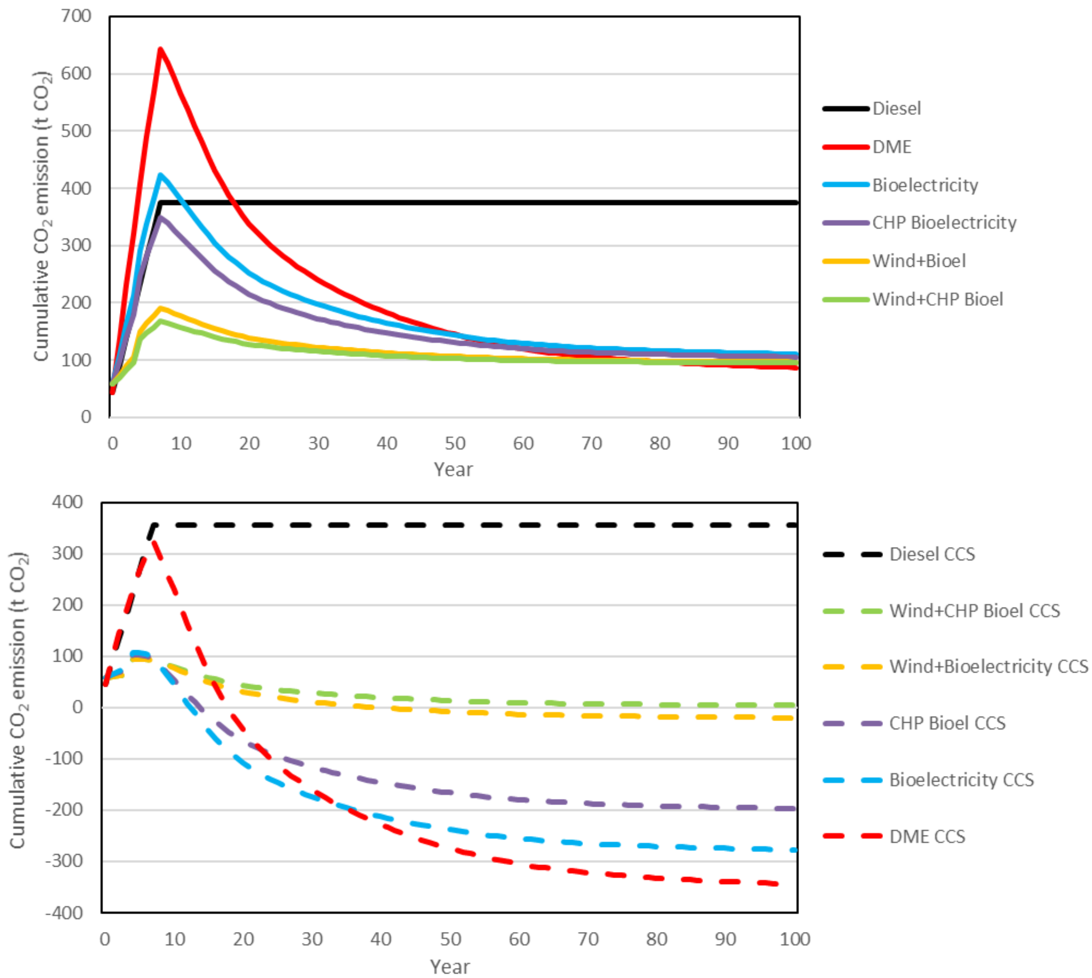
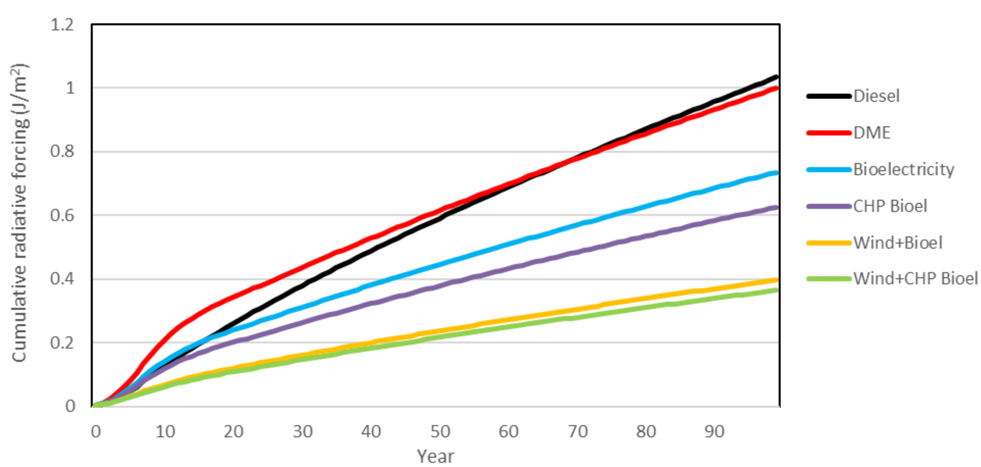


