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RESEARCH ARTICLE

Lifecycle climate impact and primary energy use of electric and biofuel cargo trucks

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Abstract

Heavy trucks contribute significantly to climate change, and in 2020 were responsible for 7% of total Swedish GHG emissions and 5% of total global CO_2 emissions. Here we study the full lifecycle of cargo trucks powered by different energy pathways, comparing their biomass feedstock use, primary energy use, net biogenic and fossil CO_2 emission and cumulative radiative forcing. We analyse battery electric trucks with bioelectricity from stand-alone or combined heat and power (CHP) plants, and pathways where bioelectricity is integrated with wind and solar electricity. We analyse trucks operated on fossil diesel fuel and on dimethyl ether (DME). All energy pathways are analysed with and without carbon capture and storage (CCS). Bioelectricity and DME are produced from forest harvest residues. Forest biomass is a limited resource, so in a scenario analysis we allocate a fixed amount of biomass to power Swedish truck transport. Battery lifespan and chemistry, the technology level of energy supply, and the biomass source and transport distance are all varied to understand how sensitive the results are to these parameters. We find that pathways using electricity to power battery electric trucks have much lower climate impacts and primary energy use, compared to diesel- and DME-based pathways. The pathways using bioelectricity with CCS result in negative emissions leading to global cooling of the earth. The pathways using diesel and DME have significant and very similar climate impact, even with CCS. The robust results show that truck electrification and increased renewable electricity production is a much better strategy to reduce the climate impact of cargo transport than the adoption of DME trucks, and much more primary energy efficient. This climate impact analysis includes all fossil and net biogenic CO_2 emissions as well as the timing of these emissions. Considering only fossil emissions is incomplete and could be misleading.

KEYWORDS
bioelectricity, cargo trucks, climate impact, cumulative radiative forcing, woody biomass, dimethyl ether

1 | INTRODUCTION

There is growing realization among policymakers and the public that action must be taken to avoid severe climate disruption (IPCC, 2022a, 2022b). Our society is profoundly dependent on fossil energy sources (IEA, 2021), which are primarily responsible for global climate change and are becoming progressively scarcer. A large reduction of fossil fuel use will require the strategic transformation of our society (UNEP, 2021). This must include the widespread deployment of high efficiency renewable energy, and technologies that reduce atmospheric greenhouse gas like bioenergy with carbon capture and storage (BECCS) (UNEP, 2022).

Forests can play important roles in mitigating climate change, by storing carbon and by producing renewable materials and fuels (FAO, 2016). In Sweden, the forestry sector has great economic and cultural significance, and there is active discussion on how forests can best be used to reduce climate change. One option is to increase the use of forest harvest residues for bioenergy, instead of leaving them in the forest to decay naturally.

Here we explore the use of forest residues to power cargo trucks, which are currently powered almost exclusively by fossil diesel fuel. In 2020, heavy duty vehicles (those with total vehicle mass greater than 3.5 t) in Sweden contributed 7% of total Swedish GHG emissions (excluding land use and international transports), and 20% of all domestic transport emissions (SCB, 2021). Globally, heavy duty trucks were responsible for 5% of all CO_2 emissions in 2020 (IEA, 2022). Using renewable energy sources can drastically reduce fossil carbon emissions from truck transport. There are several distinct pathways by which this could be done. Forest residues could be converted to liquid biofuels such as dimethyl ether (DME), via gasification and synthesis processes, and used in internal combustion engines. Residues could also be converted to electricity and used in battery electric vehicles (BEVs). Intermittent renewable electricity sources such as wind and solar could also be integrated with dispatchable bioelectricity, to provide reliable power to charge truck batteries.

There is a growing body of knowledge on sustainable transport systems and components, including focussed research on trucks powered by either electricity or biofuels. For example, Earl et al. (2018) conducted bottom-up modelling of battery electric truck operation, compared to a baseline of diesel trucking. They found abundant economic and environmental benefits from truck electrification. Liimatainen et al. (2019) estimated what percent of road freight could be electrified in Finland and Switzerland. They found high potential for battery electric trucks, particularly in Switzerland. Lombardi et al. (2020) compared trucks with different powertrain solutions, in a modelling framework of energy and carbon performance. They found battery electric trucks to have greater energy efficiency than diesel and biofuel trucks. Liu et al. (2021) modelled the performance of diesel and battery electric trucks, and evaluated their operating emissions of GHGs and other pollutants. They found emissions to be generally lower for electric trucks, depending on the source of electricity. Holmgren et al. (2021) compared the economic costs of various non-fossil energy pathways for heavy trucks, including their associated charging and fuelling infrastructures. They found battery electric trucks to have the lowest overall cost, even when including the cost of the required charging infrastructure. Nykvist and Olsson (2021) studied the economic competitiveness of battery electric trucks, under different conditions of battery performance and charging rates. They found that electric trucks using high performance batteries and rapid charging facilities can be more competitive than conventional diesel trucks. Zhang et al. (2022) compared several options for truck electrification in China, including using batteries, catenaries and fuel cells. They found that plug-in hybrid electric trucks were preferable under current conditions, but that battery and fuel cell vehicles would be preferred if the share of renewable electricity was increased.

Surprisingly little analysis has directly compared different pathways for using forest biomass to power cargo trucks. Hence, the question still rages whether renewable forest residues could most effectively be used to make liquid biofuels or bioelectricity to power trucking fleets, especially when taking into account lifecycle climate impact and primary energy use. We seek to fill this information gap, by developing and applying bottom-up models integrating the forestry, manufacturing, energy and transport sectors, considering both fossil and biogenic CO_2 emissions. Because investment in infrastructure leads to a path dependence, it is important to identify the long-term viability of suitable structures prior to their implementation. The goal of this work is to identify such viable pathways, to influence decision-making towards energy-efficient sustainable technologies with lasting benefits.

2 | DATA AND METHODS

2.1 | Analysis

We compare cargo trucks that provide equivalent service but are powered by different drivetrains and energy supply pathways. We study BEVs that are operated by electricity produced from forest harvest residues in standalone electricity plants or in combined heat and power

(CHP) plants. We also study BEVs powered by a mix of 30% electricity produced from forest residues in standalone plants or in CHP plants, combined with 70% wind electricity, or 50% wind and 20% solar electricity. We also consider liquid-fuel internal combustion vehicles (ICVs) that are operated on fossil diesel, or on DME generated from forest residues. Our system boundaries include the manufacturing of the trucks and batteries, the production of electricity and liquid fuels, and the operation of the vehicles over their lifespans. Our approach looks toward the future, considering technologies likely to be deployed within the coming decade.

We analyse three different sizes of trucks, and we assume a service life of 7 years for all trucks (Holmgren et al., 2021; Trafikverket, 2020). Basic features of the different sizes are shown in Table 1. We assume ICV and BEV trucks have the same gross vehicle mass and cargo mass, which is realistic given modern battery performance and rapid charging rates (Nykvist & Olsson, 2021). Variation of the battery lifespan and chemistry, the technology level of the energy supply, and the source and transport distance of biomass feedstock are analysed in a sensitivity study.

We track four metrics over the lifespan of each truck: (1) Energy content of the forest feedstock used for DME and bioelectricity production. (2) Primary energy use, including all end-use energy from fossil and biogenic sources, and all process losses and fuel cycle energy use. (3) Net CO_2 emissions from truck manufacturing and operation, including emissions from vehicle tailpipes, conversion facilities, feedstock extraction and transportation, as well as avoided natural decay emission if forest residues remain in the forest. (4) Cumulative radiative forcing (CRF), which estimates the energy added to or reduced from the earth system, and is used as a proxy for surface temperature change and hence climate impact.

This climate impact analysis includes all fossil and net biogenic CO_2 emission as well as the timing of these emissions. Net biogenic CO_2 emissions are the sum of actual emissions of biogenic CO_2 from the technological system using the forest feedstock, minus avoided natural decay emissions from the forest ecosystem if the forest feedstock was left in the forest. We focus on CO_2, which is the most significant greenhouse gas globally, and is especially relevant for forest-based biofuels due to their integration with forest carbon cycling. Equation (1) summarizes our calculation of CO_2 emissions, where E_t is total net CO_2 emissions, E_m is fossil CO_2 emissions from manufacturing of trucks, E_o is fossil and biogenic CO_2 emissions from operating the trucks (including emissions from logistics, feedstocks and infrastructure) and E_d is the avoided biogenic CO_2 emission from natural decay of biomass residues left in the forest. We calculate these emissions for each modelled year, and use them as annual inputs to our CRF calculations.

TABLE 1 Modelled internal combustion and battery electric trucks of different sizes.

Truck size	Gross vehicle mass (kg)	Cargo mass (kg)	Annual driving distance (km)
Small	10,000	4100	40,000
Medium	20,000	11,100	60,000
Large	40,000	25,600	125,000

$$E_t = E_m + E_o - E_d. \tag{1}$$

Cumulative radiative forcing is a more accurate measure of climate impact than net CO_2 emissions or global warming potential (GWP), particularly for systems with complex emission patterns, as it includes the timing of CO_2 emissions and removals and their cumulative effects on the global climate. We use the method described by Zetterberg (1993) to calculate CRF, using parameter values updated by IPCC (2013). The calculations use data on annual emissions of CO_2 as well as the natural removal of CO_2 from the atmosphere. These determine how the CO_2 concentration in the atmosphere changes annually, allowing us to calculate marginal changes in instantaneous radiative forcing. These changes are integrated across time and area to estimate overall impacts. We calculate CRF in units of Joules of heat accumulated in the Earth system per m^2 of tropospheric surface area (J/m^2). For more description of the calculation of CRF and its application to forest residues used as bioenergy, see Sathre and Gustavsson (2011).

2.2 | Truck manufacture

Battery electric trucks have large and heavy batteries to store energy, but the remainder of the drivetrain is fairly light, including electric AC induction motors, inverter electronics and transmissions. The fuel tank of ICV trucks is much lighter than the batteries of BEV, due to the high energy content of liquid fuels, but ICV trucks have heavier engines, transmissions, differentials and fuel and exhaust systems (Earl et al., 2018; Nykvist & Olsson, 2021). We model the primary energy use and CO_2 emissions from manufacturing BEV and ICV trucks. Table 2 shows the energy and emissions associated with producing small, medium and large trucks. These values account for production of the batteries.

Energy use for manufacturing the complete ICV trucks, and the BEV chassis excluding battery, is estimated at a rate of 68 MJ per kg of vehicle, based on (EEA, 2018a;

TABLE 2 Primary energy use and CO_2 emissions from manufacturing battery electric vehicle (BEV) and internal combustion vehicle (ICV) trucks of different sizes. BEV numbers include manufacture of two batteries used during the vehicle service life. Using data from EEA (2018a), EECA (2015), UCS (2015), Yazdanie et al. (2016), and Zhang et al. (2022).

	Truck size		
	Small	Medium	Large
Vehicle manufacture energy (GJ/vehicle)			
BEV	578	921	1448
ICV	415	610	1000
Vehicle manufacture emissions (tCO_2/vehicle)			
BEV	53	87	134
ICV	30	44	73

EECA, 2015; Galitsky & Worrell, 2008; UCS, 2015; Yazdanie et al., 2016; Zhang et al., 2022), with energy use for mechanical manufacturing processes assumed proportional to vehicle mass. We assume that manufacturing ICV trucks of a given size is the same for DME and diesel powered trucks.

