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A COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF EUROPEAN HEAVY-DUTY VEHICLES AND FUELS

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EXECUTIVE SUMMARY

Transport is the largest producer of greenhouse gases (GHGs) in the European Union (EU), contributing almost 30% to the total. Heavy-duty vehicles (HDVs), primarily commercial trucks and buses, are responsible for 26% of these emissions. Adoption of electric vehicles is expanding in the light-duty sector in Europe, but the heavy-duty sector relies almost entirely on internal combustion (diesel) powertrains; in 2021, zero-emission HDVs represented only 1% of new HDV registrations in the EU.

This paper compares the levels of GHG emissions produced by different HDV technologies in the EU and identifies which powertrain and energy pathways are most likely to provide significant GHG emission reductions in this sector. We investigate the GHG emissions over each vehicle's total lifetime for three common HDV categories: a 12-tonne truck, a 40-tonne articulated tractor-trailer, and an urban bus. We compare the emissions of the current best-in-class diesel-fueled internal combustion engine (ICE) vehicle to a natural gas (NG)-fueled variant and two zero-emission powertrain types: pure battery electric and hydrogen fuel cell electric HDVs. Within our life-cycle assessment (LCA), we include not only CO_2 emissions resulting from vehicle tailpipes, but also the GHG emissions arising from the manufacture of the vehicles and their components; vehicle maintenance; fuel production; and electricity production.

Figure ES1 illustrates the GHG emissions for 40-tonne tractor-trailer HDVs manufactured in 2021 and 2030. The figure shows emissions from diesel and natural gas ICE, pure battery electric, and fuel cell electric powertrains. Diesel and natural gas pathways include potential reductions of GHG emissions from biofuel blends. In addition, we estimate emissions from using either grid or 100% renewable electricity in the battery electric truck. The figure compares estimated GHG emissions of a fuel cell powertrain using hydrogen made from natural gas or 100% green hydrogen (hydrogen made using electrolysis powered by renewable electricity). For vehicles bought in 2030, the emissions of a blend of 50% fossil natural gas (using carbon capture and storage [CCS]) and 50% renewable hydrogen are presented.

We find that the greatest emission reductions come from powering HDVs with 100% renewable electricity, either directly by storing it in a battery or by using the renewable electricity to make green hydrogen and recover it into electricity in a fuel cell. In contrast, HDVs powered by fossil fuels with minor percentages of biofuels have the highest emissions. The percentages of bio-component are low (up to 7% volume in diesel), as the EU has limited available volumes of sustainable biofuels, which is not expected to change dramatically up to 2030.

For vehicles produced in 2030, the estimated GHG emissions for each powertrain type decline relative to 2021 vehicles, mainly due to a combination of increased vehicle efficiencies and a reduction in the GHG intensities of the fuels. Due a high uncertainty on the future development of the average hydrogen blend, several pathways are presented separately. For FCEVs produced in 2021, we compare the emissions of driving on hydrogen from fossil natural gas with those of driving on hydrogen produced from renewable electricity. For 2030 vehicles, we further display a potential future hydrogen mix of 50% hydrogen made from fossil natural gas that uses carbon capture and 50% green hydrogen, which considers that the EU adds some fuel production from this pathway by 2030 driven primarily by technology improvement, policy support, and reduced renewable electricity costs.

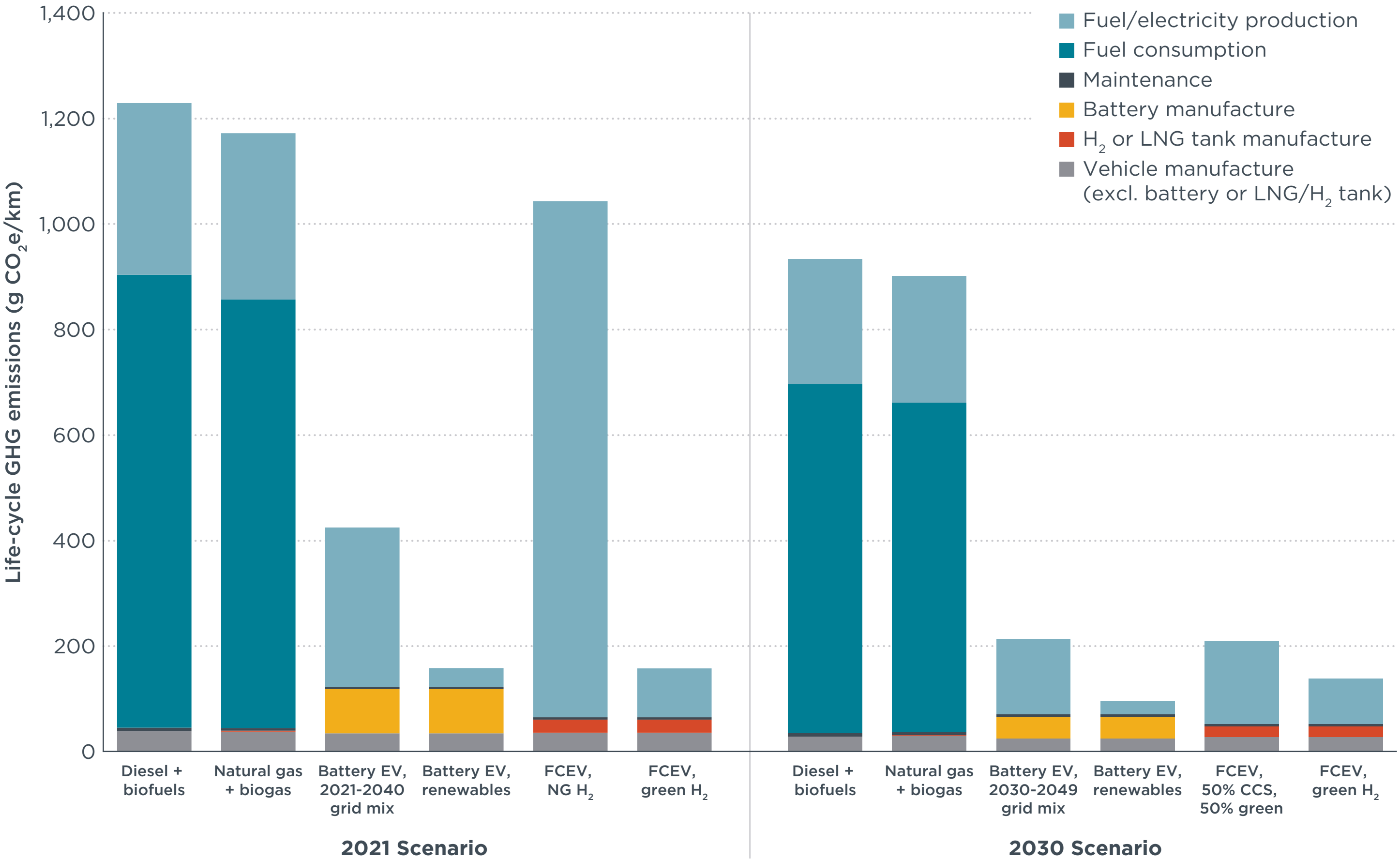

Figure ES 1. Lifecycle GHG emissions of 40-t tractor-trailer produced in 2021 and 2030.

Our analysis yields several key results:

» **Battery electric HDVs bought today correspond to GHG emission savings of 65% or more over their life cycle compared to conventional ICE HDVs.** The GHG savings emissions benefit of battery electric HDVs is due to a higher energy efficiency and lower fuel carbon intensity compared to the ICE versions. Upstream GHG emissions of the electricity has a large effect on the level of GHG savings battery electric HDVs can obtain. Substantial GHG savings over the life of the vehicle range from 65% to 77%, based on vehicle type, when EU grid average electricity is used. However, these emissions savings can increase to 94% if only renewable electricity is used. For vehicles entering service in 2030, the GHG emission benefit over diesel ICE HDVs ranges from 77% to 84% when powered by grid electricity, while using only renewable electricity allows GHG emissions savings as high as 94% compared to diesel HDVs.

» **Hydrogen fuel cell electric HDVs may provide considerable GHG emissions savings compared to diesel HDVs, but their GHG reductions depends heavily on the source of hydrogen.** When a fuel cell HDV entering service in 2021 is powered by green hydrogen made from 100% renewable electricity, we estimate that the vehicle corresponds to GHG emissions savings of up to 91% relative to a conventional ICE HDV, which is almost the same amount of GHG emission savings as battery electric HDVs using only renewable energy. In contrast, savings are as low as 15% for fuel cell HDVs using fossil hydrogen.

» **Natural gas HDVs, at best, provide marginal GHG emission savings compared to diesel HDVs. When using a near-term global warming potential (GWP) for methane, the climate impact of natural gas HDVs is higher than for diesel vehicles.** For natural gas fueled trucks and buses sold in 2021, we estimate a lifetime emission reduction from 5% to 18% compared to their diesel counterparts. The level of savings compared to diesel for vehicles produced in 2030 stays at approximately 17% for rigid trucks and urban buses, respectively. For tractor-trailers, 2030 vehicles using natural gas generate approximately 3% less emissions than their diesel counterpart. Additionally, we find that the small emissions savings from using natural gas in HDVs are lost when considering the short-term climate impact of methane emissions. Using GWP_{20}, we estimate that compressed natural gas and liquefied natural gas (LNG) have a 0% to 22% higher climate impact than diesel ICE HDVs for 2021 vehicles, largely due to upstream methane leakage.

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ACRONYMS

BEV	Battery electric vehicle
CCS	Carbon capture and storage
CI	Carbon intensity
CNG	Compressed natural gas
FAME	Fatty acid methyl ester
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
GWP	Global warming potential
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
IEA	International Energy Agency
ILUC	Indirect land-use change
LCA	Life-cycle assessment
LNG	Liquified natural gas
Mtoe	Million tonnes of oil equivalent
PHEV	Plug-in hybrid electric vehicle
PtG	Power to gas
PtL	Power to liquid
RED	Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
SDS	Sustainable Development Scenario
SMR	Steam Methane Reforming
ZEV	Zero-emission vehicle

INTRODUCTION

The EU introduced the European Climate Law in 2021 in order to meet the requirements of the Paris Agreement and limit global warming. Regulation (EU) 2021/1119 (2021) sets a goal to reduce the EU's GHG emissions by 55% by 2030 compared to 1990 levels and to reach full carbon neutrality by 2050. Bloc-wide GHG emissions in the EU have decreased by almost 25% since 1990. However, the transport sector has followed the opposite trend: transport emissions have increased by 33% to become the largest source of GHG emissions in the EU (Directorate-General for Mobility and Transport, European Commission, 2021). The European Commission notes that the EU will need to achieve a 90% reduction in overall transport emissions by 2050 to reach climate neutrality (European Commission, 2021). Our study focuses on heavy-duty vehicles (HDVs), specifically urban buses and heavy-duty trucks. The heavy-duty sector has grown at an average annual rate of 1.4% since 1995 and is the biggest contributor to the EU's transport emissions after passenger cars, contributing over 27% of sectoral emissions (Directorate-General for Mobility and Transport, European Commission, 2021).

Decarbonizing the HDV sector, defined as buses and trucks with a gross vehicle weight (GVW) over 3.5 tonnes, can be achieved through a combination of policies to reduce the climate impacts of fuels, improvements in vehicle efficiency, and innovations in vehicle technology. However, some fuel and powertrain options may inadvertently increase GHG emissions. Therefore, a careful assessment of the GHG emissions attributable to different HDV vehicle and fuel technologies is needed. In the present-day EU HDV fleet, diesel powers 96.3% of trucks and 93.5% of buses (ACEA, 2022) and is thus driving the majority of emissions from this sector.

The 2019 heavy-duty vehicles CO_2 emissions standard (*Regulation (EU) 2019/1242*, 2019) is the first EU-wide CO_2 emissions standard for HDVs. It targets the four biggest truck classes (those with a GVW above 16 tonnes), which together account for up to 70% of CO_2 emissions from HDVs. The European Commission is considering extending the scope of the standard to other vehicle types, such as smaller lorries, buses, coaches, and trailers. Under the regulation, from 2025 onwards, manufacturers will have to meet fleet-wide average CO_2 emissions reduction targets of 15% by 2025 and 30% by 2030, compared to a 2019/20 baseline period. The regulation incentivizes the uptake of zero- and low-emission vehicles, and manufacturers have pledged to increase deployment of zero-emission HDVs beyond the level that the standard requires. If legislation were to enshrine the manufacturers' commitments the 2030 target would increase to a reduction of 60% and require a full internal combustion engine (ICE) phase-out by 2040 (Mulholland et al., 2022).