Fig. 3. Cumulative CO_2 emissions including avoided decay emissions from forest slash used in energy pathways for trucks without CCS (top) and with CCS (bottom).



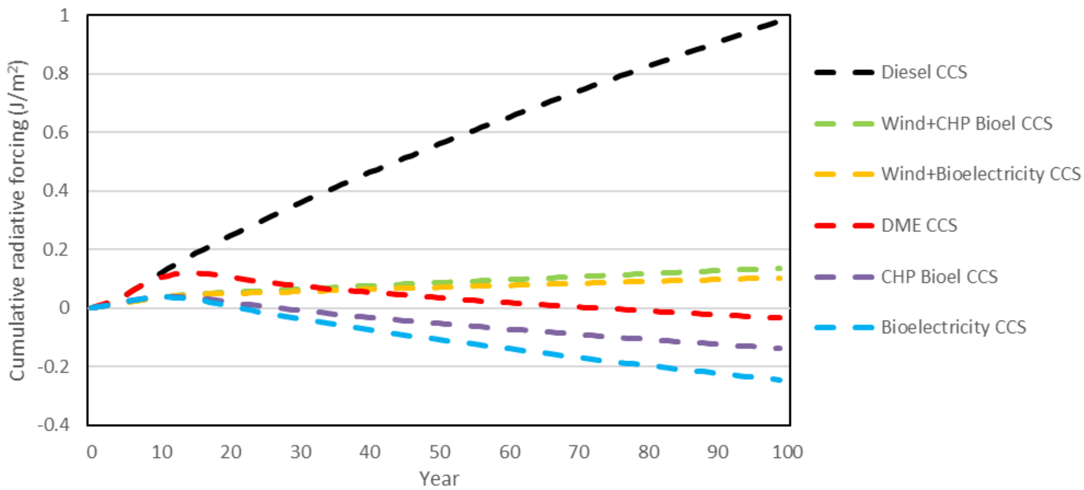


Fig. 4. Cumulative radiative forcing for energy pathways for trucks corresponding to emissions shown in Figure 3.