Battery technology is advancing rapidly, with many promising chemistries and configurations. While BEV production values shown in Table 2 are typical, there is substantial variation in specific energy use and emissions between different lithium-ion battery chemistries (Ambrose & Kendall, 2016). We consider this variability using a composite parameter called 'battery intensity' that considers the trade-offs between more intensive manufacturing processes and improved battery performance. The battery intensity parameter is comprised of the specific energy use for battery production (MJ of primary energy use/kWh of battery capacity), the carbon intensity of battery production ($kgCO_2$/MJ of primary energy use), and the mass density of battery energy storage (Wh of electricity storage/kg of battery mass), which are detailed in Table 3.

Table 4 gives the modelled energy use and CO_2 emissions for manufacturing a single battery for different size trucks. Our main calculations include the use of two medium-intensity batteries per truck service life, one at initial manufacture and one midway through the 7-year service life. Considering advances in battery longevity, we analyse in a sensitivity study the case of one battery used through the full service life of a truck.

2.3 | Truck operation

The modelled energy use for driving 1 km in BEVs and ICVs of different sizes is shown in Table 5. These are

TABLE 3 Exemplar performance characteristics of batteries of different intensities, using data from UCS (2015), EECA (2015), Yazdanie et al. (2016), EEA (2018a), Ambrose and Kendall (2016), Hao et al. (2017), IVL (Swedish Environmental Research Institute) (2019), Cusenza et al. (2019), and Almeida et al. (2019).

	Battery intensity		
Parameter	Low	Medium	High
Specific production energy (MJ/kWh)	400	800	1200
Battery production carbon intensity (kg CO_2/MJ)	100	130	160
Mass density of energy storage (Wh/kg)	100	160	280

TABLE 4 Primary energy use and CO_2 emissions from manufacturing batteries for different size battery electric trucks, with batteries of different energy and CO_2 intensities using data from UCS (2015), EECA (2015), Yazdanie et al. (2016), EEA (2018a), Ambrose and Kendall (2016), Hao et al. (2017), IVL (Swedish Environmental Research Institute) (2019), Cusenza et al. (2019), and Almeida et al. (2019).

	Battery intensity		
Truck size	Low	Medium	High
Battery manufacture energy (GJ/battery)			
Small	64	128	192
Medium	112	224	336
Large	168	336	504
Battery manufacture emissions (tCO_2/battery)			
Small	6	17	31
Medium	11	29	54
Large	17	44	81

TABLE 5 Final energy use for operating different size trucks. Battery electric vehicle (BEV) final energy is electricity, and internal combustion vehicle (ICV) final energy is lower heating value of diesel or dimethyl ether, using data from Earl et al. (2018), Forrest et al. (2020), Hill (2020), Liimatainen et al. (2019), Liu et al. (2021), Lombardi et al. (2020), Nykvist and Olsson (2021), Nyland and Erkkilä (2005), Yazdanie et al. (2016), and Zhang et al. (2022).

	Truck size		
	Small	Medium	Large
Operating energy use (MJ/km)			
BEV	2.5	4.0	5.8
ICV	7.0	9.3	12.8

average values across the lifecycle of the trucks considering all driving cycles and load factors. BEV energy is electricity and includes grid-to-vehicle charging losses. ICV energy is the lower heating value (LHV) of processed fuels delivered to fuelling stations. We assume that DME and diesel trucks of the same size have the same final energy use. BEV energy use as a percentage of ICV energy use is 36%, 43% and 45% for small, medium and large trucks. Electric trucks gain greater efficiency advantage over ICV trucks in smaller trucks used for urban cargo transport with frequent stops. The advantage is reduced in heavy trucks under steady long-distance use.

We assume that all trucks will need the same maintenance and service, whether powered by DME, electricity or diesel. BEVs may need less maintenance than ICVs (Harto, 2020), however, this will have little effect on CO_2 emissions and energy use, with greater impact on costs.

We compare 16 energy pathways to supply the final energy use. For BEVs, we study bioelectricity generated in stand-alone plants, fuelled by forest harvest residues. We also consider bioelectricity generated in cogeneration plants with CHP production, fuelled by forest harvest residues. In two pathways, 30% of the stand-alone bioelectricity or 30% of CHP bioelectricity is integrated with 70% wind electricity. We also consider 30% bioelectricity (from stand-alone or CHP plants) integrated with 50% wind electricity and 20% solar electricity. For ICVs, we consider DME that is synthesized from gasified forest harvest residues, and fossil diesel fuel that is refined from crude oil. Each of these eight pathways is analysed both with and without carbon capture and storage (CCS).

To understand the importance of technological progress, we study each energy pathway employing both conventional and emerging technology levels of energy supply. In our main case we consider emerging technologies that are likely to be deployed at greater scale during the coming 10 years. We also conduct a sensitivity study employing existing conventional technologies, to determine the dependence of our results on technology advancement. Efficiencies for the emerging and conventional technology levels are summarized in Table 6, and described in detail below. The 'biomass-to-x' conversion efficiency parameters are based on the LHV of the biomass feedstock. The CCS energy penalty is the increased fuel input per unit of delivered product. The input for wind electricity is the primary energy used for wind turbine manufacture and onshore installation, expressed as a percentage of the electricity generated during the turbine's service life. The input for solar electricity is the primary energy used for manufacturing and installing photovoltaic panels and associated hardware, expressed as a percentage of the electricity generated during the panels' service life. We note that the efficiencies listed in Table 6 for solar PV are applicable to Swedish conditions. Solar PV performance would be better in sunnier locations.

Dimethyl ether is produced by gasifying lignocellulosic feedstocks followed by catalytic synthesis. DME synthesis is typically done in a two-step process where methanol is first produced and is then dehydrated to produce DME (Hankin & Shah, 2017). It can also be produced in a single reactor using bifunctional catalysts (Fortin et al., 2020). Our modelling of DME generation uses data from seven stand-alone facilities of different scale and configuration

TABLE 6 Energy system efficiencies for emerging technology level used in the main-case analysis, and for conventional technology level used in the sensitivity study.

	Emerging, %	Conventional, %	Source
Biomass-to-DME	66	59	Lönnqvist et al. (2021), McKone et al. (2015), Nguyen and Gustavsson (2020), NREL (2015)
Stand-alone biomass-to-electricity	50	40	Danish Energy Agency (2020), Nguyen and Gustavsson (2020)
CHP biomass-to-electricity	42	31	Danish Energy Agency (2020), Nguyen and Gustavsson (2020)
Stand-alone biomass-to-heat	108	108	Danish Energy Agency (2020), Nguyen and Gustavsson (2020)
CHP biomass-to-heat	48	57	Danish Energy Agency (2020), Nguyen and Gustavsson (2020)
Input for wind electricity	3	5	Bonou et al. (2016), Chipindula et al. (2018), Davidsson et al. (2012), Mendecka and Lombardi (2019)
Input for solar electricity	5	13	Zhou and Carbajales-Dale (2018)
Diesel fuel cycle input	9	9	Gode et al. (2011)
CCS energy penalty	20	24	Wilcox (2012)

Abbreviations: CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

(Lönnqvist et al., 2021; McKone et al., 2015; Nguyen & Gustavsson, 2020; NREL, 2015). We define our main-case emerging technology level as the most efficient of the seven plants. Our sensitivity study of conventional technology is based on the average of the seven plants. These correspond to specific feedstock use of 1.52 MJ of biomass feedstock per MJ of DME for the main-case emerging technology, and 1.69 MJ per MJ for the conventional technology. Primary energy use is 1.74 MJ of primary energy per MJ of DME for the emerging technology, and 2.00 MJ per MJ for the conventional technology. These primary energy use values imply conversion efficiencies of 57% and 50% respectively.

The energy efficiency and power ratings of DME and diesel engines are virtually the same, although the fuel systems are somewhat different. The density of DME is about 80% of diesel fuel, and specific energy content (LHV) is about 70%. Therefore, about double the fuel volume of DME is needed, in relation to fossil diesel, to yield the same driving distance. Trucks using DME thus require a fuel tank twice as large as that needed for diesel trucks.

The dispatchable nature of bioelectricity can help to integrate intermittent sources of electricity like wind and solar. We consider bioelectricity generation in both stand-alone power plants and in CHP plants. For stand-alone electricity production, as a main-case emerging technology we use state-of-the-art biomass integrated gasification combined cycle (BIGCC) systems that convert forest biomass to electricity at a 50% conversion efficiency (Nguyen & Gustavsson, 2020). In our sensitivity study of conventional technology, we use steam boiler systems with a 40% conversion efficiency (Danish Energy Agency, 2020).

For CHP production, our main-case emerging technology is state-of-the-art CHP-BIGCC systems for converting forest biomass to both heat and electricity, and in a sensitivity study we consider conventional steam boiler CHP technology. We assume all the cogenerated heat is used, for example for industry and district heating. The heat demand typically limits the use of cogeneration, so the cogeneration system producing the most electricity per unit of heat (i.e. emerging technology) is used to calculate the amount of electricity and heat used in the comparisons. This is equal to 1.00 unit of electricity and 1.14 unit of heat, which we define as the functional unit for comparison. For the emerging technology without CCS, we calculate how much biomass is needed to fulfil the functional unit using stand-alone plants (3.06 units) and using CHP plant (2.38 units). The ratio of these amounts is used in the modelling of biomass use in CHP plants, that is, CHP plants use 78% of the biomass used in stand-alone plants. For the conventional technology without CCS, we calculate how much biomass is needed to fulfil the functional unit using stand-alone electricity and heat plants (3.56 units). For CHP plants, 2.01 units of biomass are needed to produce the required heat, while simultaneously cogenerating 0.62 units of electricity. For the remaining 0.38 units of required electricity, we assume that conventional stand-alone plants are used, needing 0.94 units of biomass. Thus, a total of 2.95 units of biomass are needed for the CHP system, giving a ratio of 0.83 that is used in the modelling of biomass use in conventional CHP plants. For pathways with CCS, we increase the biomass use in all plants (CHP, stand-alone heat and stand-alone electricity) based on the energy penalty which is defined as the additional energy needed to produce the same product. The calculation is summarized in Table 7.

For electricity generated by wind turbines, our emerging technology considers state-of-the-art onshore turbines with lifecycle primary energy input of 0.029 MJ per MJ of generated electricity, and carbon intensity of 2.2 g CO_{2e} per MJ of generated electricity (Bonou et al., 2016; Chipindula et al., 2018; Davidsson et al., 2012; Mendecka & Lombardi, 2019). In our sensitivity study of conventional technology, we consider more typical values of 0.05 MJ per MJ of generated electricity, and 3.9 g CO_{2e} per MJ of generated electricity.

For photovoltaic solar power, lifecycle primary energy and carbon intensity depend strongly on location, as solar insolation varies widely. We assume Swedish conditions with modest insolation, with emerging technology lifecycle primary energy input of 0.05 MJ per MJ of generated electricity and carbon intensity of 14 g CO_{2e} per MJ of generated electricity (Finnegan et al., 2018; Hsu et al., 2012; Kim et al., 2012; Zhou & Carbajales-Dale, 2018). Our sensitivity study of conventional technology has higher values of 0.13 MJ per MJ of generated electricity, and 25 g CO_{2e} per MJ of generated electricity.