The EU has introduced biofuel policy as another method of reducing transport emissions, principally through the Renewable Energy Directive (RED), which was recast in 2018 as the RED II, and by the Fuel Quality Directive (Directive 98/70/EC Consolidated Version, 2018). These directives have led to increased biofuel consumption of over 13.3 million tonnes of oil equivalent (mtoe) of fatty acid methyl ester (FAME) and hydrotreated vegetable oil in 2020, or approximately 8% of the total diesel used in the EU in on-road and off-road vehicles (EurObserver, 2022; U.S. Department of Agriculture, 2021). However, researchers have questioned the sustainability and GHG emission savings associated with many commonly used biofuels, especially when effects such as emissions from indirect land-use change (ILUC) are taken into account (Valin et al., 2015). The RED II requires minimum GHG emission savings of 50% to 65% for alternative fuels relative to a fossil fuel baseline to qualify. However, this threshold calculation does not include the GHG emissions from ILUC. When ILUC emissions are included in a biofuel's GHG emissions calculation, the biofuel often does not provide any GHG savings compared to regular diesel fuel (European Parliament and the Council of the European Union, 2018). Second-generation biofuels capable of providing meaningful GHG emission savings compared to fossil fuels are typically only available in small volumes and are subject to increasing competition for their use (USDA, 2021).

Natural gas HDVs have also been suggested as an option to reduce GHG emissions compared to diesel (AFDC, 2022; Gas Networks Ireland, 2021). Natural gas has lower carbon content than diesel and produces around 25% less CO_2 per unit of energy during combustion. Further, the technology is already growing in popularity within the EU HDV sector. According to the European Automobile Manufacturers' Association, in 2020, 11.4% of bus sales in the EU were non-diesel, and practically all of these were natural gas-fueled. In 2020, 2.9% of trucks sold in the EU were alternatively fueled, and 99% of these were fueled with natural gas (ACEA, 2021a; ACEA, 2021b). However, caution is warranted for this type of powertrain, especially when factoring in the increased GHG emissions resulting from methane leaks or slip, which can occur during the fuel production stage and while the vehicle is in use (Hmiel et al., 2020; Alvarez et al., 2018). Methane has a high global warming potential (GWP), with a global warming effect between 28 and 85 times higher than CO_2, depending on whether a 100- or a 20-year timeframe is considered and whether feedback effects are included (Stocker, T.F. et. al., 2013). A recent trial of 20 HDVs in the UK found that using pure fossil natural gas resulted in small GHG emission savings at best and small emission increases compared to using diesel at worst (Cenex, 2019). However, the total available volume of renewable methane (which includes not only biomethane but also synthetic methane made from renewable electricity) is projected to supply, at most, only 12% of future EU gas demand (Searle et al., 2018), so it has a limited ability to replace fossil natural gas.

In 2019, the EU adopted a revision of the Clean Vehicles Directive, which sets minimum targets for the public procurement of clean vehicles for EU Member States (Directive (EU) 2019/1161, 2019). Across countries, these targets range from 24% to 45% in 2025 and from 33% to 65% in 2030, depending on population and gross domestic product; the 2030 target for 15 Member States is at least 60%. While zero-emission buses qualify as "clean" vehicles, other fossil fuel-powered technologies such as plug-in hybrids, natural gas, and liquefied petroleum gas-powered vehicles would also qualify as "clean." Nevertheless, the directive mandates that Member States meet half of the percentage targets by procuring battery electric or fuel cell electric buses (Wappelhorst & Rodriquez, 2021). However, a recent analysis shows how the targets that the Commission established for HDVs are insufficient to achieve the European Union's long-term climate commitments and should be increased (Mulholland et al., 2022).

The European Commission's Strategy for Sustainable and Smart Mobility, unveiled in December 2020, sets an objective to have 80,000 zero-emission trucks on the road by 2030. By 2050, nearly all cars, vans, and buses, as well as new heavy-duty vehicles, are to be zero-emission (European Commission, 2020). Although the sales volume of light-duty battery electric vehicles (BEVs) is expanding, the share of zero-emission HDVs in the EU market remains small. ACEA (2021c) estimates that of the 6.2 million medium- and heavy-duty commercial vehicles now on the EU's roads, just 2,300 (or 0.04% of the total fleet) are zero-emission trucks. In 2020, zero-emission HDVs represented 1% of new HDV registrations in the EU; 95% of these were battery electric, with a very limited presence of fuel-cell electric technologies. Basma and Rodríguez (2021) have noted that the status of fuel cell technology in the HDV sector is still considered very nascent.

Most of the zero-emission HDV sales in Europe have been buses, which comprised close to 90% of cumulative zero-emission HDV sales between 2010 and 2020. Zero-emission truck sales are, however, rising as a share of zero-emission HDV sales, increasing from 20% making of total new zero-emission HDV registrations in

2017 to 40% in 2020 (Basma & Rodríguez, 2021) (see Figure 1). The large share of zero-emission buses in some European countries, as noted earlier, is mainly a result of regulations and mandates at the regional and municipal level in major cities like London, Paris, and Amsterdam (Basma & Rodríguez, 2021). Austria, Denmark, and the Netherlands have committed to ensuring 100% of their new bus purchases will be zero-emission technologies in the future, with Denmark and the Netherlands aiming to reach those targets by 2025 (Wappelhorst & Rodríguez, 2021).

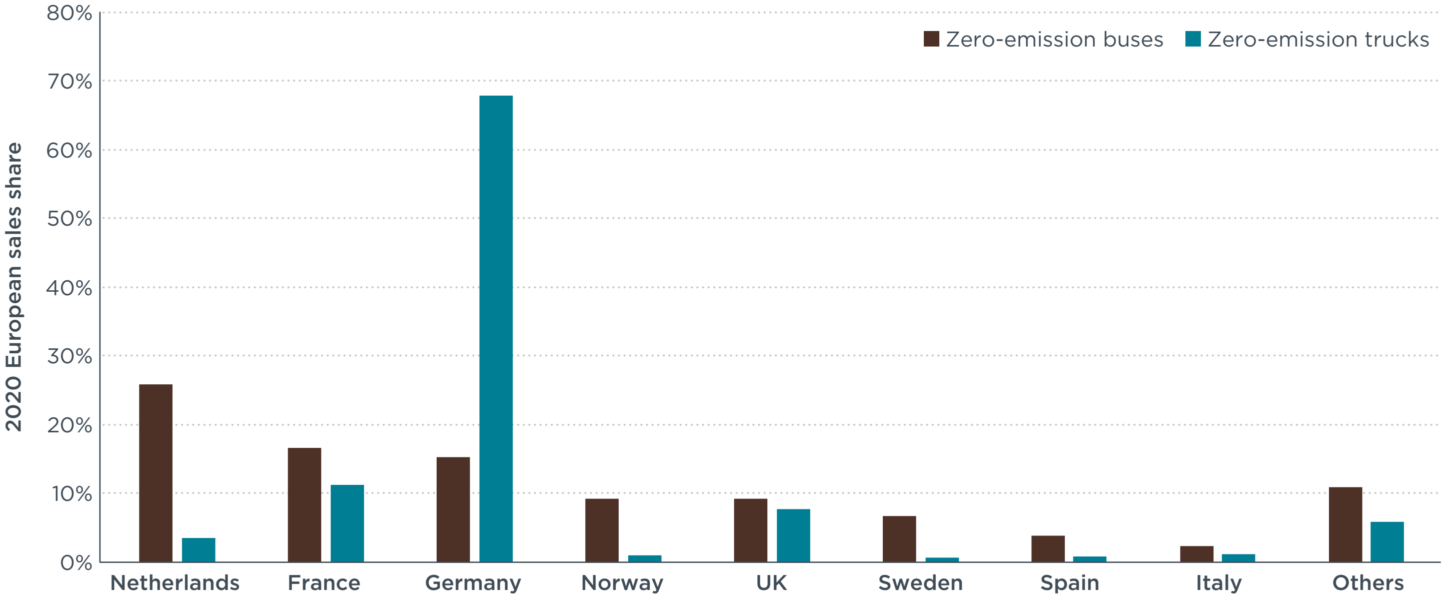

Figure 1. Share of selected countries in the total 2016 to 2020 zero-emission bus and truck sales in Europe. (Basma & Rodríguez, 2021).

Fuel cell electric vehicle (FCEV) deployment in the EU remains limited, and the vast majority of FCEV sales are passenger cars. The International Energy Agency (IEA)'s Advanced Fuel Cells Technology Collaboration Program estimated Europe had in total almost 2,700 FCEVs by the end of 2020, 131 of which were fuel cell buses, and a smaller number of which were fuel cell trucks (IEA TCP, 2021). Despite the limited deployment of FCEVs to date, the European Commission expects that hydrogen will play an important part in reducing the EU's GHG emissions. It notes the need for the hydrogen to be better deployed and decarbonized but sets a priority for the production and use of renewable hydrogen (European Commission, 2022).

This study compares the impacts of different powertrain and fuel technologies that could be used to decarbonize the HDV sector in the EU using life-cycle assessment (LCA). This analysis is necessary because while the downstream emissions of diesel HDVs surpass those of a zero-emission battery electric or fuel cell electric vehicle, more uncertainty surrounds upstream emissions due to the variety of potential sources of electricity and hydrogen. Further uncertainty exists over the emissions from vehicle manufacture for the different powertrain types. We evaluate the emissions for a selection of vehicle technologies for model years 2021 and 2030—including their upstream manufacturing emissions, upstream emissions from fuel and electricity production, and the projected changes in the mix of fuels over time—to estimate each vehicle's life-cycle emissions on a per-kilometer basis.

METHODOLOGY

GOAL AND SCOPE

The goal of this study is to identify the powertrain and fuel technologies that allow a deep decarbonization of the HDV sector within existing or planned policy frameworks in the European Union. To that end, it estimates the life-cycle GHG emissions of Euro VI diesel, compressed or liquefied natural gas (CNG or LNG)-powered ICE HDVs, battery electric HDVs and hydrogen fuel cell HDVs. The study considers the best-in-class HDVs available in 2021 and compares them with estimates of the equivalent HDVs expected to be available in the EU in 2030. We include non-CO_2 emissions based on GWP in units of an equivalent amount of CO_2 (CO_2e). This study principally considers a 100-year GWP (GWP_{100}) for natural gas, where each 1 g of CH_4 equates to 30 gCO_2e. We also conduct a sensitivity analysis to assess the effects of using a 20-year GWP (GWP_{20}) to determine the near-term warming impacts of the different technologies. The study includes the main sources of methane emissions, which occur during the production, distribution, and consumption of natural gas, both when it is used in natural gas vehicles and to produce hydrogen. We also include the methane slip emissions from natural gas vehicles.

This study uses a life-cycle approach with a scope that includes the full life cycle of a vehicle, including GHG emissions arising from vehicle production, maintenance, and recycling (i.e., the vehicle cycle) and GHG emissions from fuel and electricity production and consumption (i.e., the fuel cycle). These emission sources are combined into a single value based on the functional unit of gCO_2e/km traveled throughout a vehicle's lifetime. We do not include the emissions from the construction and maintenance of infrastructure for vehicle production and recycling, vehicle chargers and fueling stations, emissions corresponding to road infrastructure, and infrastructure for the transport and distribution of fuels. These are either similar across the different powertrain types or have only a small influence on total life-cycle GHG emissions.

The assessment of the life-cycle GHG emissions principally follows an attributional approach. As such, we take into account the average GHG emissions attributable to each vehicle and fuel path during their lifetime. We estimate some values, such as the ILUC emissions arising from biofuel production, using a consequential LCA approach. Thus, these values reflect the production-induced changes in the wider economy. In this study, we assume the GHG intensity of grid electricity to be the average grid GHG emissions of the EU grid mix.

VEHICLES STUDIED

The study focuses on three types of HDVs: a 12-t rigid truck, a 40-t articulated truck (tractor-trailer), and an urban bus. While this study assesses the state of the art for both diesel and natural gas-fueled HDVs, we do not analyze experimental ICEs currently under development and which may enter commercial use in the future. Further details on such engines are described in Ricardo (2020).

The unladen 12-tonne truck mass is calculated using manufacturers' specifications, following identification of the six top-selling trucks in the segment in the EU in 2020 (IHS Markit, 2021), which represent 92% of sales in this category.[1] The estimated level of tailpipe CH_4 emissions are negligible for diesel fueled trucks compared to overall levels of CO_2e emissions per kilometer, while N_2O emissions for diesel HDVs are notable. For example, N_2O emissions contribute approximately 50 gCO_2e/km for the diesel-fueled tractor-trailer. We take CH_4 emission calculations for vehicles fueled by natural gas from Mottschall et al., (2020).