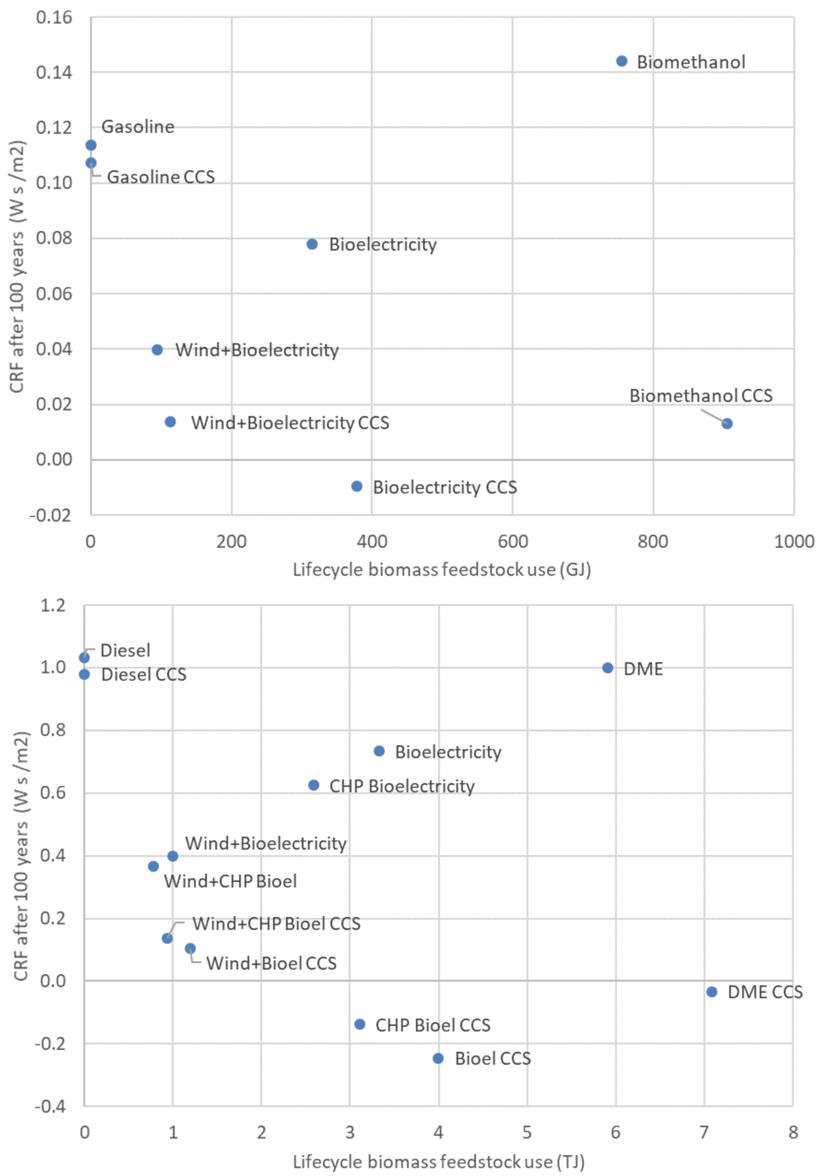


Fig. 5. Lifecycle biomass feedstock use vs. CRF after 100 years, for cars (top) and trucks (bottom) powered by different energy pathways.

3.2 Scenario analysis

The forest biomass feedstock is a limited resource and the end-use analysis, the vehicle analysis, must be considered in the context of biomass supply, otherwise the understanding of the results may be misleading. If more biomass is used in one sector, less biomass can be used in other parts of the society. The annual current Swedish harvest of slash is of about 10 TWh while Sweden's potential slash harvest is of about 65 TWh/year [25]. Here, we allocate annually 60 and 20 TWh of slash for energy paths to power Swedish driving of cars and trucks, respectively. Cars in Sweden travelled a total of 68.7 billion km in 2018 [26] while trucks in Sweden travelled a total of about 4.74 billion km per year (average of latest 6 years, 2015-2020) [12]. These travel distances are used in the scenario analysis. If more biomass is needed to fulfil the transport requirement than allocated, we assume that gasoline or diesel is used. If less biomass is needed for transport than allocated, the surplus biomass is used to produce electricity in standalone BIGCC plants. The produced bioelectricity from surplus biomass substitutes fossil gas electricity produced in a combined cycle facility at 60% efficiency using gas emitting 69 kg CO_2 per GJ [27].

Figure 6 shows cumulative CO_2 emissions resulting for energy pathways in the scenario analysis, while Figure 7 show CRF corresponding to emissions in Figure 6. The figures show that the greatest climate impacts occur when liquid biofuels are used, followed closely by liquid fossil fuels. The lowest climate impacts occur when electric vehicles are powered by renewable electricity from wind and cogeneration with CCS. Efficient pathways result in negative carbon emission balances after 100 years, and the most efficient pathways with CCS result in negative CRF, or global cooling, after 100 years.