We assume an integration of 30% dispatchable bioelectricity with 70% intermittent electricity, as means to maintain stability and continuity of the power grid. The intermittent portion is 70% wind power in the Wind + Bioelectricity and Wind + CHP pathways, and is 50% wind power plus 20% solar power in the Solar + Wind + Bioelectricity and Solar + Wind + CHP pathways. Vehicle-to-grid (V2G) integration can also be used for grid stability and optimization, by utilizing truck batteries to store grid electricity. We do not explicitly consider V2G integration here.

For diesel fuel, fuel cycle emissions from the transport and refining of crude oil are 10.3 g CO_2 per MJ of diesel (Masnadi et al., 2018), and tailpipe emissions are 73.6 g CO_2 per MJ of diesel (Gode et al., 2011). Fuel cycle primary energy use is 0.09 MJ per MJ of diesel (Gode et al., 2011).

Carbon capture and storage is intended to capture CO_2 that would otherwise enter the atmosphere, and direct

TABLE 7 Calculation of relative amounts of biomass feedstock used in stand-alone and CHP plants.

	Production (units)		Biomass used (units)			
	Electricity	Heat	Stand-alone electricity	Stand-alone heat	CHP	Total
Emerging (no CCS)						
Stand-alone	1.00	1.14	2.00	1.06	—	3.06
CHP	1.00	1.14	—	—	2.38	2.38
Ratio						78%
Emerging (CCS)						
Stand-alone	1.00	1.14	2.40	1.27	—	3.67
CHP	1.00	1.14	—	—	2.86	2.86
Ratio						78%
Conventional (no CCS)						
Stand-alone	1.00	1.14	2.50	1.06	—	3.56
CHP	1.00	1.14	0.94	—	2.01	2.95
Ratio						83%
Conventional (CCS)						
Stand-alone	1.00	1.14	3.10	1.31	—	4.41
CHP	1.00	1.14	1.17	—	2.49	3.66
Ratio						83%

Abbreviations: CCS, carbon capture and storage; CHP, combined heat and power.

it to long-term storage in geological formations. There is an energy cost when CCS is implemented, because of the inherent thermodynamic work required to separate CO_2 from gas mixtures. This energy penalty is typically defined as the percent increased fuel input per unit of delivered product, and its magnitude depends on the compounds, concentrations and processes involved (Sathre et al., 2011). CO_2 concentration is higher during the gasification process than during post-combustion capture or direct air capture, therefore the work of separation is lower at this stage. Biomass gasification is used in both BIGCC and DME plants, thus we assume that both processes have the same energy penalty. We assume the energy penalty is 20% and 24%, respectively, for emerging and conventional CCS technologies (Wilcox, 2012). Conventional steam turbine plants employ combustion rather than gasification, and are subject to the higher 24% energy penalty. For all processes we assume that 90% of the CO_2 is captured and permanently sequestered. CCS cannot be practically implemented in small-scale mobile applications, thus we do not consider capture of tailpipe emissions from diesel and DME trucks. We do, however, consider the capture of process emissions from petroleum refineries and DME generation. There are relatively few process CO_2 emissions from petroleum refineries that produce numerous co-products, but DME generation is less efficient and has significant emissions that may be captured.

2.4 | Biomass supply

As biomass feedstock to produce electricity and DME, we use forest residues from final fellings. Approximately 10 TWh of slash (i.e. branches and treetops) is currently harvested each year from Swedish forests, although it is estimated that annual potential slash harvest could reach 65 TWh, and combined slash and stump harvest could reach 107 TWh per year (IRENA, 2019). To avoid environmental degradation from increased residue harvesting, it may be necessary to take measures such as ash recycling and restricting harvest on some sites (de Jong et al., 2017). The Swedish Forest Agency has guidelines for extracting forest fuels and applying recycled ash (Swedish Forest Agency, 2019). This analysis is not limited to Swedish forestry, and is also relevant for forest residues harvested in other regions with similar boreal forest conditions under active management.

Harvesting and transporting the biomass feedstock requires energy, and Table 8 details the specific fossil fuel consumption for obtaining slash and stumps. Slash is the

TABLE 8 Specific fossil energy use for harvesting and transporting forest residues, per dry ton of delivered biomass (Gustavsson et al., 2015).

	MJ per ton	
	Slash	**Stumps**
Local transport		
Recovery (lifting, bunching, forwarding)	189	569
Roadside chipping	77	96
Truck transport (100 km)	145	145
Total	411	810
International transport		
Local transport to terminal	411	810
Train transport (250 km)	19	19
Ship transport (1000 km)	56	56
Total	486	885

biomass feedstock considered in our main case. In our sensitivity study we include stumps as feedstock, which need more energy to harvest. This difference is because slash harvesting involves simply picking up cut branches and treetops from the forest floor, while stump harvesting requires physically ripping stumps from the soil. All harvest residue is assumed to have a moisture content of 50%, a specific heat of 16.8 MJ per kg dry mass, and a carbon content of 50% by dry mass. In our main case we assume the biomass feedstock is transported internationally, first 100 km by truck to a depot, then 250 km by train to a port, and finally 1000 km by ship to its point of use. In our sensitivity study we consider local supply of the biomass, assuming truck transport of 100 km.

2.5 | Forest biomass decay

When considering the climate impact of harvesting forest residues for bioenergy, an important question is what would have happened to the residues if they had not been harvested and instead were left in the forest (Sathre & Gustavsson, 2011). Biomass that is removed from the forest and burned or gasified will immediately release its stored carbon into the atmosphere. In contrast, if the biomass remains in the forest it will decay naturally and release its stored carbon over a time span of decades. As a part of our study, we account for all biogenic CO_2 emissions from the bioenergy pathways, and the consequent avoided CO_2 emissions from the natural decay of the forest residues. The net total biogenic CO_2 emission is the emission from the bioenergy pathways, minus the avoided CO_2 emissions that would have occurred if the slash or stumps had remained in the forest. We track these emissions over a 100-year period.

We use the Q model (Rolff & Ågren, 1999) to estimate the decay rate of forest residues that are left in the forest. We use model parameter settings for central Sweden (Hyvönen & Ågren, 2001). This model is an application of the continuous quality theory, in which biomass entering the soil decays at rates that vary over time for stems, branches, needles and roots. We estimate the mass of these fractions in the harvested residues using biomass expansion factors (Lehtonen et al., 2004), and assume that 50% of slash is from Scots pine (*Pinus silvestris*) trees and 50% from Norway spruce (*Picea abies*) trees, that treetops comprise 10% of the total stem mass, and that 80% of needles fall off before the slash is removed from the forest.

2.6 | Truck end-of-life

The average age of heavy duty vehicles in use in Europe was 8.13 years in 2014, an increase from 7.52 years in 2000 (EEA, 2018b). Data are sparse on the end-of-life fate of heavy trucks, which are not covered by the European Union's End of Life Vehicles Directive that is focused on smaller vehicles. About 94% by weight of scrapped passenger cars and light goods vehicles was reused, material recycled or used for energy in the EU in 2017 (Eurostat, 2020). The Swedish number was 97%. It is expected that rates of material recovery and reuse are similarly high for heavy duty vehicles.

As the BEV truck market expands it will create additional end-of-life possibilities for vehicle batteries. Using second-life BEV batteries for stationary grid storage can help the integration of solar and wind electricity (Sathre et al., 2015). Second-life BEV batteries can also be used to increase the charging capacity of electric charging stations, reducing the need to expand grid electrical capacity. The more rapidly that BEV use scales up, the quicker that second-life batteries can be used for grid storage. Materials can be recovered from post-use lithium-ion batteries, using pyro- and hydrometallurgical recycling technologies, used separately or in combination (Lv et al., 2018). Many external sectors affect the post-use vehicle management, because of the diversity of post-use components and materials. The end-of-life stage of trucks is not included in our modelling.

3 | RESULTS EXCLUDING AVOIDED BIOGENIC DECAY CO_2 EMISSION

3.1 | Main-case results

In the main-case analysis of electric trucks, we use two medium-intensity batteries during the 7-year truck lifespan. The forest slash, transported internationally, is converted to electricity, heat and DME by using emerging energy systems. The same technology level is used for wind and solar electricity and carbon capture processes.

Specific CO_2 emissions from main-case operation of trucks using 16 different energy pathways are shown in Figure 1, in units of g CO_2 per km. Figure 1a distinguishes between small-, medium- and large-size trucks. The lowest and highest pathway emissions are from the Wind + CHP CCS and DME pathways, with 43 and 1570 g CO_2 per km for medium-size trucks respectively. Figure 1b distinguishes between locations of emission from a medium-size truck: the vehicle tailpipe, the

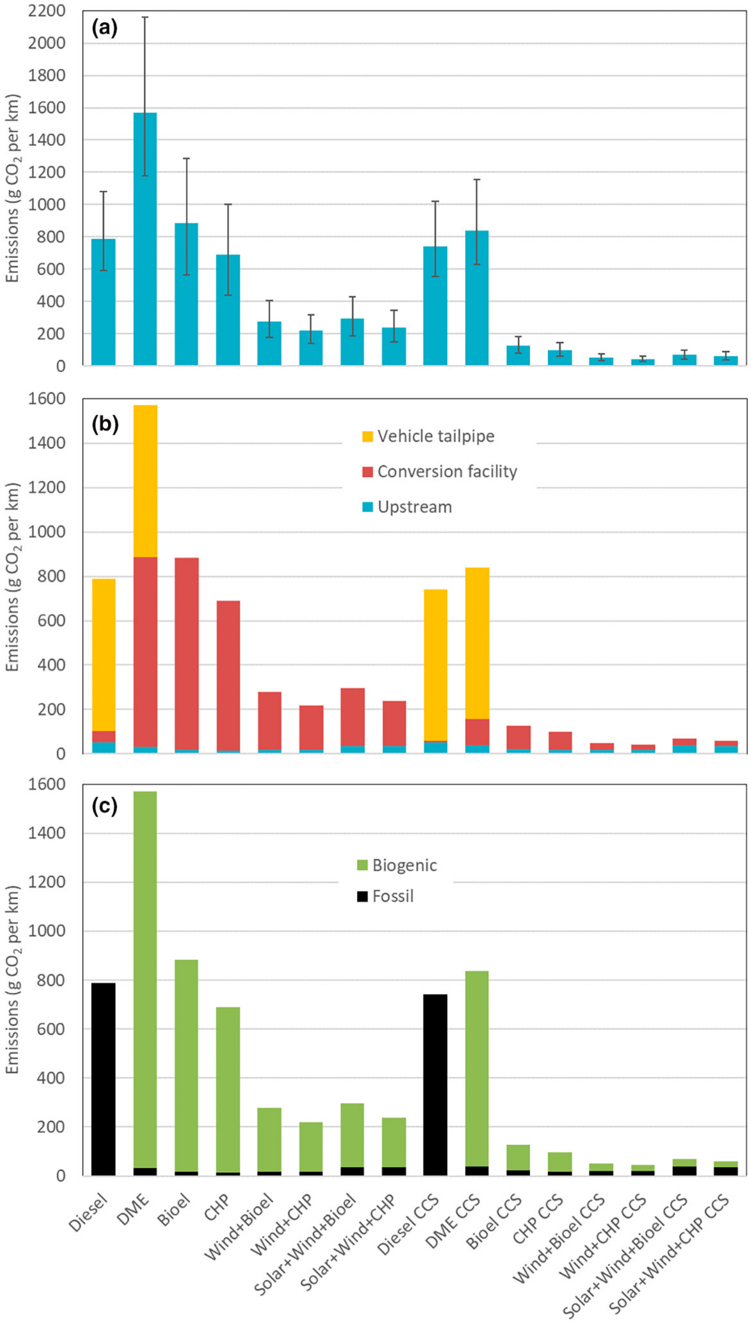

FIGURE 1 Specific CO_2 emissions (g CO_2 per km) from operating a truck using different energy pathways. (a) Main bars show total emissions from medium-size trucks, and error bars show total emissions from small and large trucks. (b) Medium-size truck emissions from different locations of the energy pathways: upstream, conversion facility and vehicle tailpipe. (c) Medium-size truck emissions from biogenic and fossil sources. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

conversion plant, and the upstream sources including forest operations, crude oil supply and wind/solar infrastructure. Using CCS significantly decreases CO_2 emissions from Bioelectricity and CHP pathways, while the reduction from DME and Diesel pathways is low because tailpipe CO_2 emissions are not captured due to technical reasons. Figure 1c distinguishes between fossil and biogenic CO_2 emissions. The fossil CO_2 emissions are very low for the non-diesel pathways, coming from biomass harvest and transport, and infrastructure for solar and wind installations. They equal about 1% to 5% of the emission from Diesel pathways, with the lowest fossil emissions coming from the Wind + CHP pathway, and the highest coming from the DME pathway.