1 This calculation includes content supplied by IHS Markit Group Limited; Copyright IHS Markit Group Limited, 2021.

The mass of the 40-tonne tractor-trailer consists of the combined mass of the tractor unit and the trailer mass. The unladen weight of the tractor unit comes from the European Environmental Agency (EEA, 2021b). We obtain the weight of the trailer from the 2015 value from Sharpe and Rodríguez (2018) and fuel consumption figures for the tractor-trailers from a study which analyzed the heavy-duty CO_2 standards baseline data for EU trucks (Ragon & Rodríguez, 2021).

We obtain the unladen weight of urban buses from a 2018 study carried out by TU Berlin (Göhlich et al., 2018). Fuel consumption figures are from an energy assessment of battery electric buses and diesel buses conducted by Basma et al. (2019).

VEHICLE CYCLE

The vehicle cycle comprises the cradle-to-grave GHG emissions of vehicle production, maintenance, and disposal. Vehicle production and disposal include three categories of components: the battery for battery electric HDVs, the hydrogen tank (incl. fuel cell) or LNG tank for fuel cell and LNG HDVs, and the rest of the vehicle, which is denoted as glider and powertrain.

Table 1. Scope of GHG emissions considered in the vehicle cycle.

Glider and powertrain	• Production of the vehicle, including raw material extraction and processing • Component manufacture and assembly • Recycling of vehicle components
Battery	• Production of the battery packs, including extraction and processing of raw materials • Cell production and pack assembly • *Not included:* Second-life use and recycling
Hydrogen or LNG tank	• Production of the hydrogen tank (incl. fuel cell) or LNG tank • Includes raw material extraction and processing, and component manufacture • *Not included:* Component recycling/disposal
Maintenance	• In-service replacement of consumables, including tires, exhaust/aftertreatment, coolant, oil, urea, and others

The fuel or energy consumption figures for all three HDVs for both model years are included in Table 2. For all HDV segments, the 2030 vehicles are assumed to have an about 25% lower fuel or energy consumption than observed for current models. A summary of our assumptions and data sources for vehicle parameters is shown in Table 3. We assume a slight decline in the weight of the HDVs in 2030.

Table 2. Fuel and energy consumption figures used.

	Powertrain	2021	2030	Unit	Source
12-t trucks	Diesel + biofuels	25.97	19.48	L/100km	Ragon and Rodríguez (2021)
	CNG + biogas	22.66	16.99	kg/100km	Estimated using above & ratio of 40-t NG-to-diesel
	Battery EV	110.00	80.00	kWh/100km	Basma and Rodriguez (in press)
	Fuel cell EV	190.00	138.06	kWh/100km	Basma and Rodriguez (in press)
40-t tractor-trailers	Diesel + biofuels	33.05	24.99	L/100km	Basma et al. (2021)
	LNG + biogas	28.83	21.80	kg/100km	Mottschall et al. (2020)
	Battery EV	138.06	98.89	kWh/100km	Basma and Rodriguez (in press)
	Fuel cell EV	238.33	222.22	kWh/100km	Basma et al. (2021)
Buses (urban)	Diesel + biofuels	55.77	41.45	L/100km	Basma et al. (2019)
	CNG + biogas	47.52	35.31	kg/100km	Rodman Oprešnik et al. (2018)
	Battery EV	170.00	122.70	kWh/100km	Basma et al. (2020)
	Fuel cell EV	305.56	253.46	kWh/100km	NREL (2021)

Table 3. Summary of assumptions and data sources for vehicle parameters.

Parameter	Vehicle category	Vehicle year	Value	Data source	Notes
Vehicle unladen weight	12-t truck	2021	4,176 kg	IHS Markit, 2021	Specs of six top-selling trucks in the segment in 2020, represents 92% of category sales
		2030	3,800 kg	ICCT own assumption	Assumes some weight reduction in the chassis at around 300 kg
	40-t tractor-trailer	2021	14,884 kg	Basma et al. (in press)	
		2030	13,084 kg	Basma et al. (in press)	
	Urban bus	2021	11,600 kg	Göhlich et al. (2018)	
		2030	11,600 kg	ICCT own assumption	Assumes equal to 2021
Battery capacity and specific energy	12-t truck	2021	300 kWh	Basma, Beys, et al. (2021)	Assumes typical range 200-250 km
			Energy density	Basma, Beys, et al. (2021)	Assumes 0.14 kWh/kg
		2030	250 kWh	ICCT own assumption	Assumes a typical range of 200-250 km
			Energy density	Basma, Beys, et al. (2021)	Assumes 0.25 kWh/kg
	40-t tractor-trailer	2021	900 kWh	Basma, Beys, et al. (2021)	Provides a 500-km range
			Energy density	Basma, Beys, et al. (2021)	Assumed 0.14 kWh/kg
		2030	700 kWh	ICCT own assumption	Provides a 500-km range
			Energy density	Basma, Beys, et al. (2021)	Assumes 0.25 kWh/kg
	Urban bus	2021	300 kWh	Basma, Beys, et al. (2021)	Assumes a typical range of 200-250 km
			Energy density	Basma, Beys, et al. (2021)	Assumes 0.14 kWh/kg
		2030	250 kWh	Göhlich et al (2018)	Assumes a typical range of 200-250 km
			Energy density	Basma, Beys, et al. (2021)	Assumes 0.25 kWh/kg
Hydrogen tank capacity	12-t truck	2021	20 kg	ICCT own assumption	
		2030	15 kg	ICCT own assumption	
	40-t tractor-trailer	2021	45 kg	Basma et al. (in press)	Based on a 500-km driving range
		2030	33 kg	Basma et al. (in press)	
	Urban bus	2021	37 kg	Solaris (2021)	Hydrogen-fueled urban bus
		2030	30 kg	ICCT own assumption	

The GHG emissions of the production and recycling of the vehicles' glider and powertrain are based on a HDV emission factor in t CO_2e/t vehicle from Scania (2021), while the GHG emissions from the production of batteries and fuel cell systems come from the GREET model (Argonne National Laboratory, 2020) and ICCT (Bieker, 2021). The figures are described further in Table 4. We apply segment-specific weights of each HDV type registered in Europe, along with the manufacturing emission factor from Scania (2021), to estimate the manufacturing emissions for each HDV. We separately calculate the emissions associated with the battery and fuel cell systems using the aforementioned emission factors for these systems, along with the expected size necessary for them to provide the required vehicle range. As the economy is expected to decarbonize continuously, we assume the GHG emission factors are lower in 2030 as energy inputs required for the manufacture of HDVs become lower-carbon. This assumption agrees with the expected greening of electricity via higher renewable penetration and reduced fossil fuel-generated electricity, as outlined in the IEA's World Energy Outlook (IEA, 2020).

Table 4. Summary of vehicle manufacturing emission factors.

Parameter	Value	Data source	Notes
HDV glider and powertrain manufacturing emissions	3.2 t CO_2e/t (2021) 2.9 t CO_2e/t (2030)	Scania (2021)	Extrapolated from total truck CO_2 figure of 27.5 tonnes. Figure is increased by 6% for NG versions
Battery manufacturing emissions	58 kgCO_2e/kWh (2021) 37 kgCO_2e/kWh (2030)	Derived from Bieker (2021) and ANL (2020)	Represents the carbon per kWh of battery based on a weighted EU market mix of batteries made in the EU, the US and China for 2021, and EU-made for 2030
Fuel cell and H_2 storage tank manufacturing emissions	4.2 t CO_2e (2021) and 3.4 t CO_2e (2030) per 5 kg gaseous storage tank and fuel cell per fuel cell and 5 kg gaseous storage tank	Derived from Bieker (2021) and ANL (2020)	Unit = a fuel cell and 5 kg tank. Emissions multiplied to get necessary total gaseous H_2 storage for HDVs.

We calculate the impact of battery production using life-cycle GHG emission factors (in kgCO_2e/kWh) that reflect the GHG emissions of batteries used in Europe. Some batteries will be made in Europe using European energy inputs, while other batteries will be made in China, Japan, South Korea, and the United States and imported into Europe. Adjusting these emission factors, along with the battery capacities (in kWh), provides a likely emissions estimate for manufacturing batteries. For HDVs registered in 2021, the GHG emission factors of the battery production are principally based on the most common battery chemistry (using lithium nickel manganese cobalt oxide (NMC622) cathodes) and the regional mix of batteries produced in Europe and imported from other world regions. For the share of batteries made in China, we assume lithium iron phosphate batteries as the battery type. For HDVs expected to be registered in 2030, these factors correspond to an even share of high-nickel NMC811 and lithium iron phosphate batteries that would be produced domestically in Europe. The emissions associated with battery production are expected to be lower in future as the electricity grid that powers these factories becomes less carbon-intensive over time. Table 4 provides a summary of the emissions factors for manufacturing the HDVs, including separate manufacturing emissions for batteries.

We base battery capacity assumptions for battery electric HDVs in 2021 on ICCT's own technology analysis with the intention to provide a reasonable and practical range for the vehicle. The trend of declines in battery costs in conjunction with likely increases in battery densities, we assume the BEV batteries produce more power per kilogram in 2030. Further, battery recycling is likely to reduce the GHG emissions impact of batteries significantly. Due to uncertainty regarding future recycling processes, however, we exclude the corresponding GHG emission credits from this assessment.

Emissions of GHGs from the production of both the hydrogen tank and fuel cell in FCEVs vary based on the capacity of the hydrogen tank and mostly come from the energy-intensive production of the hydrogen tank. For the purposes of this study, we assume the storage system for gaseous hydrogen to be a series of smaller tanks linked to provide the necessary storage. We therefore scale the GHG emissions associated with their production proportionally to the emissions associated with a single tank currently produced for lighter duty vehicles (NREL, 2021; Hyundai, 2022). The hydrogen systems are assumed to be produced with 20% lower GHG emissions in 2030. As materials from carbon fiber-reinforced plastic are currently incinerated or disposed as landfill, we do not consider the recycling of hydrogen tanks in this analysis. Recycling processes are being developed to reduce the emissions from the hydrogen system in future (Karuppannan Gopalraj & Kärki, 2020). For the 40-tonne fuel cell tractor-trailer both liquified and gaseous pathways were modeled, with the gaseous hydrogen pathway presented in the charts. Due to data gaps, we use production emissions for a gaseous hydrogen tank as a proxy for the liquid hydrogen tank. For the LNG-fueled tractor trailer, we estimate upstream emissions for the LNG tank based on manufacturing energy intensity as estimated by Hu et al. (2022); these are combined with an assumption of 900 kg for the tank's weight and the associated upstream steel manufacturing emissions as estimated in ANL (2020).

We include the relatively small contribution of maintenance emissions to overall vehicle cycle emissions. Scania, in a study comparing an ICEV and a BEV truck, found that if tires are excluded, the environmental impact of maintenance is "insignificant in the whole," contributing between 0.1% and 0.3% of the life-cycle emissions for both ICEV and BEV (Scania, 2021). They noted difficulty with defining an average figure for the share of maintenance emissions (excluding tires) because of the wide range of how vehicles are used and operate. Low-maintenance emissions relative to the total emissions per kilometer is consistent with similar findings for HDVs by Ricardo (2020) and also for light-duty vehicles (Bieker, 2021). In this study, maintenance GHG emissions are low, ranging from 4 gCO_2e/km to 7 gCO_2e/km, and thus agree with previous analyses of both diesel and the alternate powertrains.

We include an assumption for battery electric HDVs of one battery replacement throughout the vehicle life, a middle-range assumption based on a review of estimated battery lifetimes. Specific to its medium-sized rigid trucks, Volvo Trucks (2020) estimates a lifetime of between 8 to 10 years for the batteries. Production emissions of batteries are expected to decline over time as the electricity grid continues to decarbonize. For this analysis, we consider the upstream production emissions of the replacement battery to be the same as for the first battery, so the value can be considered an overestimate.

Lifetime mileage

Based on a recent ICCT analysis by Mulholland et al. (2022) we consider an average useful vehicle lifetime of 20 years for all three HDV segments. With the EU average distribution of annual mileage of 12-tonne rigid trucks, 40-tonne articulated trucks, and urban buses per vehicle age from TRACCS (2013), we determine an accumulated lifetime mileage of 900,000 km, 1,300,000 km, and 900,000 km, respectively. Further, the distribution of the annual mileage per vehicle age, indicates a decrease in the annual mileage of 6%-7% per year of vehicle operation. By considering this decrease, the carbon intensity of the fuel and electricity mix in the first years of operation is accounted for with a higher proportion than the carbon intensity of the mixes in the later years.

Table 5. Considered vehicle lifetime and lifetime mileage.