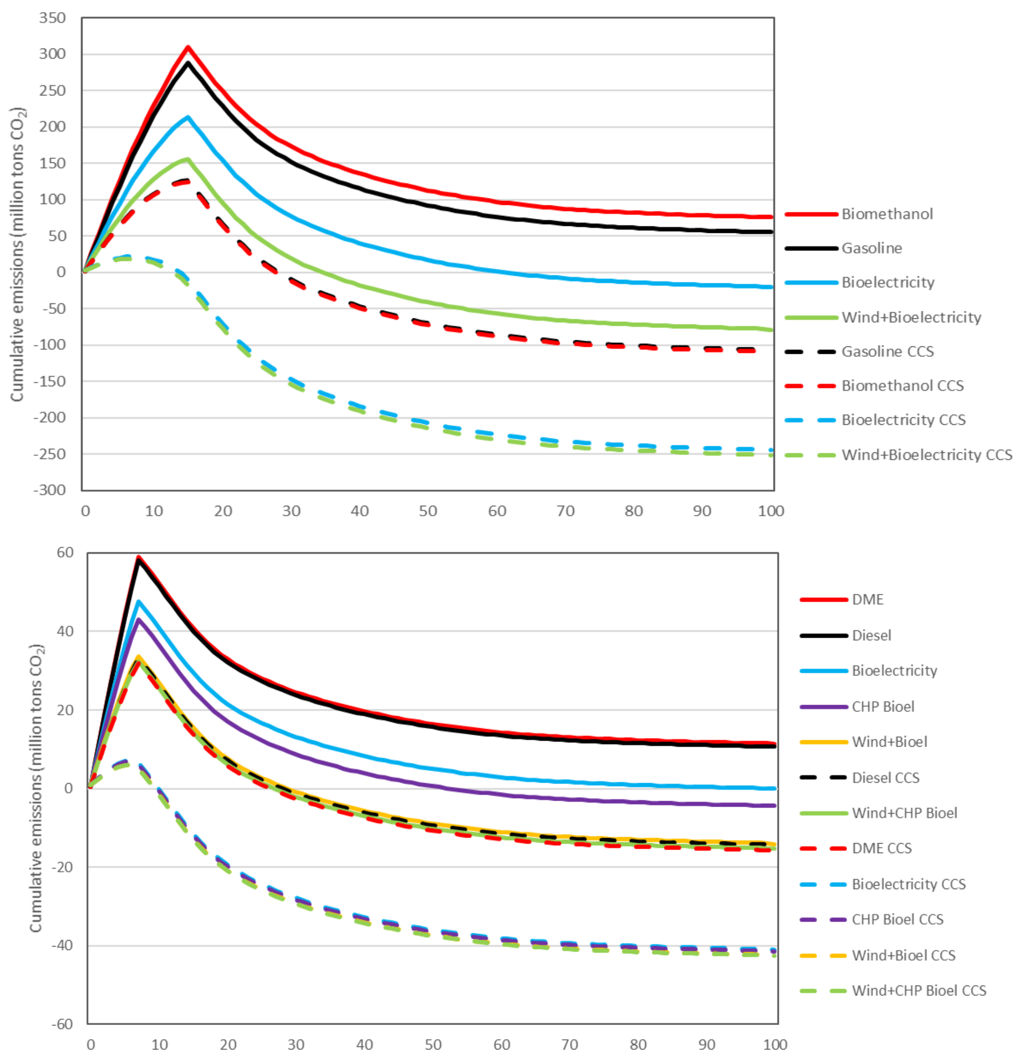


Fig. 6. Cumulative CO_2 emissions resulting from different energy pathways when allocating 60 TWh of slash yearly as feedstock to drive 68.7 billion km in cars (top) and when allocating 20 TWh of forest slash per year as feedstock to drive 4.74 billion km in trucks (bottom). Some lines overlap and are difficult to see.