Figure 2 shows the cumulative biomass feedstock used to operate a medium-size truck for 7 years for the 14 pathways using biomass, wind and solar. The DME pathways use the most biomass, and Wind + CHP pathways use the least. The difference between the pathways using Wind and those using Wind + Solar is insignificant and is not visible in the figures. The biomass use increases in pathways with CCS, to cover the energy penalty. No biomass is used in the Diesel pathways.

The total cumulative primary energy use is highest for manufacturing and driving a DME-fuelled truck for 7 years, about four times greater compared to the pathways using wind and solar electricity (Figure 3). The ICVs have somewhat lower manufacture energy use than the BEVs, mainly as a result of the battery production. However, the higher manufacture energy use of BEVs is quickly balanced by the BEV operational energy which is much lower than the ICVs. The battery replacement during the service life of BEVs has a modest impact on primary energy use, indicated by the discontinuous slope of the lines in Figure 3 midway through the service life of BEV trucks. The primary energy use for the DME pathway increases significantly with CCS, and the CHP and Bioelectricity pathways also exhibit a substantial CCS energy penalty. Table 9 shows the total lifecycle primary energy use of different sized trucks powered by different energy pathways.

The cumulative biogenic and fossil CO_2 emissions from manufacture and 7-year operation of a medium-size

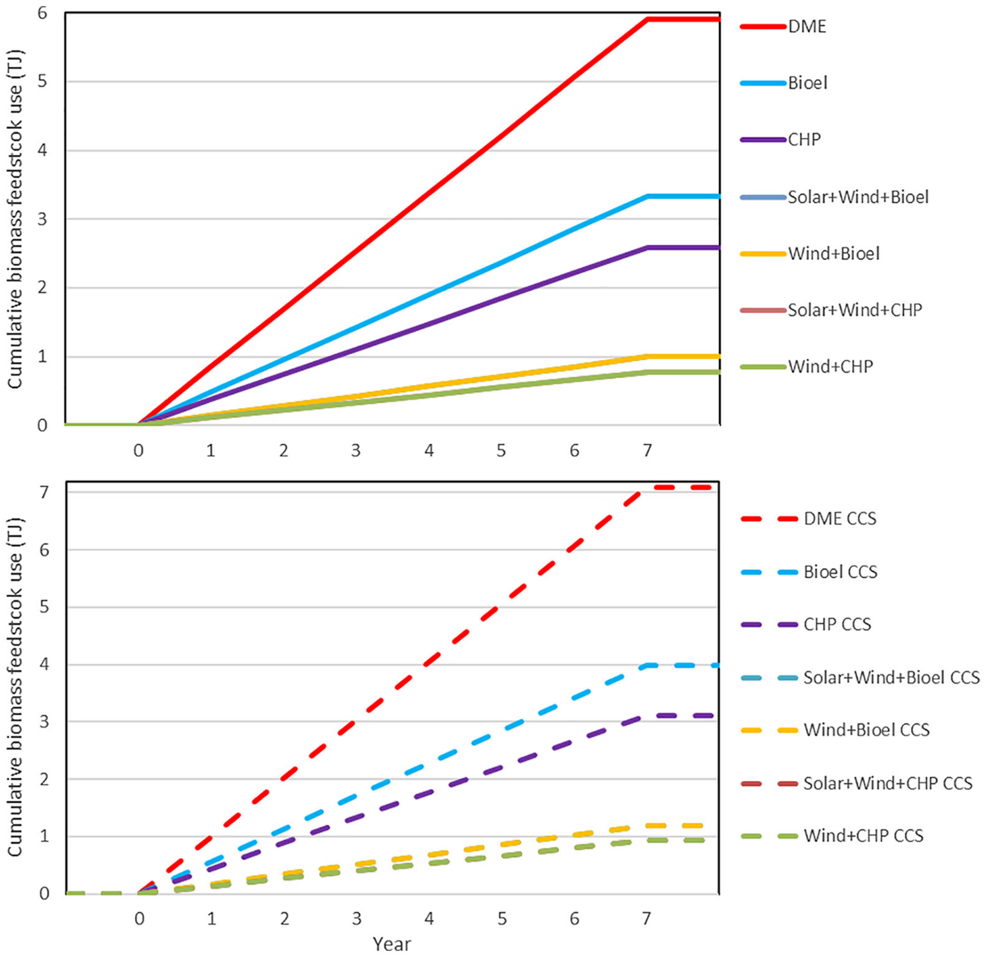

FIGURE 2 Cumulative biomass feedstock used for operating a medium-size truck during 7 years. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

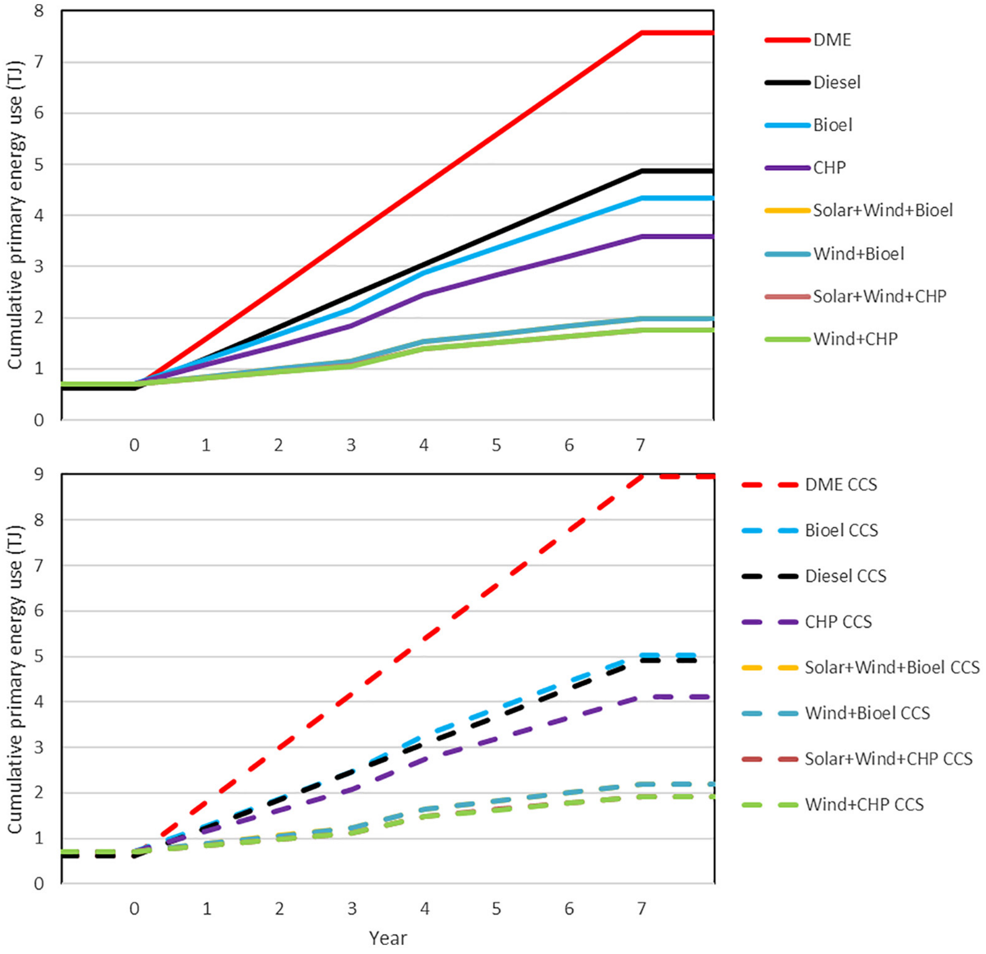

FIGURE 3 Cumulative primary energy used for manufacturing and operating a medium-size truck for 7 years. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

truck show that diesel and CHP have roughly the same CO_2 emissions without CCS (Figure 4). The DME pathways have the highest emissions, both with and without CCS. The pathways using wind and solar all have low emissions, with and without CCS. Bioelectricity and CHP pathways also have very low emissions when using CCS. Table 10 shows total lifecycle CO_2 emissions for different size trucks powered by different energy pathways, excluding avoided forest decay CO_2 emissions.

The CO_2 emissions in Figure 4 are converted to CRF over 100 years and shown in Figure 5. The CRF follows closely the pattern of the cumulative CO_2 emissions shown in Figure 4.

3.2 | Sensitivity study results

In our sensitivity study we vary each parameter one at a time from its main-case value, and calculate the effects on the four metrics. The parameters considered in the sensitivity study are summarized in Table 11. Forest decay emissions are not considered.

The results on the four metrics are shown in Tables S1–S4. The two battery-related parameters only affect the manufacturing phase of BEVs. The use of only one battery during the truck service life instead of two batteries decreases the primary energy use by roughly 5% for the Bioelectricity pathway, and by roughly 13% for the more energy-efficient Wind + CHP pathway. The large truck is modelled to travel 875,000 km during its 7-year career, so battery replacement during the truck service life may be needed, although progress is being made on Li-ion cells that could power a BEV for a million kilometres (Harlow et al., 2019). The effect of varied battery intensity is roughly equal to that of a single battery replacement. Different battery chemistries, for example LFP, NMC and LMO, have clearly different production impacts (Almeida et al., 2019; Hao et al., 2017) but the lifecycle impact of these differences is modest.

Stumps are used as biomass feedstock in the sensitivity study, instead of slash. Stumps need about twice as much energy to harvest and chip, compared to slash (see Table 8). This difference has little impact on the overall results. A more significant difference is the rate of natural decay if

TABLE 9 Total lifecycle primary energy use of different sized trucks, including manufacture and operation for 7 years.

