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

Documentation

1 Analysis description

We compare cargo trucks that provide equivalent service but are powered by different drivetrains and energy supply pathways. We study battery electric vehicles (BEVs) that are operated by electricity produced from forest harvest residues in stand-alone 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 stand-alone 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 [13,16]. 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 [14]. 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.

Table 1. *Modelled ICV and BEV trucks of different sizes.*

Truck size	Gross vehicle mass (kg)	Cargo mass (kg)	Annual driving distance (km)
Small	10000	4100	40000
Medium	20000	11100	60000
Large	40000	25600	125000

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 of 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.

$$E_t = E_m + E_o - E_d \qquad \text{(Equation 1)}$$

CRF 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 [17] to calculate CRF, using parameter values updated by IPCC [18]. The calculation uses 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 per m^2 of surface area ($J\ m^{-2}$). For more description of the calculation of CRF and its application to forest residues used as bioenergy, see [19].

2 Truck manufacture

BEV 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 [9,14]. 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.

Table 2. *Primary energy use and CO_2 emissions from manufacturing BEV and ICV trucks of different sizes. BEV numbers include manufacture of two batteries used during the vehicle service life, using data from [15,20,21,22,23].*

	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

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 [15,20,21,22,23,24], 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 [25]. 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 3. *Exemplar performance characteristics of batteries of different intensities, using data from [20,21,22,23,25,26,27,28,29].*

Parameter	Battery intensity		
	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 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 2 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.

Table 4. *Primary energy use and CO_2 emissions from manufacturing batteries for different size BEV trucks, with batteries of different energy and CO_2 intensities using data from [20,21,22,23,25,26,27,28,29].*

Truck size	Battery intensity		
	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

3 Truck operation

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

Table 5. *Final energy use for operating different size trucks. BEV final energy is electricity, and ICV final energy is LHV of diesel or DME, using data from [9,10,11,12,14,15,22,30,31,32].*

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

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 [33], 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 electricity generated in stand-alone biomass integrated gasification combined cycle (BIGCC) plants, fuelled by forest harvest residues. We also consider electricity generated in BIGCC plants with combined heat and power production (CHP-BIGCC), fuelled by forest harvest residues. In two pathways, 30% of the stand-alone BIGCC electricity or 30% of CHP-BIGCC electricity 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 refined fossil diesel fuel from crude oil. Each of these 8 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, for example improved systems for BIGCC technology. 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 on-shore 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.

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%	[34,35,36,37]
Stand-alone biomass-to-electricity	50%	40%	[36,38]
CHP biomass-to-electricity	42%	31%	[36,38]
Stand-alone biomass-to-heat	108%	108%	[36,38]
CHP biomass-to-heat	48%	57%	[36,38]
Input for wind electricity	3%	5%	[39,40,41,42]
Input for solar electricity	5%	13%	[46]
Diesel fuel cycle input	9%	9%	[48]
CCS energy penalty	20%	24%	[50]

DME 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 [51]. It can also be produced in a single reactor using bifunctional catalysts [52]. Our modelling of DME generation uses data from 7 stand-alone facilities of different scale and configuration [34,35,36,37]. We define our main-case emerging technology level as the most efficient of the 7 plants. Our sensitivity study of conventional technology is based on the average of the 7 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, though 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 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 BIGCC systems that convert forest biomass to electricity at a 50% conversion efficiency [36]. In our sensitivity study of conventional technology, we use steam boiler systems with a 40% conversion efficiency [38].

For combined heat and power 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, i.e. 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.

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%**

For electricity generated by wind turbines, our emerging technology considers state-of-the-art onshore turbines with life cycle 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 [39,40,41,42]. 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, life cycle primary energy and carbon intensity depends strongly on location, as solar insolation varies widely. We assume Swedish conditions with modest insolation, with emerging technology life cycle 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 [43,44,45,46]. 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 [47], and tailpipe emissions are 73.6 g CO_2 per MJ of diesel [48]. Fuel cycle primary energy use is 0.09 MJ per MJ of diesel [48].

CCS is intended to capture CO_2 that would otherwise enter the atmosphere, and direct 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 [49]. 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 [50]. 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 permanent 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.

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, though it is estimated that annual potential slash harvest could reach 65 TWh, and combined slash and stump harvest could reach 107 TWh per year [53]. 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 [54]. The Swedish Forest Agency has guidelines for extracting forest fuels and applying recycled ash [55]. This analysis is not limited to the use of Swedish forest residues, 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 [56]. Slash is the 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.

Table 8. *Specific fossil energy use for harvesting and transporting forest residues, per dry ton of delivered biomass [56].*

	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

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 [19]. 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 [57] to estimate the decay rate of forest residues that are left in the forest. We use model parameter settings for central Sweden [58]. 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 [59], and assume that 50% of slash is from Scots pine (*Pinus silvestris*) trees and 50% from Norway spruce (*Picea abies*) trees, that tree-tops comprise 10% of the total stem mass, and that 80% of needles fall off before the slash is removed from the forest.

[Reference numbers refer to 2023 article in *Global Change Biology – Bioenergy*]