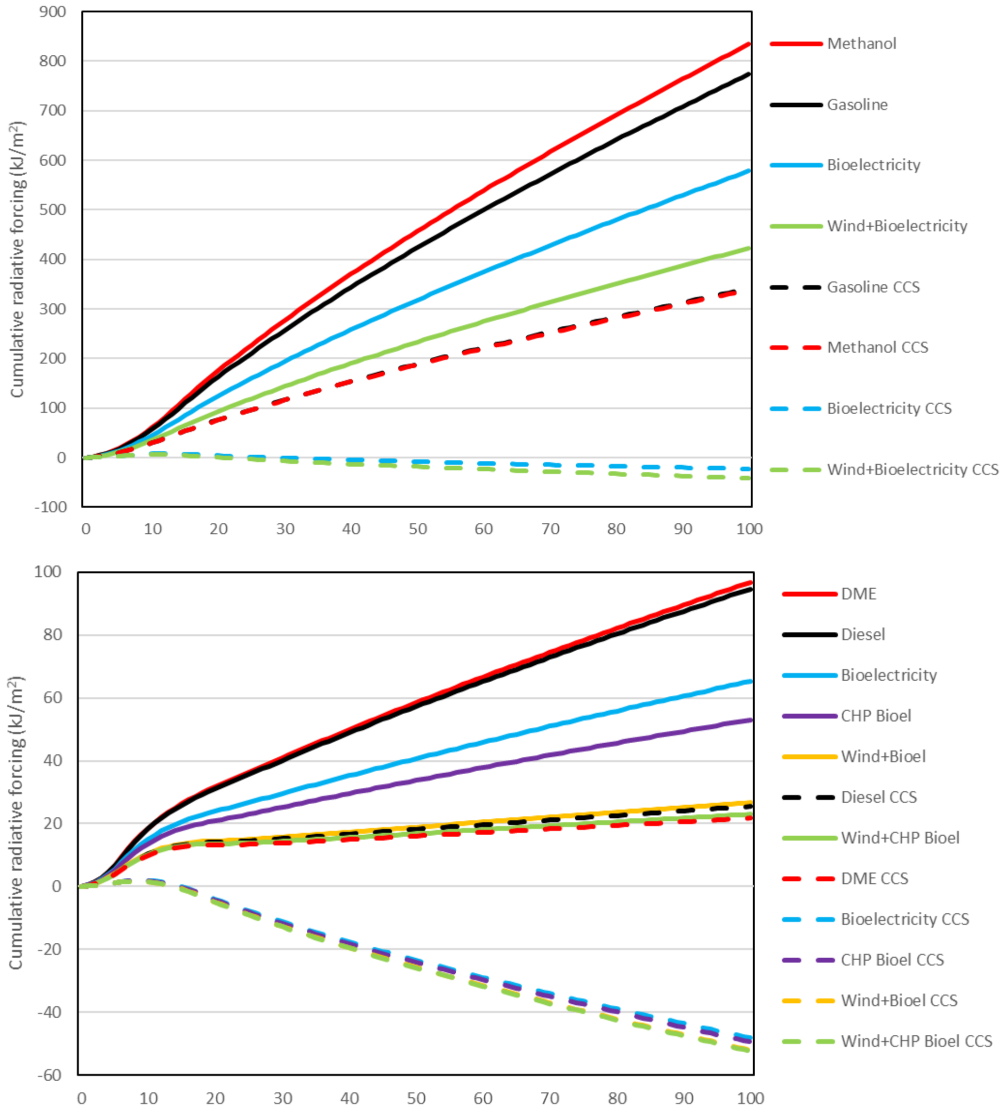


Fig. 7. Cumulative radiative forcing for cars (top) and trucks (bottom) corresponding to emissions shown in Figure 6. Some lines overlap and are difficult to see.

4. DISCUSSION AND CONCLUSIONS

We have analysed the lifecycle climate implications of alternate pathways to power cars and trucks. We find that the pathways using electricity to power BEVs have strongly lower climate impacts, compared to the ICV pathways using methanol, DME, gasoline and diesel. The lowest emissions are seen when wind and biomass electricity is used to power BEVs. The highest emissions occur when biomethanol and DME are used, followed closely by gasoline and diesel. While this analysis is specific to Sweden, our general conclusions are also valid for other countries and regions.

CCS can bring significant climate benefit to some transport energy pathways. CCS is particularly effective on BEVs, which have no tailpipe emissions, because CO_2 can be efficiently captured at BIGCC electricity generating facilities. CCS is much less effective on ICV cars and trucks, because the capture process cannot be scaled down to individual vehicles. Nevertheless, biomethanol and DME production has substantial process emissions that can be captured.

We thus find that a wise transport strategy is to pursue the electrification of the vehicle fleet, accompanied by a ramp-up of renewable electricity generation. Stable electricity is easier to achieve by integrating intermittent sources like wind together with dispatchable sources like bioelectricity. Combination of wind and CHP-bioelectricity will give high resource efficiency and climate mitigation with wind integration benefits. BECCS may also be deployed for net negative carbon emissions, as needed to reach IPCC climate goals.

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