	Small	Medium	Large
Lifecycle primary energy use (TJ)			
Diesel	2.54	4.86	13.2
Diesel CCS	2.57	4.92	13.3
DME	3.89	7.57	20.9
DME CCS	4.59	8.96	24.9
Bioel	2.03	4.34	11.8
Bioel CCS	2.32	5.03	13.9
CHP	1.71	3.59	9.52
CHP CCS	1.93	4.12	11.1
Wind + Bioel	1.03	1.98	4.66
Wind + Bioel CCS	1.11	2.19	5.28
Wind + CHP	0.93	1.75	3.97
Wind + CHP CCS	1.00	1.91	4.46
Solar + Wind + Bioel	1.03	1.99	4.68
Solar + Wind + Bioel CCS	1.12	2.19	5.30
Solar + Wind + CHP	0.93	1.76	3.99
Solar + Wind + CHP CCS	1.00	1.92	4.48

Abbreviations: CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

slash and stumps are left in the forest, which is analysed in Section 4. The transport distance of the biomass has little impact on the metrics, showing that local or international sourcing of biomass feedstock is not a critical factor.

In our main-case analysis we assume that emerging energy technologies will continue to be developed and deployed, leading to greater efficiencies in biomass-to-electricity, biomass-to-heat, biomass-to-DME, wind and solar electricity and carbon capture processes. The sensitivity study uses currently conventional energy technologies, resulting in substantially reduced overall performance due to lower conversion efficiencies, particularly increasing the use of biomass and primary energy. Nevertheless, the relative ranking of the renewable-based pathways is independent of specific technology advancement, making our general conclusions robust.

4 | RESULTS INCLUDING AVOIDED BIOGENIC DECAY CO_2 EMISSION

As discussed in Section 2.5, biomass residues that remain in the forest will decay naturally over time and release their carbon content into the atmosphere. If these residues are harvested and used as bioenergy, the stored biogenic carbon is released immediately from the technical system, and the decay emissions from the forest are avoided. Here we calculate the net biogenic CO_2 emissions, by subtracting the avoided CO_2 emissions coming from natural decay of forest residues, from the actual biogenic emissions coming from the combusted/gasified biomass. Net emissions therefore decrease over time, as the gradual emissions from natural decay are avoided. Figure 6 shows the cumulative CO_2 emissions from the natural decay of slash and stumps used in seven bioenergy pathways without CCS, for one medium-size truck operated for 7 years, if the biomass had been left in the forest and not used for bioenergy. The rate of decay is quite slow, thus our analysis covers a 100-year time period. Slash decays faster than stumps, but after 100 years both have almost completely decomposed. Pathways without CCS (not shown in Figure 5) have similar decay emissions, but are proportionally higher due to the greater amounts of biomass required.

Figure 7 shows the lifecycle cumulative CO_2 emissions of a truck using either of eight energy pathways without CCS, including the avoided CO_2 emissions from natural decay of forest slash. The trucks are driven for the first 7 years, and the avoided decay emissions from each year's forest slash are followed over 100 years. For the seven pathways that use slash, their cumulative CO_2 emissions are greatest at Year 7, the final year of truck operation, and then start to decrease due to the growing avoided decay emissions. DME peaks at 643 t CO_2, Bioelectricity at 424 t CO_2, CHP at 349 t CO_2, Wind + Bioelectricity at 191 t CO_2 and Wind + CHP peaks at 168 t CO_2. The difference between pathways using Wind and Wind + Solar is insignificant and not visible in the figure. When using stumps (shown in Figure S1), the peaks are higher because the avoided decay emissions occur later in time (see Figure 6). After 100 years the decay of slash is mostly completed and a small amount of carbon has been transformed to soil carbon, so the impact of avoided CO_2 emissions for different biomass pathways is about the same, and the remaining emissions are from the initial truck manufacturing and the fossil emissions from forest operations. Hence, the DME pathway has the lowest net emissions in the long run because it has the lowest manufacturing emissions of the biomass pathways. In contrast, emissions from the Diesel pathway increase linearly during the 7 years of operation, then remain constant at 375 t CO_2 for the duration. Summary statistics for cumulative emissions after 100 years from manufacturing, operation and forest decay are presented in Table S5.

Figure 8 shows the CRF for eight energy pathways without CCS, based on the CO_2 emissions shown in Figure 7. The DME and Diesel pathways have very similar CRF, showing that from a climate perspective, it is no better to use forest residues to produce DME than to let the residues remain in the forest and use diesel. The

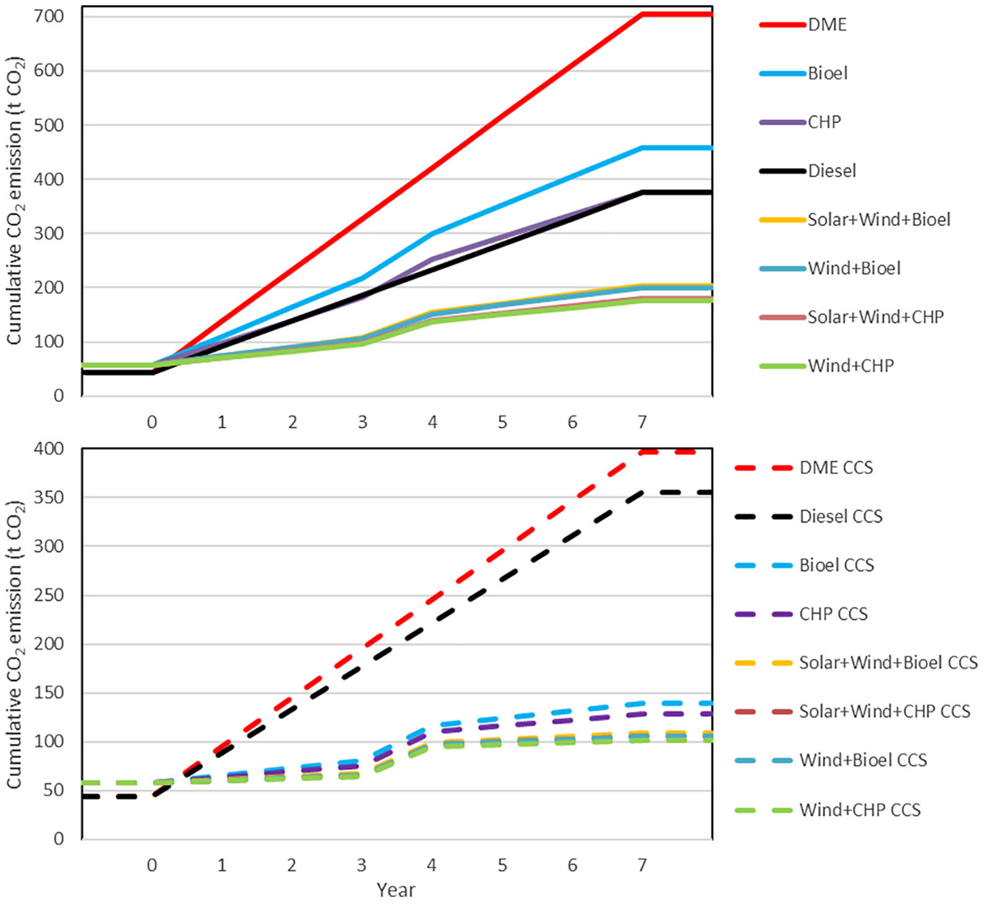

FIGURE 4 Cumulative biogenic and fossil CO_2 emissions from manufacturing and operating a medium-size truck for 7 years, excluding avoided forest decay CO_2 emissions. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

Wind + CHP pathway has the lowest CRF, with a climate impact less than half of the DME and Diesel paths. There is very little difference between the pathways using Wind and those using Wind + Solar. When stumps are used instead of slash, the CRF is greater in proportion to the biomass used, therefore is much higher in the DME pathway (see Figure S2).

Figure 9 shows the cumulative CO_2 emissions including avoided CO_2 emissions from decay of forest slash used in eight energy pathways with CCS. Net negative CO_2 emissions occur when BECCS is used. Pathways that use more biomass feedstock have greater quantities of captured and sequestered CO_2. Hence, the DME pathway has the most negative CO_2 emission, followed by other bioenergy paths. Although the DME pathway uses much more biomass feedstock than the other pathways (Figure 6), its cumulative emissions are only marginally more negative than the Bioelectricity and CHP pathways because the DME tailpipe emissions cannot be captured. The cumulative emissions of the Diesel pathway peak after 7 years of operation and then remain constant at 355 t CO_2, somewhat lower than without CCS as some CO_2 is captured at the refinery. Summary statistics for cumulative emissions after 100 years from manufacturing, operation and forest decay are presented in Table S5.

Figure 10 shows the CRF for eight energy pathways with CCS. The Diesel CCS pathway has the highest CRF. Analogous figures for stumps are shown in Figure S3 and S4. CRF from DME CCS is much higher when stumps are used instead of slash. This pronounced difference is because the stumps decay more slowly than slash, therefore fewer emissions are avoided early in the 100-year period and more heat energy is accumulated in the earth system. The CHP CCS and Bioelectricity CCS pathways using slash have clearly negative CRF after 100 years, leading to global cooling, because the cumulative CO_2 emissions peaked early and became significantly negative (see Figure 9).

5 | EFFICIENT UTILIZATION OF THE AVAILABLE BIOMASS SUPPLY

As forest land area and hence forest biomass is a limited resource, an analysis of final energy use should be understood in the context of biomass supply to avoid misleading results. If more biomass is supplied to one part of the

TABLE 10 Total lifecycle CO_2 emissions for manufacture and operation of different size trucks, excluding avoided forest decay CO_2 emissions.

	Small	Medium	Large
Lifecycle CO_2 emissions (t CO_2)			
Diesel	196	375	1020
Diesel CCS	186	356	965
DME	360	704	1964
DME CCS	206	397	1082
Bioel	210	458	1260
Bioel CCS	75	140	295
CHP	175	376	1011
CHP CCS	70	128	259
Wind + Bioel	101	201	480
Wind + Bioel CCS	61	105	190
Wind + CHP	91	176	405
Wind + CHP CCS	59	102	179
Solar + Wind + Bioel	103	205	492
Solar + Wind + Bioel CCS	62	109	202
Solar + Wind + CHP	92	180	417
Solar + Wind + CHP CCS	61	106	191

Abbreviations: CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

economy, then less biomass can be used in other parts. To account for these complexities, we conduct a scenario analysis where a fixed amount of forest biomass is allocated to powering the truck transport sector. When more efficient transport pathways are used, the given biomass is sufficient for transport and some is left over for other purposes. When less efficient pathways are used, the given biomass is insufficient and additional fossil fuel is needed for transport.

Trucks in Sweden travel a total of about 4.74 billion km per year (average of latest 6 years, 2015–2020, data from Trafikanalys, 2019). The greatest share of this (3.60 billion km) is by large trucks (>26 t total weight), while medium trucks (16 to 26 t total weight) travel about 0.81 billion km per year, and small trucks (3.5 to 16 t total weight) travel only 0.33 billion km per year on Swedish roads. The amount of forest biomass required to supply this annual transport, for the 14 non-fossil energy pathways for different truck sizes, is shown in Figure 11.