Parameter	Vehicle category	Value	Data Source	Notes
Vehicle lifetime	**12-t truck**	20 years	Mulholland et al. (2022)	Age at which at 50% of heavy trucks in the EU have been retired
	40-t tractor-trailer	20 years	Mulholland et al. (2022)	Age at which at 50% of heavy trucks in the EU have been retired
	Urban bus	20 years	Mulholland et al. (2022)	Age at which at 50% of buses in the EU have been retired
Lifetime mileage	**12-t truck**	856,000 km	TRACCS (2013)	Accumulated annual mileage, 20 years
	40-t tractor-trailer	1,243,000 km	TRACCS (2013)	Accumulated annual mileage, 20 years
	Urban bus	881,000 km	TRACCS (2013)	Accumulated annual mileage, 20 years

FUEL CYCLE

This analysis includes the full life-cycle GHG emissions associated with the fuel or electricity consumed during vehicle operation in the fuel cycle. These emissions include well-to-tank emissions from the production of the feedstock and fuel, and tank-to-wheel emissions from the fuel consumption in the vehicle. The fuel, electricity, and hydrogen consumption values correspond to real-world driving conditions rather than test-cycle vehicle efficiency. The study assesses the impacts of both the grid-average upstream GHG emissions of electricity sourced from the EU average grid, as well as the life-cycle emissions attributable to renewable electricity sources. We attribute upstream emissions for infrastructure to build new renewable electricity capacity to these emissions; however, even with infrastructure emissions included, these emissions are substantially lower than that of fossil fuels or the current grid average (Prussi et al., 2020). The fuel mix assumptions are intended to reflect averages for the EU. Changes in the average carbon intensity of the fuel and electricity mix over the lifetime of the 2021 and 2030 HDVs are based on stated policies. As a result, and as the grid and the fuels decarbonize into the future, a vehicle using these energy sources will have a lower fuel cycle impact further in the future along its expected lifetime. While both vehicle model years will benefit from this greening effect, the 2030 vehicle will benefit more as it begins life with lower carbon fuels and energy sources than the 2021 model.

Table 6. Scope of GHG emissions considered in fuel cycle.

Fossil fuels	• Crude oil/natural gas extraction (including flaring), processing and transport, and fuel refining and distribution; all including methane leakage • CO_2, methane, and nitrous oxide (N_2O) emissions of fuel consumption
Biofuels	• Plant cultivation/waste collection, processing and transport, and fuel production and distribution • Indirect land use change GHG emissions of plant cultivation • Methane and N_2O emissions of fuel consumption
Electricity	• GHG emissions of electricity generation, including new power plant infrastructure for renewable energy, transmission, distribution, and charging losses
Hydrogen	• For electrolysis-based hydrogen: GHG emissions of electricity, adjusted by energy losses during electrolysis and hydrogen compression or liquefaction • For natural gas-based hydrogen: natural gas extraction, processing, and transport; steam reforming and hydrogen compression; all including methane leakage • *Not included:* Long-distance hydrogen transport

Table 7 gives an overview of the GHG intensity of the various energy and fuel sources examined in this study. We assume that the diesel mix consumed by HDVs contains a small fraction of biofuels, consistent with existing EU policy commitments. We estimate the upstream GHG emissions for biofuels as these have their own separate life-cycle GHG emissions. For the EU biofuels mix, we assume a B7 (7% by volume) biodiesel blend currently in diesel fuel. For FAME, the main feedstocks are rapeseed and palm oil, followed by used cooking oil and smaller amounts of animal fat and soybean oil. Similar feedstocks are considered for hydrotreated vegetable oil production, and the specific shares of feedstocks for both biofuels come from Prussi et al. (2020) and are shown in Figure 3.

Table 7. Carbon intensity of fuels and energies used.

			12-t truck	40-t truck trailer	Bus	Emissions factor
Electricity	IEA SPS Scenario (main electricity CI in model)	2021 vehicles	194	197	197	gCO_2e/kWh
	IEA SDS Scenario (lower CI electricity sensitivity)		161	164	164	gCO_2e/kWh
	IEA SPS Scenario (main electricity CI in model)	2030 vehicles	128	129	129	gCO_2e/kWh
	IEA SDS Scenario (lower CI electricity sensitivity)		95	96	96	gCO_2e/kWh
Hydrogen	Hydrogen from natural gas	2021 vehicles		410		gCO_2e/kWh
	Renewable hydrogen	2021 and 2030 vehicles		39		gCO_2e/kWh
	Blend: 50% renewable H_2 and 50% CCS natural gas H_2	2030 vehicles		71		gCO_2e/kWh
Fossil fuels (including biofuel blend)	Diesel	2021 vehicles		97.5		gCO_2e/MJ
	CNG			67.4		gCO_2e/MJ
	LNG			75.4		gCO_2e/MJ
	Diesel	2030 vehicles		95.1		gCO_2e/MJ
	CNG			65.2		gCO_2e/MJ
	LNG			74.7		gCO_2e/MJ

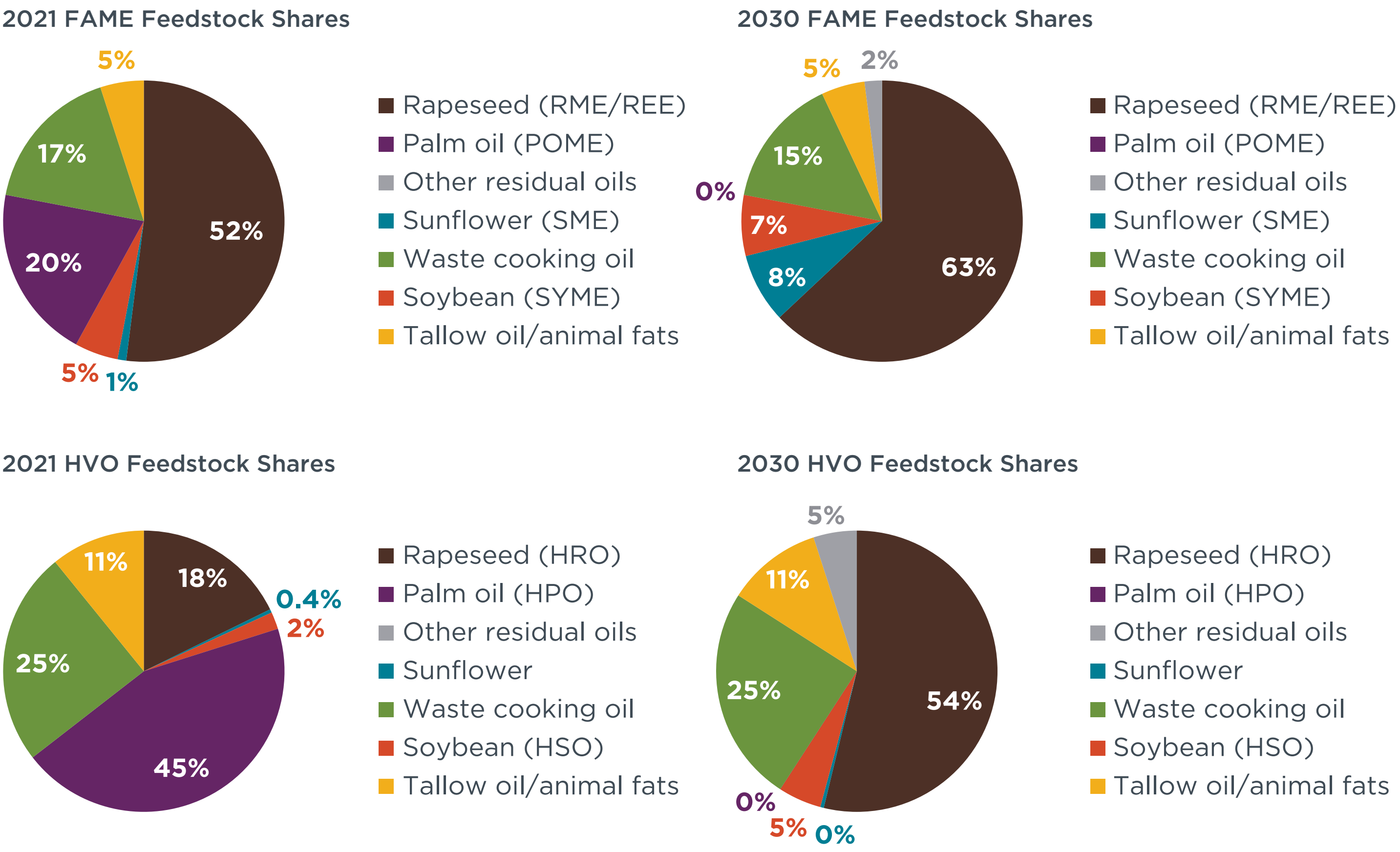

Figure 2. Share of biofuel feedstocks for 2021 and 2030 (ICCT assumptions based on stated policies).

While the overall EU biofuel blend level is considered to remain at 7% by volume for 2030, the primary change is a phase-out of palm oil by 2030, replaced by increased volumes of mainly rapeseed oil, with smaller extra volumes of soybean oil and sunflower oil. We include ILUC emission factors for the food-based biofuel feedstocks based on an ILUC emissions assessment of biofuels in the EU (Valin et al., 2015).

For natural gas, we assume 3.4% bio-component for 2021 (a mix of silage maize-based and waste-based biomethane), which we assume will increase to nearly 5% by 2030, based on an assumed increase in production of the waste-based biomethane fraction. The LCA emissions for fossil natural gas are based on Prussi et al. (2020), which include CNG and assume it is mainly sourced by pipeline with a minor fraction coming from LNG imports, while LNG itself is assumed to be based entirely on imports via ship. We note that ongoing geopolitical events related to the 2022 war in Ukraine are likely to affect assumptions on natural gas sourcing going forward. For the natural gas pathways, we include methane slip (or leakage) that we consider to occur both upstream of the vehicle during the fuel production phase and during the use of the vehicle itself. For the 40-tonne tractor-trailer, we model an LNG vehicle, whereas we assume that both the 12-tonne truck and the urban bus would use CNG. The increased range between fuel stops for an LNG vehicle compared to a CNG vehicle comes at a cost of higher GHG emissions, as natural gas requires more energy to compress it to a liquid state instead of to a gas, and the manufacturing emissions for the LNG fuel tank are higher than for a CNG tank.

For battery electric HDVs, we explore the impacts of using grid-average electricity as well as renewable-only electricity. Renewable electricity in the EU is considered to be a split of 67% wind and 33% solar power, and the renewable electricity GHG intensity includes the GHG impact of building new generation equipment (Moomaw et al., 2011). The GHG intensity of the EU's electricity grid has been declining over the past two decades and is projected to decrease further. Projections on the generation mix in the EU are from IEA (IEA, 2022), while the life-cycle carbon intensity for the different types of electricity come from the IPCC in Moomaw et al. (2011). In addition, the annual mileage over the lifetime of the vehicles decreases, which results in a higher weighting of the carbon intensity of the fuel or energy in the early years.

As Bieker (2021) noted in a previous LCA analysis of light-duty vehicles, any projection of future electricity mix carries large uncertainties. Similar to Bieker, this work incorporates data from the IEA's World Energy Outlook (IEA, 2020) on the types and shares of electricity generation expected in the future. We compare a conservative baseline, the Stated Policy Scenario (SPS), with the IEA's more optimistic Sustainable Development Scenario (SDS). The latter of these scenarios projects advancements in the power sector that comport with the Paris Agreement's goal of limiting global warming to below 2°C. We assume transmission and distribution losses in the electricity network of 6% (i.e., we increase the GHG emissions per kilowatt-hour of the electricity by 6%) (Worldbank, 2018). In addition, we include a charging loss rate of 5% in the assessment of electricity emissions; the 5% charging loss matches the overnight charging loss in Scania (2021) for rigid battery electric trucks.

For FCEVs bought in 2021, we compare the emissions of using hydrogen produced from fossil natural gas using steam methane reforming (SMR) with the emissions of using only green hydrogen. For vehicles bought in 2030, we further show the emissions of using a blend of 50% blue fossil hydrogen produced using CCS during SMR and 50% green hydrogen produced from renewable electricity-powered hydrolysis. We reflect in the lower production emissions the change in the upstream emissions for hydrogen production in future compared to the current supply, which is 100% fossil. The potential future blend of blue and green hydrogen has an 83% lower GHG intensity relative to the SMR natural gas case. For hydrogen produced from natural gas, we include upstream methane leakage emissions of 0.34 g CH_4 per MJ hydrogen (Argonne National Laboratory, 2020). Upstream methane emissions are the same for hydrogen production from natural gas regardless of whether CCS is present; the primary difference between conventional SMR hydrogen and blue hydrogen is that the CO_2 emissions from the steam-reforming process are captured with CCS. We model the hydrogen used in the 40-tonne tractor-trailer FCEV as both compressed and liquefied. The liquified pathway allows a greater range between fuel stops for this vehicle, but it generates higher GHG emissions than a comparable vehicle using compressed hydrogen, principally due to the extra energy needed to liquify the hydrogen, which increases its GHG intensity by 16%.