In our scenario analysis we allocate 20 TWh of forest slash each year to drive a truck fleet 4.74 billion km. If driving this distance requires more energy than 20 TWh, diesel is used to supplement the allocated slash. If less biomass is needed to power the truck fleet, we use the surplus biomass to produce electricity that substitutes for fossil

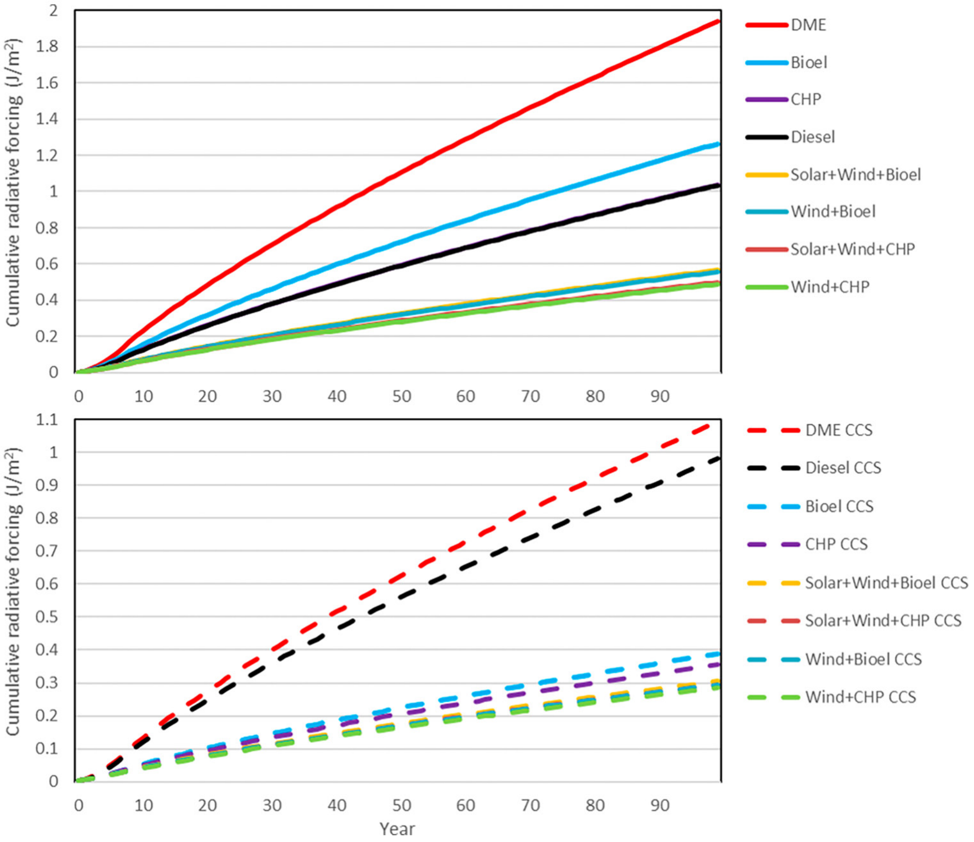

FIGURE 5 Cumulative radiative forcing resulting from emissions shown in Figure 4. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

TABLE 11 Summary of sensitivity study parameters.

Parameter	Main case	High case	Low case
Battery lifespan	2 per truck	NA	1 per truck
Battery chemistry	Medium intensity	High intensity	Low intensity
Biomass source	Forest harvest slash	Forest harvest stumps	NA
Biomass transport	International	NA	Local
Energy technology level	Emerging	Conventional	NA

Abbreviation: NA, not applicable.

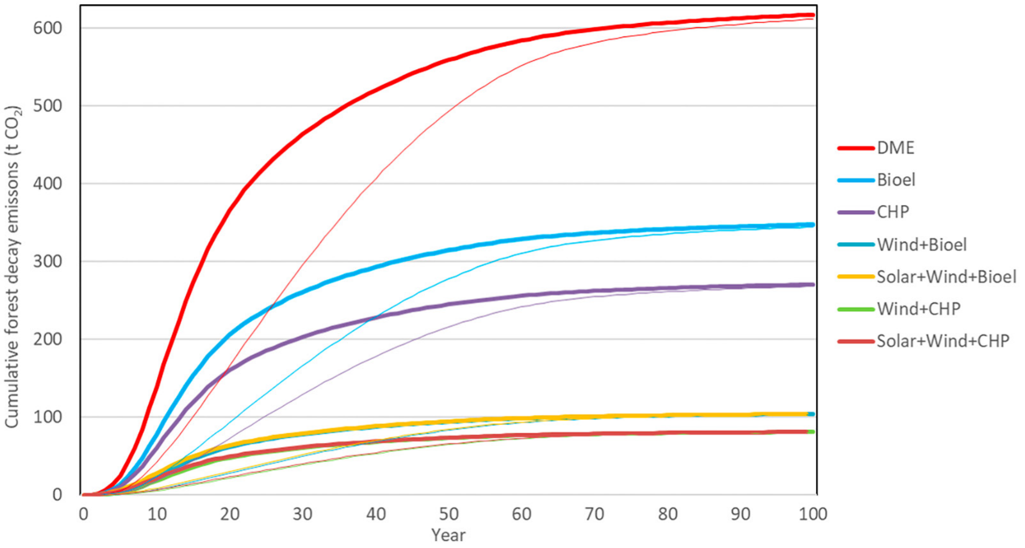

FIGURE 6 Cumulative emissions of biogenic CO_2 from the natural decay of forest residues used in seven different truck bioenergy pathways for 7 years, if the residues had been left in the forest and not used for bioenergy. The thin lines show stump decay, while the thick lines show slash decay. CHP, combined heat and power; DME, dimethyl ether.

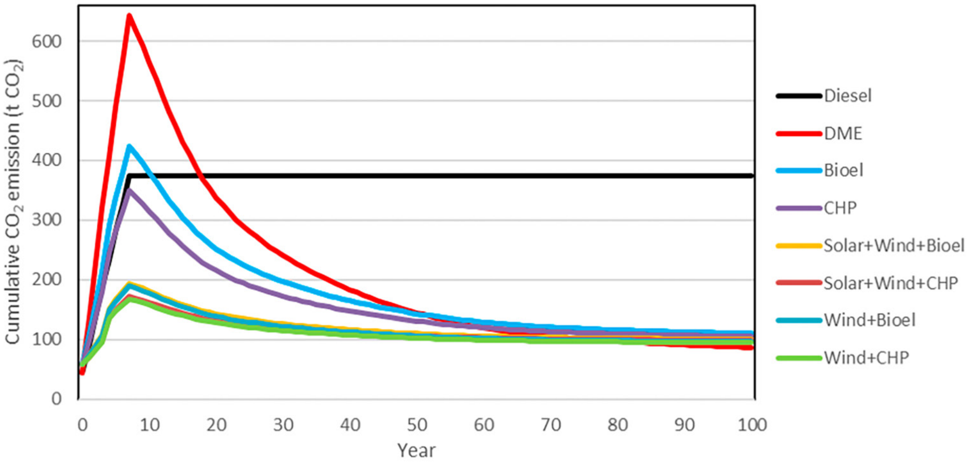

FIGURE 7 Cumulative CO_2 emissions from eight energy pathways without CCS, including avoided decay emissions from forest slash. The trucks are driven for the first 7 years. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

gas-fired electricity. This electricity is in addition to the electricity used for transport in the BEV pathways. We assume the additional electricity is generated in stand-alone BIGCC powerplants with or without CCS. The electricity substitutes fossil gas electricity generated in combined cycle plants at 60% efficiency using gas emitting 69 kg CO_2

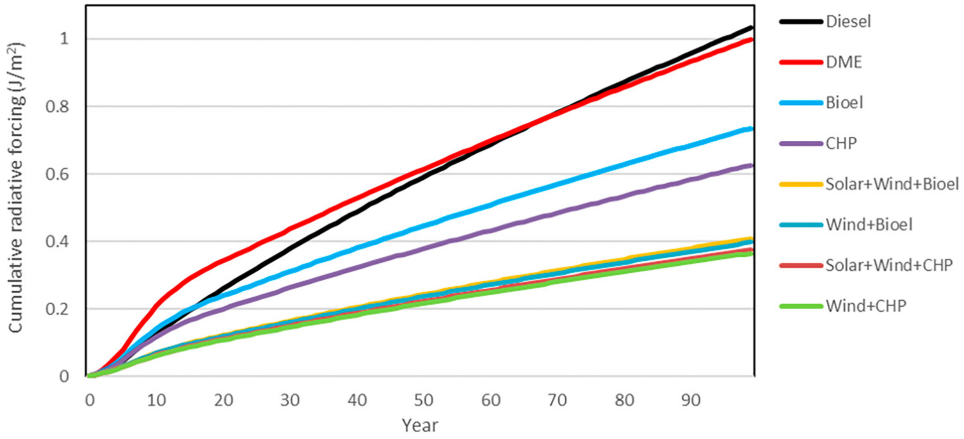

FIGURE 8 Cumulative radiative forcing resulting from emissions shown in Figure 7. CHP, combined heat and power; DME, dimethyl ether.

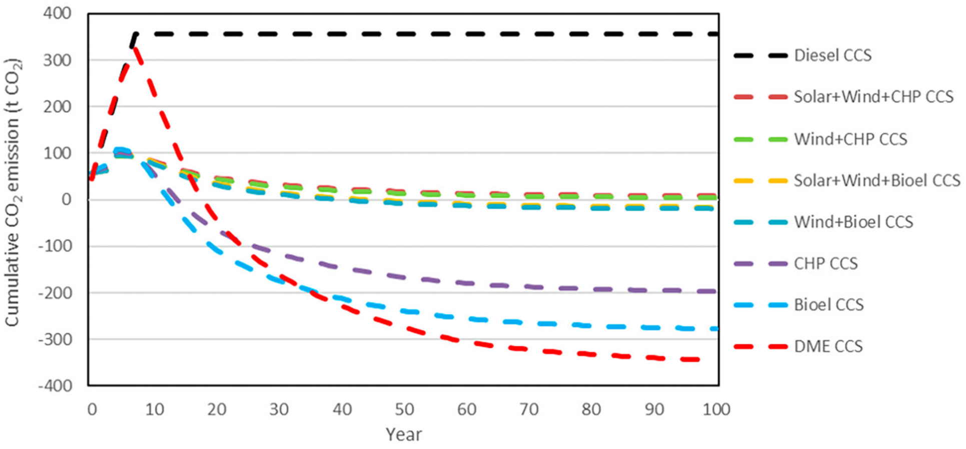

FIGURE 9 Cumulative CO_2 emissions from eight energy pathways with CCS, including avoided decay emissions from forest slash. The trucks are driven for the first 7 years. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

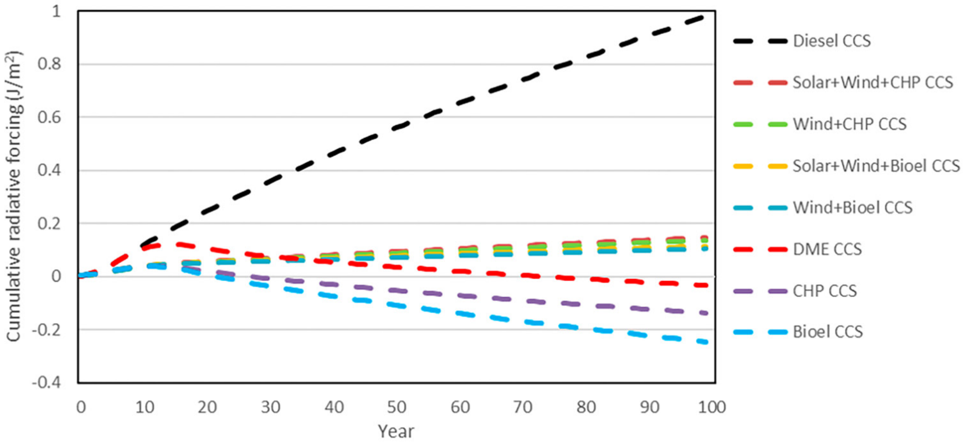

FIGURE 10 Cumulative radiative forcing resulting from emissions shown in Figure 9. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

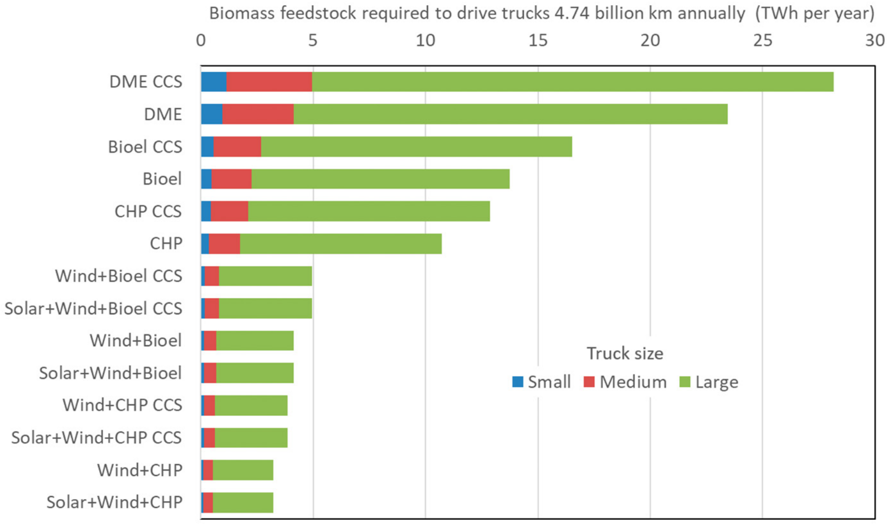

FIGURE 11 Required biomass feedstock to drive a truck fleet 4.74 billion km, using 14 different energy pathways. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

per GJ (Gode et al., 2011). In a sensitivity analysis we use the additional electricity to substitute fossil coal electricity generated at 50% efficiency using coal emitting 107 kg CO_2 per GJ (Gode et al., 2011).

Table 12 shows the results of this analysis, distinguishing five types of CO_2 emissions: (1) Fossil emissions from the harvest and transport of slash; (2) Biogenic emissions from the biomass used to power trucks; (3) Biogenic emissions from the surplus biomass used to generate electricity; (4) Avoided fossil emissions from substituted gas-fired electricity; (5) Fossil emission from diesel fuel used to power trucks. Avoided slash decay emissions are not included.

The pathways using Bioelectricity, CHP, Wind and Solar are all able to fulfil the transport requirements with the allocated 20 TWh of slash, and have surplus slash to produce additional electricity for other uses. The DME pathways do not fulfil the transport requirement with the allocated slash, and require supplemental diesel use. The Diesel pathways use 15.5 TWh of diesel for transport, and the 20 TWh of slash is available to generate 10 TWh of electricity. Figure 12 shows the total annual CO_2 emissions for each of the 16 pathways. Figure S5 shows the analogous figure when surplus biomass is used to generate electricity that substitutes for coal-fired electricity.

Expanding this scenario analysis, we assess the climate impacts during the complete lifecycle of cargo trucks in Sweden, including manufacturing and operating the trucks using different energy pathways. In pathways that fulfil the transport requirements without using all of the allocated 20 TWh of slash, we consider avoided emissions from the displacement of fossil gas-fired electricity. We also consider the avoided emissions from slash that would have decayed in the forest if it had not been harvested and used for bioenergy. Our analysis covers the 7-year period when trucks are manufactured and driven, and an additional 93 years of natural decay of unharvested slash.

Manufacturing emissions are estimated based on the number of trucks in the national fleet, and the average service life of each truck. We estimate the fleet size by dividing the total kilometres driven by trucks in Sweden per year by the kilometres driven annually per truck (Table 1). We assume that 1/7 of the total fleet is manufactured per year, as the average service life is 7 years. Operating emissions include the five types of emissions listed in Table 12. Avoided decay emissions are based on 20 TWh of slash annually for 7 years, and 93 years of continuing emissions from natural decay.

The cumulative biogenic and fossil CO_2 emissions during 100 years are shown in Figure 13. Among pathways that do not use CCS, the emissions are greatest in the DME and Diesel pathways. In the pathways that use Wind and Solar, the cumulative CO_2 emissions become negative because of avoided fossil emissions from gas-fired electricity production. When CCS is used, net CO_2 emissions become negative for all pathways.

Figure 14 shows the CRF corresponding to the emissions from Figure 13. The highest CRF is in the DME and Diesel pathways without CCS, while the CRF is much lower for the other pathways. The CRF of all pathways is reduced when CCS is used, but for the DME and Diesel pathways with CCS the CRF is still positive (global heating) after 100 years. All of the BEV pathways with CCS have strongly negative CRF after 100 years, resulting in global cooling.

6 | DISCUSSION AND CONCLUSIONS

We have compared different energy pathways to power cargo trucks. Each pathway is a series of physical

TABLE 12 Scenario results when 20 TWh of slash is allocated per year as feedstock to drive a truck fleet 4.74 billion km using 16 energy pathways, including annual diesel used for truck operation, additional bioelectricity produced and the associated biogenic and fossil CO_2 emissions. Avoided slash decay emissions are not included.

	TWh per year		Million tons CO_2 per year						
	Diesel used	Bioelectricity produced	Fossil emission for feedstock	Biogenic emission for transport	Biogenic emission for electricity	Avoided fossil gas emissions	Solar/wind emissions	Diesel emissions	Total emissions
Diesel	15.48	10.00	0.17	0.00	7.88	−4.14	0.00	4.73	8.63
Diesel CCS	15.48	8.33	0.17	0.00	0.79	−0.35	0.00	4.45	5.06
DME	2.28	0.00	0.17	7.88	0.00	0.00	0.00	0.70	8.74
DME CCS	4.48	0.00	0.17	3.41	0.00	0.00	0.00	1.29	4.87
Bioel	0.00	3.12	0.17	5.42	2.46	−1.29	0.00	0.00	6.75
Bioel CCS	0.00	1.45	0.17	0.65	0.14	−0.06	0.00	0.00	0.89
CHP	0.00	4.64	0.17	4.22	3.66	−1.92	0.00	0.00	6.12
CHP CCS	0.00	2.98	0.17	0.51	0.28	−0.12	0.00	0.00	0.83
Wind + Bioel	0.00	7.94	0.17	1.63	6.25	−3.29	0.04	0.00	4.80
Wind + Bioel CCS	0.00	6.27	0.17	0.20	0.59	−0.26	0.04	0.00	0.73
Wind + CHP	0.00	8.39	0.17	1.27	6.61	−3.47	0.04	0.00	4.61
Wind + CHP CCS	0.00	6.73	0.17	0.15	0.64	−0.28	0.04	0.00	0.72
Solar + Wind + Bioel	0.00	7.94	0.17	1.63	6.25	−3.29	0.10	0.00	4.86
Solar + Wind + Bioel CCS	0.00	6.73	0.17	0.15	0.64	−0.28	0.10	0.00	0.79
Solar + Wind + CHP	0.00	8.39	0.17	1.27	6.61	−3.47	0.10	0.00	4.67
Solar + Wind + CHP CCS	0.00	6.73	0.17	0.15	0.64	−0.28	0.10	0.00	0.77

Abbreviations: CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

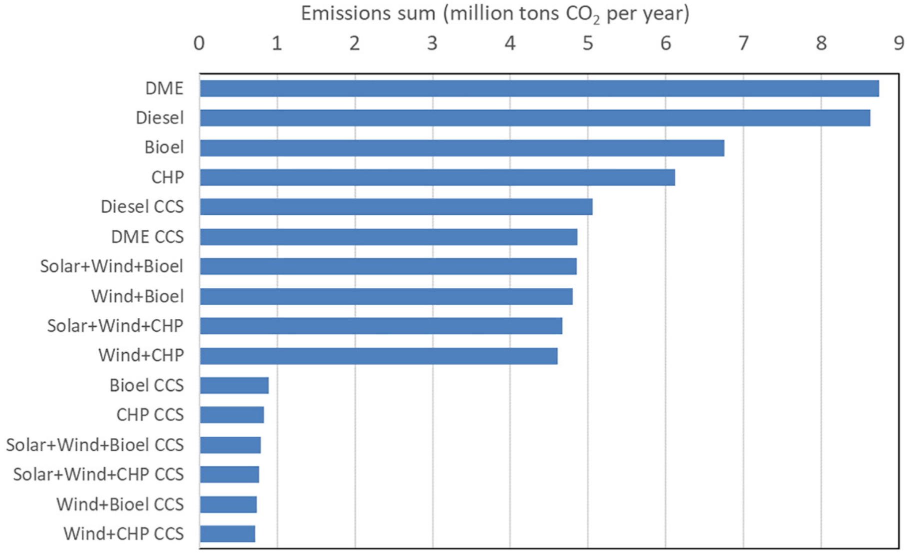

FIGURE 12 Total annual biogenic and fossil CO_2 emissions when 20 TWh of slash is allocated per year as feedstock to drive a truck fleet 4.74 billion km. Avoided slash decay emissions are not included. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

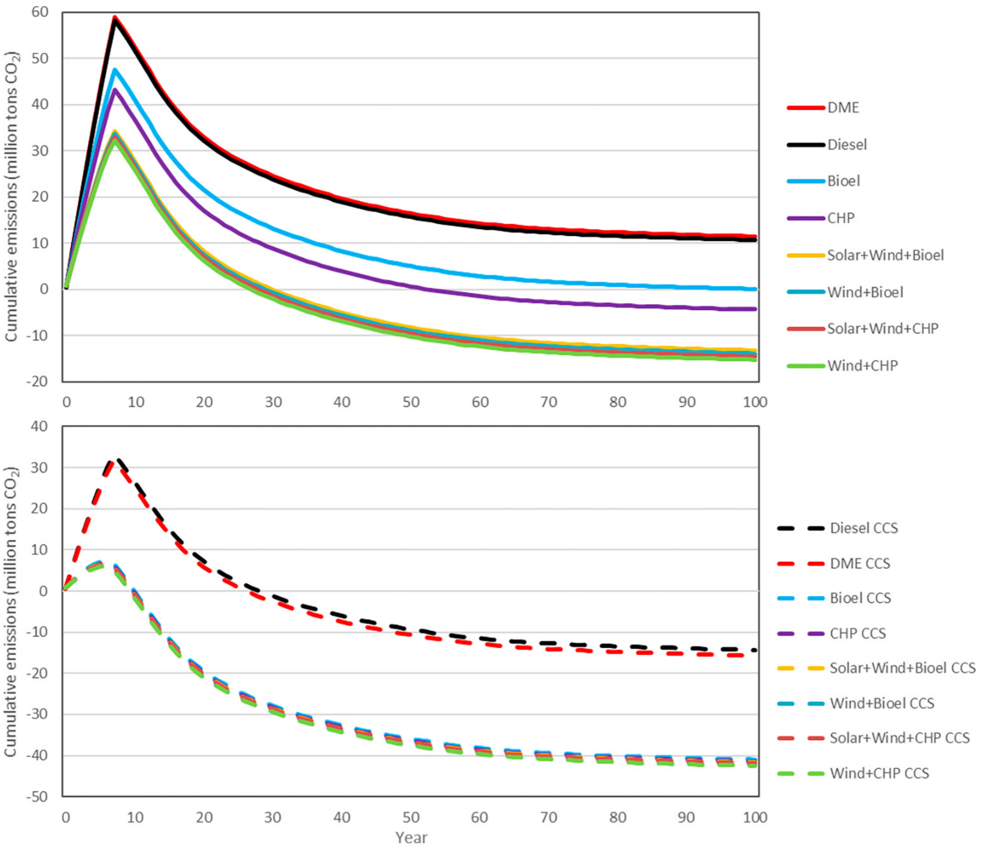

FIGURE 13 Cumulative CO_2 emissions resulting when 20 TWh of slash is allocated per year to drive a truck fleet 4.74 billion km using 16 energy pathways. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

processes, from accessing primary energy sources, to conversion of primary energy into energy carriers, to conversion of energy carriers into final transport services. We consider four primary energy sources, wind, solar, forest residues and crude oil, and all four are accessed quite efficiently. Conversion of crude oil into diesel, and wind