RESULTS

Figure 3 through Figure 5 illustrate the life-cycle GHG emissions in gCO_2e/km for HDVs in Europe powered by diesel- or natural gas-fueled ICEs, along with battery electric HDVs and fuel cell HDVs over the lifetime of vehicles produced in 2021. Each of the following three charts represents a different HDV type: the first gives results for 12-tonne trucks, the second for tractor-trailers, and the third for urban buses.

In each graph below, the columns illustrate the total, per-kilometer GHG emissions for each fuel and powertrain option analyzed. Each column shows the different contributors to the overall emissions per powertrain. The dark blue sections represent the combustion emissions of the fuel, and the lighter blue sections (at the top of each column) represent the emissions associated with the fuel or energy production. Non-CO_2 tailpipe emissions (CH_4 and N_2O) are included as equivalent amounts of CO_2 in the combustion emissions section, as their overall effect per kilometer is minor, adding between 39g and 65 gCO_2e/km for the diesel and natural gas variants. The graphs show that emissions from producing the fuel and emissions from combustion typically constitute the largest part of the total emissions for each pathway, except when large amounts of renewable energy are used. Manufacturing emissions are also included for the vehicles, and for the batteries, hydrogen or LNG tanks, where necessary (colored yellow and orange, respectively). We include maintenance emissions, but these make up a small part of the per-kilometer emissions.

2021 VEHICLES

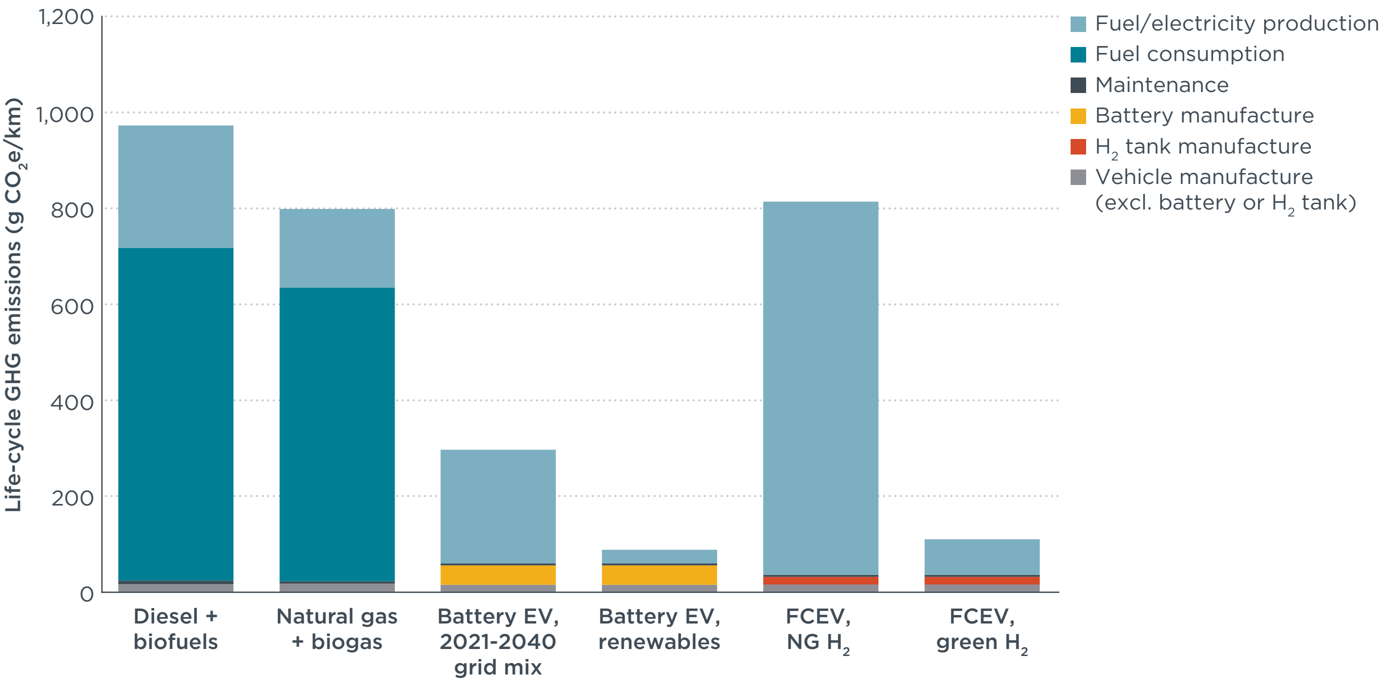

Figure 3. Life-cycle GHG emissions of 12-t rigid trucks driven in the EU in 2021 to 2040.

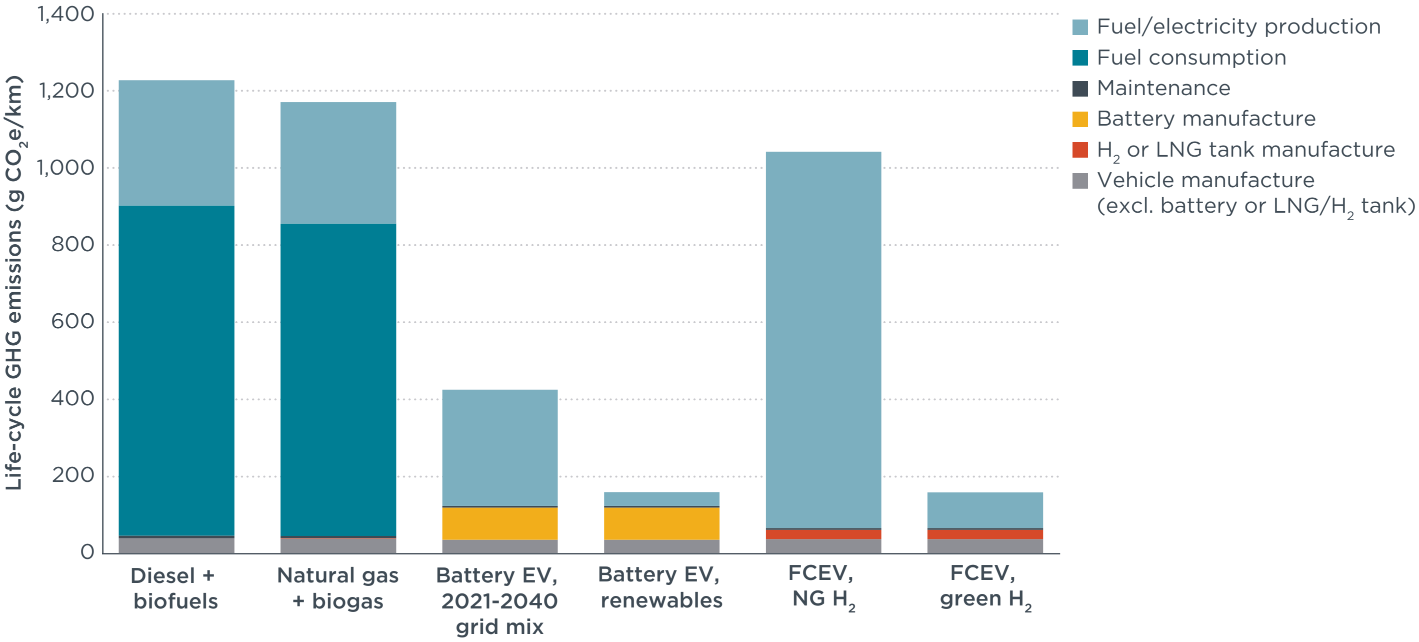

Figure 4. Life-cycle GHG emissions of 40-t tractor-trailers driven in the EU in 2021 to 2040.

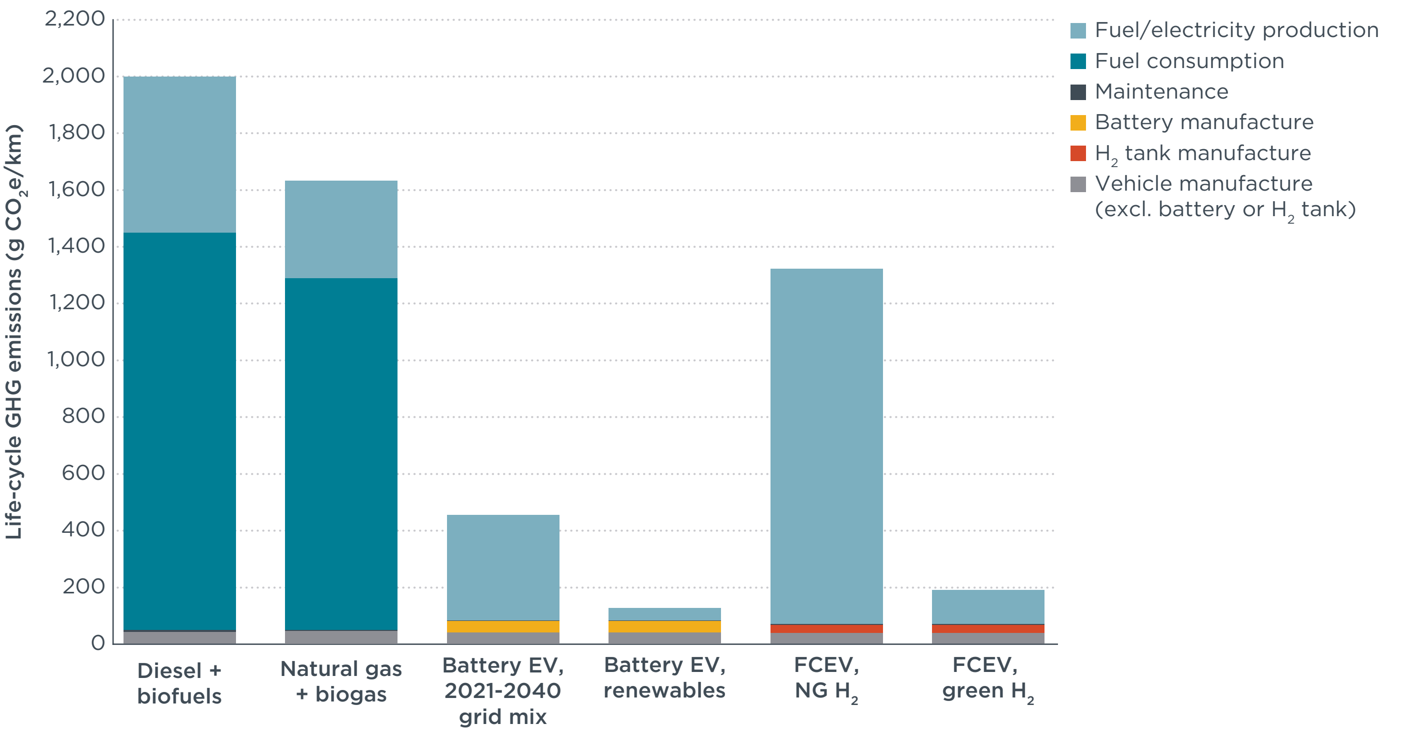

Figure 5. Life-cycle GHG emissions of urban buses driven in the EU in 2021 to 2040.

For vehicles produced in 2021, we estimate that the battery electric HDVs have substantially lower emissions than diesel HDVs across all three HDV types. We estimate that when battery electric HDVs use the average EU grid electricity, they reduce GHG emissions per kilometer compared to pure diesel ICE HDVs by between 65% and 77%. This already large improvement in performance is increased further if the same electric HDV is supplied with 100% renewable electricity; in this case, the range of GHG emissions reductions per kilometer for battery electric HDVs compared to diesel ICE HDVs grows to between 87% and 94%. Our assumption of one battery replacement in the assumed HDV lifetime increases the battery manufacturing emissions for the battery electric HDV. This methodological choice, in conjunction with the comparatively large battery considered for the tractor-trailer, results in the

40-tonne tractor-trailer generating the highest GHG emissions associated with battery manufacturing for all three HDVs.

We estimate that fuel cell HDVs can reduce GHG emissions compared to diesel powertrains, but the degree to which this happens relies principally on (a) the source of the hydrogen, and (b) whether gaseous or liquified hydrogen is used. We find that fuel cell HDVs principally using SMR-derived gaseous hydrogen can reduce the GHG emissions compared to a state-of-the-art Euro VI diesel HDV by between 15% for tractor-trailer HDVs and 34% for urban buses. While these GHG reductions appear to offer improvement, the benefits are substantially greater when the fuel cell powered HDV is supplied with green hydrogen made from 100% renewable energy. Using green hydrogen, we estimate that the fuel cell HDV will reduce life-cycle GHG emissions compared to a diesel version by between 87% for tractor-trailers and 91% for urban buses. The reductions achieved by the fuel cells powered with 100% renewable hydrogen provide comparable emissions savings to battery electric HDVs powered by 100% renewable electricity.

Regarding the use of liquid versus gaseous hydrogen, the liquefaction of hydrogen uses more energy than producing gaseous hydrogen and requires a more robust fuel tank capable of holding liquid rather than gas. We assumed the HDVs store gaseous hydrogen via a number of small hydrogen tanks. However, if we assume the 40-tonne tractor-tractor uses liquid hydrogen instead and stores it in a single large tank, we see an increase in emissions. The extra energy required for liquefaction causes most of this increase. A 2021 model year 40-tonne FCEV tractor-trailer using compressed fossil-derived hydrogen (i.e., hydrogen produced from natural gas) generates lifetime GHG emissions of 1,042 gCO_2e/km. Using liquefied hydrogen instead increases emissions by 15% to 1,194 gCO_2e/km. The emissions of the liquified hydrogen FCEV thus approach those of the diesel ICE version, which emits 1,268 gCO_2e/km.

Comparing diesel ICE HDVs to natural gas-fueled HDVs (with a fossil content of 96.6% and a 3.4% share of biomethane), we estimate that these vehicles would generate relative GHG savings of 18% for rigid trucks and urban buses but generate only a lifetime reduction of 5% in the GHG emissions of the 40-tonne tractor-trailers.

2030 VEHICLES

Figure 6 through Figure 8 illustrate the life-cycle GHG emissions in gCO_2e/km for HDVs in Europe powered by diesel- or natural gas-fueled ICEs, along with battery electric HDVs and fuel cell HDVs. These graphs illustrate the results for vehicles produced in 2030 and operated through 2049. As before, each graph represents a different HDV type, and each column delineates emissions from fuel production and consumption, maintenance, and manufacture.

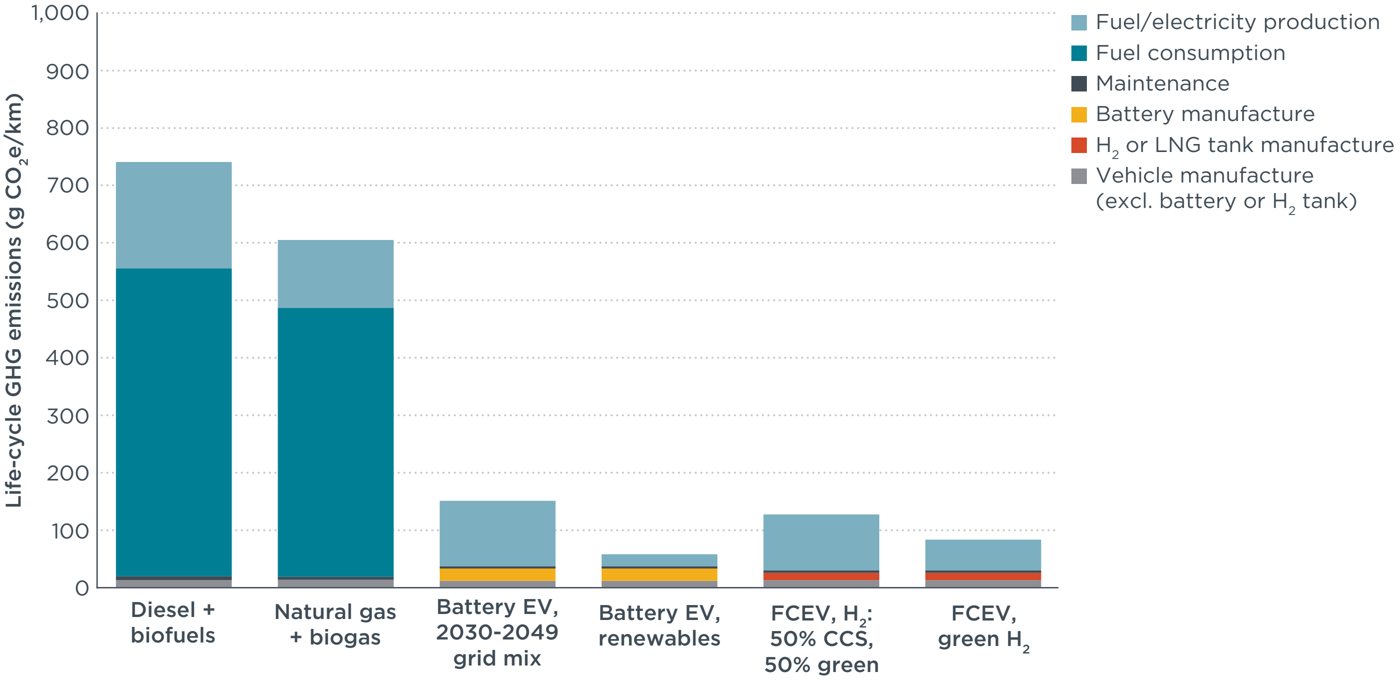

Figure 6. Life-cycle GHG emissions of 12-t rigid trucks driven in the EU in 2030 to 2049.

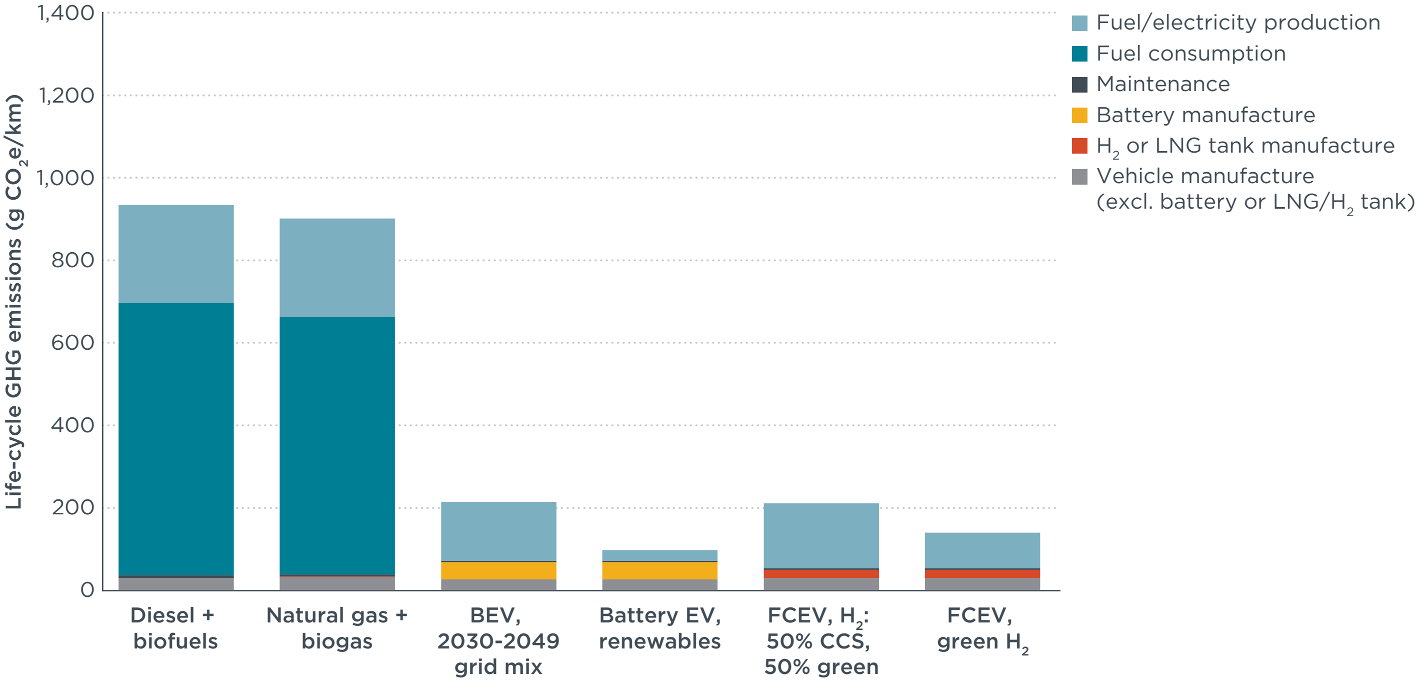

Figure 7. Life-cycle GHG emissions of 40-t tractor-trailers driven in the EU in 2030 to 2049.

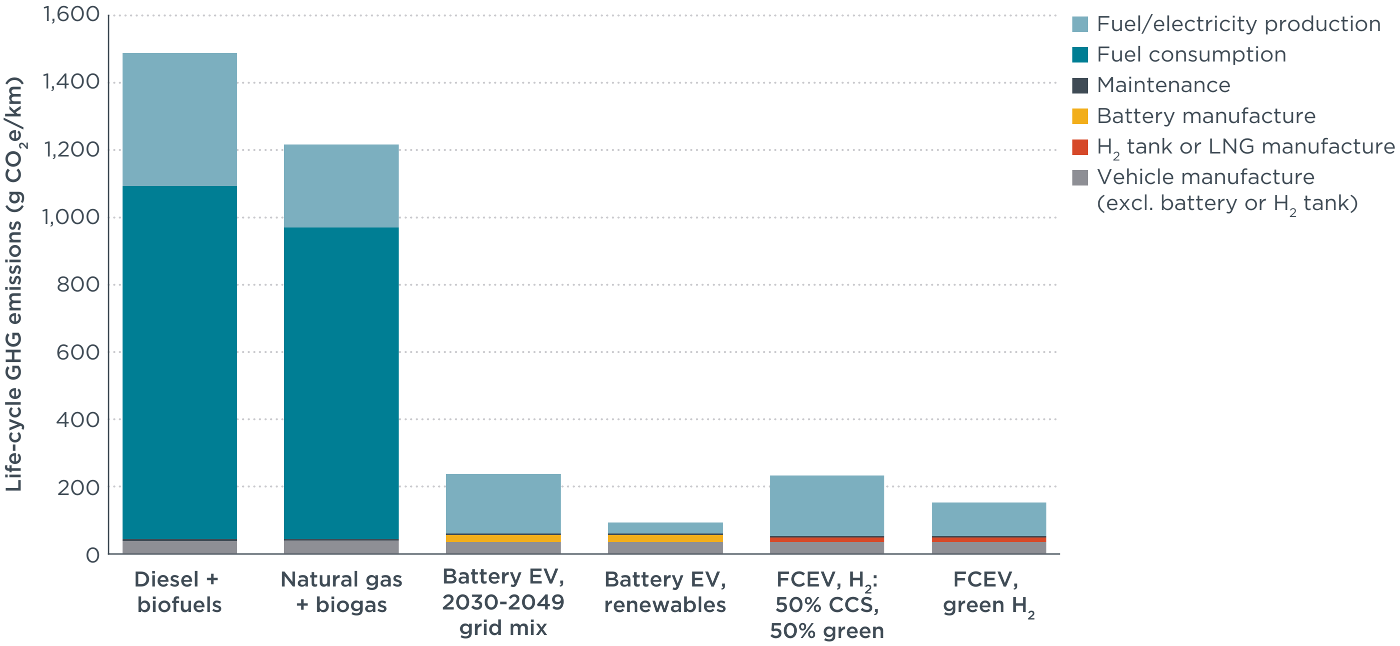

Figure 8. Life-cycle GHG emissions of urban buses driven in the EU in 2030 to 2049.

For HDVs produced in 2030, emissions for all vehicles and fuel pathways are lower compared to 2021 vehicles due to a combination of generally lower-carbon fuels and the assumption of an about 25% lower fuel or energy consumption than observed for current models. For the baseline HDV technology (pure ICE-powered HDVs fueled with diesel), GHG emissions improve slightly compared to the 2021 model year. We observe life-cycle emission reductions of 24% to 26% across the three vehicle categories for the ICE drivetrain, primarily due to lower fuel consumption.

We estimate that battery electric HDVs driven from 2030 to 2049 provide large life-cycle GHG emissions savings compared to the more fuel-efficient 2030 diesel counterparts; If average EU grid electricity is used, they generate a lifetime GHG emissions benefit of 77% to 84%. These percentage savings over the diesel baseline are greater than for 2021 vehicles; while the diesel ICEs are assumed to be more efficient, the combined effect of more efficient battery electric HDVs and further decarbonization of the electricity grid has a greater impact. Powering the battery electric HDVs using 100% renewable electricity instead of grid electricity, the savings compared to diesel ICEs are higher, with savings ranging from 89% (for the tractor-trailers) to 92% to 94% (for both 12-tonne trucks and urban buses).