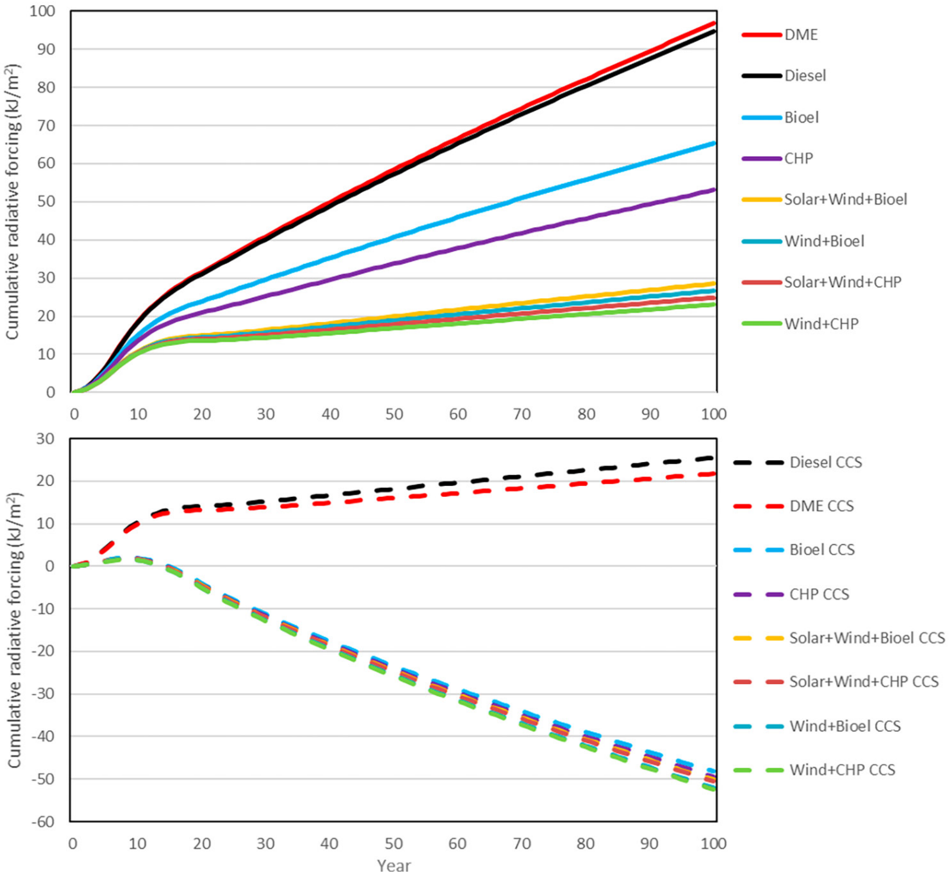

FIGURE 14 Cumulative radiative forcing resulting from emissions shown in Figure 13. CCS, carbon capture and storage; CHP, combined heat and power; DME, dimethyl ether.

and solar into electricity, is very efficient using modern oil refineries, wind turbines and solar cells. System supply efficiency of forest biomass into useful energy carriers is quite variable, and is most efficient for cogeneration plants producing heat and electricity, somewhat less efficient in biorefineries producing DME, and least efficient in stand-alone electricity plants (Table 6). Final conversion of energy carriers into transport service is the most variable process, and is significantly more efficient in BEVs compared to liquid-fuelled ICVs. Due to more efficient drivetrains, electric trucks require less than half of the end-use power needed by ICV trucks (Table 5).

We conclude that battery electric trucks offer lower lifecycle primary energy use and CO_2 emissions, compared to internal combustion trucks. The lowest energy use and climate impact is found when electric trucks are powered by wind and cogenerated bioelectricity. The results are about the same when including solar electricity in addition to wind electricity. In regions with better solar insolation conditions than in Sweden, such as countries in lower latitudes, solar panels produce more electricity daily and over more days. This increases the specific solar electricity production, making more electricity per manufactured photovoltaic unit.

Implementation of CCS has strongly varying effectiveness for different energy pathways. ICV trucks, both diesel and DME powered, emit substantial carbon emissions from their exhaust pipes, which is impractical to capture using CCS technology. In contrast, BEV trucks have no emissions during operation, and most emissions occur during conversion of forest residues into electricity. As these emissions occur in large-scale fixed facilities, they can be efficiently captured and stored in geologic formations. DME production also occurs in large-scale facilities, from which conversion-related emissions can be captured, but emissions from final combustion in vehicles are substantial and cannot be captured.

The most efficient pathways involve wind and solar electricity and cogenerated bioelectricity. Wind turbines are a very efficient method of generating electricity, with relatively little upfront energy use and carbon emissions during turbine manufacture and installation, followed by several decades of clean power production. Solar photovoltaic systems also perform well, with advances in cell design and manufacture such as thin film deposition leading to improved efficiency. The economics and energetics of wind and solar power are steadily improving, due to advances in design, sizing and siting (Masanet et al., 2013).

Cogeneration of electricity and heat also increases the system efficiency and reduces cost and biomass use, compared to separate production (Truong & Gustavsson, 2013). Heat storage can be used to help level out supply variations in district heating systems, making cogenerated power more dispatchable. Integrating intermittent wind and solar electricity and dispatchable bioelectricity will help enable grid stability and reliable supply. Further optimization can come from smart grids that control battery charging times and rates.

Battery lifespan and chemistry, the technology level of energy supply, and the biomass source and transport distance were all varied to understand how sensitive the results are to these parameters. The sensitivity analysis shows that our results are robust, leading to the same conclusions for a wide span of parameter variation. Still, emerging energy technologies have greater efficiencies in biomass-to-electricity, biomass-to-heat, biomass-to-DME, wind and solar electricity and carbon capture processes, leading to a more efficient use of the energy resources. Using current conventional energy technologies will result in significantly reduced overall performance due to lower conversion efficiencies, particularly increasing the use of biomass. Nevertheless, the relative ranking of the renewable-based pathways is independent of specific technology advancement.

The forest biomass is a limited resource and if more biomass is supplied to one part of the economy, then less biomass can be used in other parts. Therefore, the final energy use must be understood in the context of biomass feedstock supplied to the transportation sector. Our scenario analysis of current truck transportation service in Sweden shows that the use of biomass feedstock varies by a factor of about 9 between the different renewable energy pathways, having strong implications on climate impact and resource use efficiency. The CRF is highest for Diesel and DME pathways and much lower for the other pathways. With CCS, the DME and Diesel pathways give global heating after 100 years while all of the BEV pathways result in global cooling, having strongly negative CRF after 100 years.

In analyses of the climate effects of bioenergy, the CO_2 uptake from plant photosynthesis must be accounted for. This can either be done in a retrospective manner that accounts for the CO_2 uptake by plants prior to their harvest for bioenergy, or in a prospective manner that accounts for the future CO_2 uptake by re-growth of plants after their harvest for bioenergy. Accounting for both retrospective and prospective CO_2 uptake in the same analysis would result in double counting, and should be avoided. In our analysis we account for the CO_2 uptake that occurred prior to harvest, because this avoids the uncertainty of future scenarios. Thus, we account for carbon that had previously been taken up by the growing trees, and track this carbon as it is immediately emitted to the atmosphere if the biomass is harvested and used for bioenergy, or as it is gradually emitted to the atmosphere if the biomass is not harvested and decays naturally in the forest.

Traditionally, tree stemwood has been the primary economic product of forestry, and harvest residues such as branches and treetops have been left in the forest. Increasingly, however, foresters in Nordic countries are harvesting these residues for use as bioenergy (IRENA, 2019). Although our analysis is based on Swedish forest practices, the analysis is also relevant for forest residues harvested in other regions with similar boreal forest conditions under active management. Whether slash or stumps are used as biomass feedstock will affect the climate impact. Harvesting stumps uses more energy than harvesting slash, and slash decays more quickly if it is left in the forest. Both slash and stumps can be effective sources of bioenergy. However, the faster natural decay of slash relative to stumps results in less CRF when slash is harvested for bioenergy, compared to stumps.

There are clear long-term differences between sustainably sourced bioenergy that involves cyclical carbon flows between the biosphere and the atmosphere, and fossil energy that involves one-way carbon flows from the geosphere to the atmosphere. Nevertheless, even sustainable bioenergy is not fully climate neutral and does contribute to climate change, because it releases carbon into the atmosphere that would otherwise remain stored in plant biomass for some time. All CO_2 in the atmosphere, whether of fossil or biogenic origin, results in radiative forcing that leads to climate change. Our analysis uses temporally explicit modelling of CO_2 emissions to, and removals from, the atmosphere. We include all fossil and net biogenic CO_2 emission as well as the timing of these emissions. We are therefore able to accurately calculate the CRF of different energy systems, and distinguish between the climate impact of different bioenergy and fossil energy systems.

The CRF metric can be used to assess the climate change impact of any system that has emissions and/or removals of greenhouse gases, and is well suited to compare systems that have GHG emissions and/or removals at different points in time. The GWP metric is suitable for comparing simple systems that have pulse emissions at the same time. IPCC states that “most prominently used are the GWPs, which integrate the calculated radiative forcing contribution following an idealized pulse (or one-time) emission, over a chosen time horizon” (IPCC, 2021). GWP is recommended for reporting the national emissions of diverse GHGs where annual emissions of each GHG are treated as pulse emissions and are converted to the common unit of CO_2 equivalent. However, for complex systems with dynamic emission patterns, the CRF metric more accurately describes the actual climate impact. In such cases, cumulative emissions or GWP would give misleading results. In our analysis, the emission patterns are very complex and occur over an extended time period, and CRF is a metric that accurately captures this complexity. An analysis based only on fossil emissions, or on static calculations of biogenic emissions, is incomplete and could be misleading.

Overall, we find that the electrification of the cargo truck fleet, together with an increase in renewable electricity generation, is a wise transport strategy. Maintaining a stable and sustainable electricity supply will require the integration of intermittent sources such as wind and solar with dispatchable sources such as bioelectricity. BECCS can be used to produce net negative CO_2 emissions, which may be needed to avoid severe climate disruption. Using harvest residues from sustainable forestry to generate bioelectricity, well integrated with intermittent wind and solar electricity, is a viable energy pathway to power battery electric cargo trucks. This contrasts sharply to the DME pathways, which have climate impact that is very similar to the Diesel pathways.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Swedish National Data Service at https://doi.org/10.5878/0h1w-e950.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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