2030 fuel cell HDVs powered by a mix of 50% renewable and 50% blue hydrogen show 78% to 85% lower life-cycle GHG emissions than diesel vehicles. When using 100% green hydrogen, the GHG savings increase further to 85% for the tractor-trailers and 89% to 90% for both 12-tonne trucks and urban buses, which is similar to the battery electric HDVs using 100% renewable electricity.

Looking at natural gas-fueled HDVs, we observe GHG emissions savings of up to 18% for the urban bus compared to the baseline. However, similar to 2021, the natural gas-fueled tractor-trailer exhibited a decrease in GHG emissions of only 3% compared to a diesel version. We estimate that the 12-tonne truck using natural gas has a 18% GHG savings compared to diesel.

DISCUSSION

Our analysis illustrates how a transition from diesel to electric powertrains provides large reductions in GHG emissions even with the EU average electricity mix. Over their lifetime, battery electric HDVs produced today correspond to 65% to 77% lower life-cycle GHG emissions than current best-in-class diesel HDVs. The reduction in GHG emissions that the battery electric HDVs provide is principally due to the vehicles' higher energy efficiency and the lower carbon intensity of the average electricity mix compared to diesel fuel. As the grid incorporates more renewable electricity over time, the emissions from driving on grid electricity will decline even further. The results suggest that even when factoring in high efficiency improvements for future diesel-fueled HDVs, the relative advantage of battery electric HDVs over diesel ICE vehicles in GHG emissions is expected to increase further for vehicles produced in 2030.

We find that fuel cell HDVs have great potential to provide large GHG emissions reductions, but we estimate only modest reductions in GHG emissions versus diesel HDVs if hydrogen originating from fossil natural gas is used as the main feedstock for hydrogen production. However, if the hydrogen comes from additional renewable energy, then the overall emissions savings become comparable to that of battery electric HDVs using 100% renewable electricity. The energy demand in fuel cells for driving on renewable electricity-based hydrogen is three times higher than if the electricity is used directly in BEVs. While renewable capacities remain limited, the availability of renewable electricity for less efficient technologies is a concern (Ueckerdt et al., 2021). To avoid diverting this renewable electricity from an existing use, the renewable energy for FCEVs must come from new, additional power plants. Though the GHG emissions from hydrogen combustion are zero, upstream production emissions can be the highest of all pathways analyzed here if natural gas is used. It is therefore critical that if fuel cell HDVs are chosen over diesel HDVs, the upstream hydrogen production is either from additional renewable electricity or incorporates CCS to achieve meaningful life-cycle GHG savings relative to diesel HDVs. We find that using fossil natural gas without CCS will, at best, result in very minor savings compared to diesel.

Unlike fuel cell HDVs, battery electric HDVs can provide substantial GHG emissions savings compared to diesel ICE HDVs using the existing electricity grid. At a global scale, the supply chain for renewable hydrogen is considered minimal, and its use is limited to a few small projects (International Renewable Energy Agency, 2021). The IEA has estimated that, in 2020, renewable hydrogen accounted for approximately 0.03% of hydrogen production for energy and chemical feedstocks (IEA, 2021). Thus, while having the potential to provide low GHG emissions, fuel cell HDVs would currently rely on fossil hydrogen, which would result in fewer GHG savings than battery electric HDVs currently using EU grid-average carbon intensity electricity. Further, the costs of renewable hydrogen production in the EU are significant, although with subsidies this production could reach price parity with diesel fuel in 2030 (Zhou & Searle, 2022). Given the current lack of green hydrogen and the high costs of production, and the ability of battery electric HDVs to provide significant GHG emissions savings, battery electric HDVs are currently more promising than fuel cell HDVs to provide the EU HDV sector with significant GHG emissions savings compared to diesel. While battery weight can affect payload capacity, battery electric HDVs in the EU are allowed an additional 2 tonnes on their maximum overall weight, which helps reduce this effect (*Regulation (EU) 2019/1242*, 2019).

Comparing diesel ICE HDVs with natural gas-powered versions, natural gas generates lower emissions than diesel during its production, but emissions during its use in natural gas HDVs are similar to, and in some cases higher than, emissions in diesel HDVs. Methane leakage is included in this analysis; we include leakage arising during production and supply in addition to methane slip from vehicle operation. While these vehicles' methane emissions are minor, methane leakage during fuel production and supply is more significant. While using a greater share of biomethane in the natural gas may result in lower GHG emissions, the GHG intensity can vary widely depending on which feedstock it is made from (Prussi et al., 2020). Furthermore, the supply of highly sustainable feedstocks is not scalable in the manner required to power the EU's HDV fleet (Searle et al., 2021). Even with strong policy support, Searle et al. estimate that low-carbon biomethane could supply the EU-27 with only 2% of its total natural gas consumption in 2030 and 6% in 2050. Thus, natural gas HDVs are unlikely a viable route to achieving meaningful decarbonization of the HDV sector. We also explore the potential risks from natural gas HDVs in the sensitivity analysis which follows, factoring in a higher GWP value to illustrate the climate impact of natural gas in the near term.

The GHG intensity of the electricity grid of Member States varies depending on the sources used to make electricity and the level of imports and exports (EEA, 2021a; Moro & Lonza, 2018). We illustrate how a greener grid factoring in emission reductions from 2021 to 2030 improves the GHG emissions of the battery electric HDV. Even with higher GHG intensity electricity, BEVs can support GHG savings compared to diesel versions. For example, if a 12-tonne battery electric truck consumes the average electricity of an individual EU Member State with grid GHG emissions at the higher end of the range of grid GHG emissions in the EU, such as Poland at 600 gCO_2e/kWh (EEA, 2021a), and when assuming that the carbon intensity would not change during the 20-year lifetime of the vehicle, the GHG emissions savings compared to diesel would fall from 70% to 18% or less. As another example, the GHG intensity of electricity produced in the EU from natural gas within the RED recast (Giuntoli et al., 2017) is 412 gCO_2e/kWh; using this electricity in an urban bus in the 2021 scenario, for example, would reduce GHG emissions versus diesel from 77% to 57%. Carbon intensity of electricity grids varies not only between Member States but by the time of day, depending on the generating mix (electricityMap, 2022). The time at which a BEV is charged affects the GHG emissions of the BEV per kilometer. However, an analysis by the U.S. National Renewable Energy Laboratory in 2016 evaluated the emissions associated with EV charging and found that the average composition and generation capacity of the grid has a greater effect on the GHG emissions of an electric vehicle than the charging scenario, which included different charging times (McLaren et al., 2016).

The EU grid is getting greener: in 2020, it was 54% less GHG-intensive than in 1990. Up to 2010, greater efficiencies in fossil electricity production was the primary driver of the reduction in the EU grid's GHG intensity, but since then, the decrease in GHG emissions is considered to be due almost exclusively to the transition from fossil fuels to renewable fuels in electricity generation (EEA, 2021a). Increased electrical demand due to increased electric vehicle usage differs from only having increased marginal electricity demand during peak load times; electric vehicles are also charged at times outside peak load hours. Electric vehicles will continue to come onto the grid gradually over many years concurrent with utilities bringing on new electricity generators to supply them. Electric vehicles will change load demand patterns, but the effect of these changes in practice is not yet clear, especially as utilities are continually adapting, for example, by offering new time-of-use fee structures. Assuming a worst-case scenario—in which electric vehicles will only be charged at peak load times, and the added electricity supply to meet new demand will be fossil-based—ignores the decarbonization trend of the EU grid and the variety of times at which drivers charge their electric vehicles. The net effect of adding more electric vehicles to the grid paired with the addition of more renewable electricity generation over the coming years means it is reasonable to assume the resulting GHG intensity of the electricity used to power these EVs will likely be similar to the average EU grid mix.

SENSITIVITY ANALYSIS

In this section, we investigate changes to certain input parameters for the LCA to identify their impacts on the overall results.

Methane global warming potential

A key parameter this study evaluates is the potential impact of upstream methane leakage on the overall GHG emissions produced by natural gas HDV pathways. Methane emissions are a key contributor to the overall emissions impact of both natural gas-powered HDVs and fuel cell-powered vehicles using hydrogen derived from natural gas. These emissions may occur during both the production and distribution of the natural gas and in the use phase of the vehicle.

Methane emissions are characterized through an equivalent amount of CO_2 (CO_2e) based on methane's GWP. Using a 100-year GWP, 1g of fossil CH_4 = 30 gCO_2e. However, using a 20-year GWP, the impact is almost three times higher at 85 gCO_2e (IPCC, 2013). A 20-year GWP emphasizes that methane has a higher climate impact than CO_2 in the first years after emission, while it continuously decomposes to CO_2 and thereby approaches the climate impact of CO_2 in the long term. By comparison, N_2O emissions remain practically the same regardless of which of the two GWPs is used.

Using the 20-year GWP for methane increases the GWP of both the fuel cell HDVs using natural gas-derived hydrogen and natural gas-fueled HDVs. Considering the 40-tonne tractor-trailer, the 5% GHG emissions decrease previously exhibited by the LNG variant of 2021 vehicles becomes a larger net emissions increase of 22% when compared to diesel (see Figure 9). For the 40-tonne tractor-trailer, the emissions from the LNG version reach 1,500 gCO_2e/km compared to 1,228 gCO_2e/km for the diesel version. Looking at the fuel cell variant of the same HDV, the small GHG savings compared to diesel when using fossil natural gas as feedstock for hydrogen production decrease further, shrinking to under 2%.

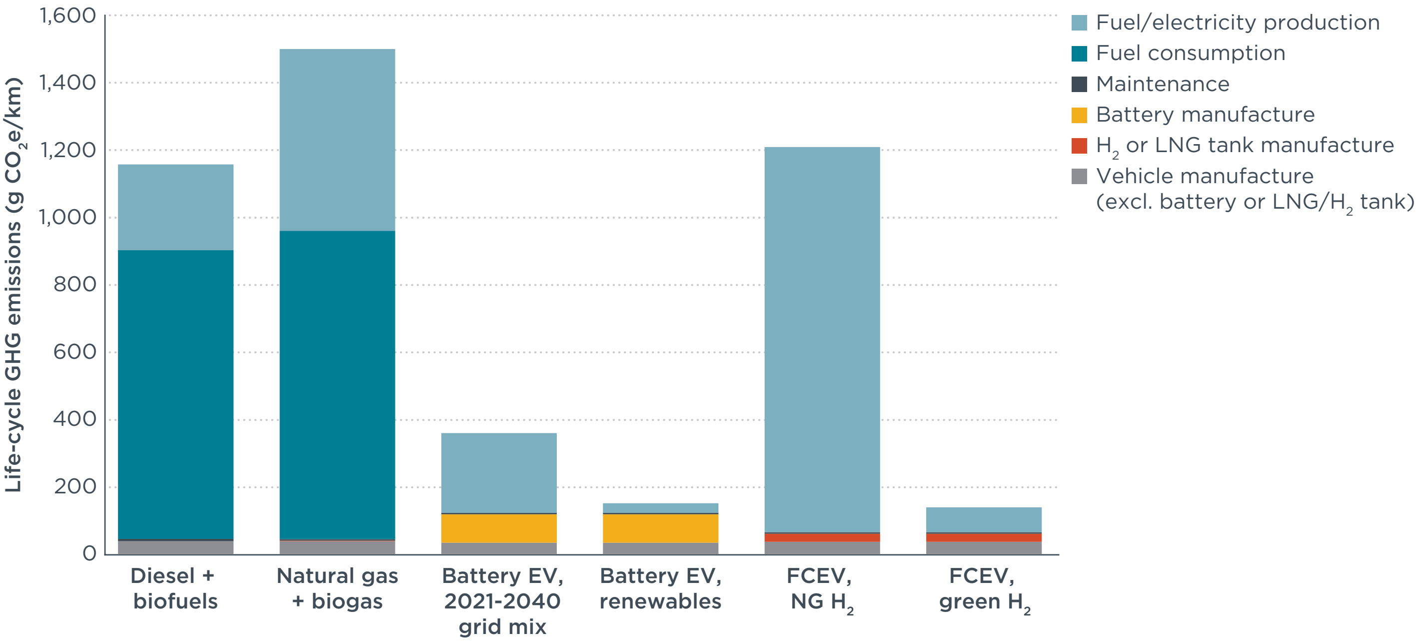

Figure 9. 20-year global warming potential of the life-cycle GHG emissions of 40-t tractor-trailers driven in the EU in 2021 to 2040.

Power-to-liquids

We develop a sensitivity analysis to compare the GHG emissions resulting from fueling a 40-tonne HDV powered by diesel containing 2.6% of an electrofuel, which in this case can also be called a power to liquid (PtL), as shown in Figure 10.

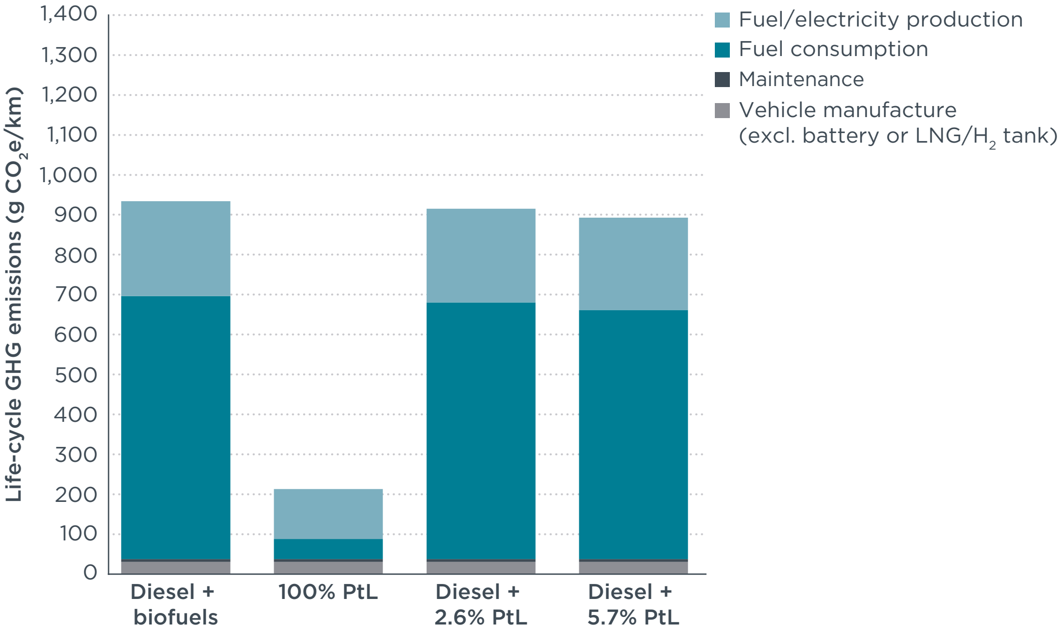

Figure 10. Life-cycle GHG emissions of 40-t tractor-trailers driven in the EU in 2030 to 2049 comparison of (i) diesel + biofuels, (ii) a pure renewable power to liquid (PtL) pathway, (iii) European Commission legislative proposal for a 2.6% PtL blend in diesel in 2030, and (iv) a 5.7% PtL blend considered by the European Parliament.

We sourced the PtL pathway input data from Prussi et al. (2020). We also include the upstream emissions attributable to renewable electricity generation to produce PtL fuel, consistent with the emission factors used for the 100% renewable battery electric pathway, based on conversion yields estimated by Prussi et al. (2020). The pathway models the conversion of renewable electricity to syndiesel, with methanol made in an interim step before being transformed into synthetic diesel. The CO_2 is considered to be captured at a point source from flue gases (Prussi et al., 2020).

The first column in Figure 11 shows the emissions per kilometer of a diesel ICE 40-tonne tractor-trailer using diesel fuel containing 7% biofuels. The second column shows the emissions for the same type of vehicle using a PtL fuel made with 100% renewable electricity. The third column shows the same type of vehicle powered with diesel containing 2.6% PtL. We chose this blend percentage of PtL in diesel to follow the 2.6% target for blending renewable fuels of non-biological origin (RFNBO) for 2030 proposed for the EU in the current RED II revision. We added a fourth column, showing a 5.7% PtL blend, as considered in the European Parliament in September 2022 (European Parliament, 2022).

While the second column in Figure 11 (pure PtL using 100% additional renewable electricity) initially appears to provide promising levels of GHG reductions compared to the diesel and biofuel blend, the third and forth columns show the very minor effect that PtL blended at the 2.6% or 5.7% blend in diesel foreseen by draft legislation has on reducing the GHG emissions of a 40-tonne tractor-trailer; it reduces emissions by 2% to 4%, respectively.

In a study on the decarbonization potential of electrofuels in the EU, Searle & Christensen (2018) found that because of high production costs, electrofuels are expected to deliver little to no renewable fuel volumes and GHG reductions in the EU leading up to 2030, even if they have strong support from renewable energy policy. A more recent study by Zhou et al. (2022) estimated the average e-kerosene production cost (i.e., excluding transport, storage, profit, and taxes) in the EU to be €2.8/liter currently, decreasing to €1.5/liter by 2050. In both studies, the researchers noted the importance of ensuring the renewable electricity used in electrofuels is fully additional in order to enable GHG savings. This additionality is especially important for electrofuels as noted by Bieker (2021); the required amount of renewable electricity to produce electrofuels is 6 times higher than if using the electricity directly in BEVs.

Electricity grid decarbonization

In the main calculations, this study considers the future development of the average EU electricity mix during the lifetime of the vehicles based on the Stated Policy Scenario (SPS) from the IEA's World Energy Outlook (IEA, 2020). When considering a more optimistic development as outlined in the IEA's Sustainable Development Scenario (SDS), the GHG emissions benefit of battery electric HDVs is even more pronounced. Over the lifetime of vehicles produced in 2021, using the SDS results in 4% to 6% additional GHG savings compared to the conservative grid mix scenario, or 40–61 gCO_2e/km. For 2030 vehicles, the absolute reduction is lower at 29–46 gCO_2e/km, but the percentage of reduction increases to 4%–6%.

Figure 11 compares the emissions of the 2030 battery electric 40-tonne tractor-trailer when using the optimistic SDS (right side) to using the more conservative grid scenario (left side). In this case, the GHG emissions reduction for a battery electric 40-tonne tractor-trailer charged using grid electricity in the conservative scenario is 77%. If the grid would develop as in the optimistic scenario, the battery electric version would reduce GHG emissions by 81% compared to the diesel version.

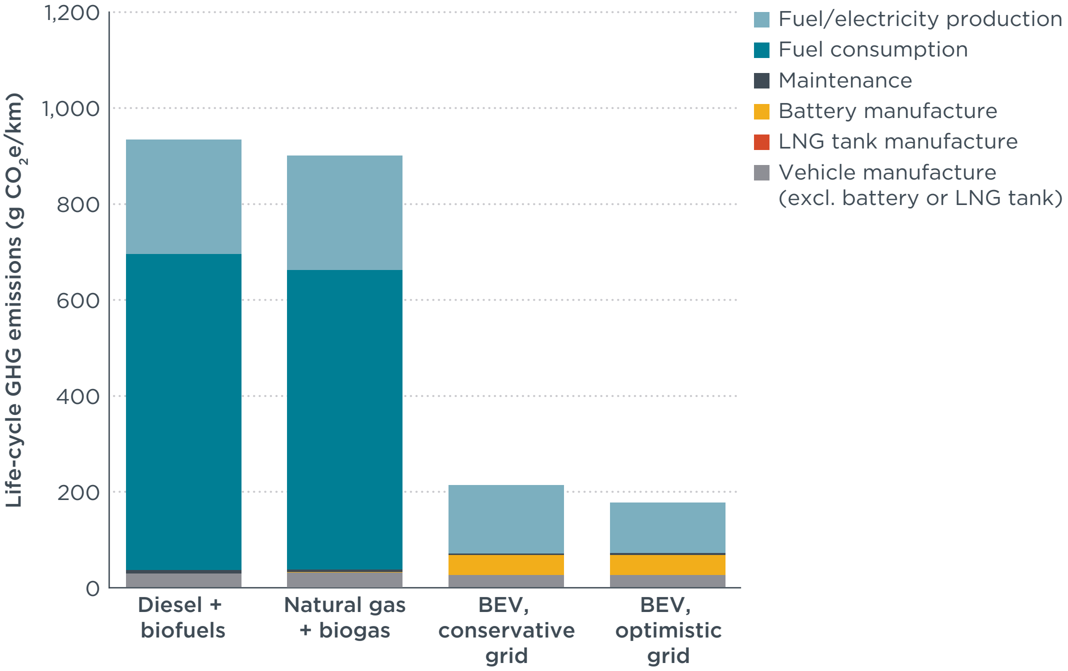

Figure 11. Life-cycle GHG emissions of 40-t tractor-trailers driven in the EU in 2030 to 2049 – Effect of faster grid decarbonization on battery electric version.

CONCLUSIONS

The EU intends to address its growing GHG emissions from transport, as this sector has become the primary source GHG emissions in the region. Taking action will help the EU meet its carbon neutrality goals. This study investigates the life-cycle GHG emissions produced by the main powertrain and fuel options in the EU's HDV sector. The study examines the magnitude of GHG emissions reductions over the lifetime of HDVs bought in 2021 and in 2030. Our study assesses both the expected efficiency improvements in the vehicles themselves and the effect of expected lower carbon fuels and electricity in the future. The results of this study are intended to inform policy decisions on technology choices that will provide the best GHG emissions reductions. We arrive at the following key findings:

» **Over their lifetime, current battery electric HDVs using electricity from the average EU grid provide large GHG emissions reductions of between 65% to 77% compared to diesel ICE HDVs.** These GHG emission reductions compared to diesel HDVs increase further (up to 94%) when the battery electric version is powered with 100% renewable electricity. If the grid decarbonizes faster than projected, the reductions will be even higher. However, the aggregate impact of HDV charging on electricity demand may warrant further research to identify the impacts of new demand and charging behavior on grid capacity, as well as the carbon intensity of supplied electricity.

» **The level of GHG emissions reductions provided by fuel cell HDVs compared to diesel ICE HDVs can be significant but depends on the feedstock used to make the hydrogen.** Using natural gas to make hydrogen for use in fuel cell HDVs can result in GHG savings as small as 15% compared to a diesel ICE HDV. This is the case even if the natural gas supply gradually includes CCS and the addition of some renewable hydrogen. However, when the fuel cell is powered with hydrogen made from renewable electricity, the GHG savings increase to as much as 91%. Currently, green hydrogen production volumes remain minimal. Transitioning to fuel cell HDVs without a concurrent increase in green hydrogen may be much more emissions-intensive than using battery electric HDVs powered by the existing electricity grid. Furthermore, accounting for efficiency losses associated with green hydrogen production, renewable hydrogen uses a greater quantity of electricity per kilometer than charging BEVs and will likely necessitate additional renewable electricity capacity.

» **At best, natural gas-powered HDVs provide minor GHG savings compared to diesel HDVs. At worst, they increase GHG emissions.** Vehicles using natural gas and a fraction of biomethane, depending on HDV type, provide lifetime GHG emissions savings of only 5% to 18% compared to their conventional, diesel-fueled counterparts. Lifetime climate impacts can be significantly higher if there is a higher amount of methane leakage during the production and transport of the natural gas. Emissions for the 40-tonne tractor-trailer increase by 22% compared to diesel when we apply a higher near-term global warming potential. Using biomethane instead of natural gas in HDVs is greatly limited by biomethane's likely future availability; by 2030, and even with strong policy support, only 2% of natural gas consumption in the EU could be supplied with low-carbon biomethane (Searle et al, 2021).

» **Power to liquid fuel made with 100% renewable energy and blended with diesel fuel at the level foreseen by European legislation provides GHG savings of just 2% compared to diesel.** Diesel HDVs will benefit from efficiency improvements going from 2021 to 2030 vehicles. A 40-tonne tractor-trailer is considered to become 25% more fuel-efficient in our analysis. However, the changes to the fuel mix in that timeframe will be small. The supply of sustainable biofuels will be limited, and production of electrofuels will be limited due to their high production costs. Even if the production of electrofuels reaches the levels envisaged by the most recent draft EU legislation, and if that production is powered entirely by renewable electricity from new additional sources, diesel HDVs will still be comparatively more GHG emissions intensive compared to pure battery electric HDVs. The GHG savings achievable by battery electric HDVs are considerably greater than diesel ICE HDVs fueled with PtL fuel blended at optimistically high levels.

Overall, our analysis finds that zero-emission HDVs can offer steep emissions savings compared to diesel and natural gas-powered HDVs. Enacting fuel efficiency and CO_2 emission standards that prioritize zero tailpipe emission HDVs can be a crucial lever to bring these vehicles into the market and begin the phase-out of ICE vehicles in new sales. The transition can be further assisted by fiscal policies, hydrogen fueling and electric charging infrastructure, and zero-emission zones.

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