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Accelerating to zero

Speeding up the decarbonization of heavy-duty vehicles in the EU

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Contents

Summary

The objective of this report is to analyse the current status and outlook for decarbonization of the heavy-duty vehicle sector in the EU. We focus in particular on developments over the coming 10 years, and how much the sector's emissions could be reduced through energy efficiency improvements, electrification, and increased biofuel deployment.

Three indicative pathways are constructed to showcase different trajectories to reach the 2050 net-zero target. The estimated emissions reduction from three measures' categories would equal 24% compared to the 2019 emission levels; this overall reduction is not in line with the more "aggressive" of the three pathways, i.e. the pathway already under way with a linear decrease of emissions to net zero in 2050.

No single alternative measure is sufficient on its own for aligning to the faster reductions' pathways, so all alternatives need to be combined. The options considered for emissions reduction are generally commercially available, and the targets for electrification by 2030 are ambitious, albeit in line with targets expressed by European manufacturers in the previous months.

The present contribution from heavy-duty vehicles to the EU 2030 climate plan for the "Fit for 55" package is small. Decarbonization measures for heavy-duty vehicles have a much greater potential to contribute to reducing European emissions in line with the Paris Agreement.

List of abbreviations

ACEA	European Automobile Manufacturers' Association
BEV	Battery Electric Vehicle
CBDR	Common but differentiated responsibilities
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
ICE	Internal Combustion Engine
IEA	International Energy Agency
NDC	Nationally Determined Contributions
RED	Renewable Energy Directive
SDG	Sustainable Development Goal
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WTW	Well-to-Wheel

1. Introduction

Categorizing certain sectors as “difficult to decarbonize” or “hard to abate” has become increasingly common in the broad climate change mitigation discussion. The exact criteria for a sector to be classified as such are not clear, but one condition tends to be that direct electrification – drawing upon the past decade’s cost reductions in solar, wind and batteries – would not suffice to eliminate emissions. Sectors typically included in the hard-to-abate category include heavy industry such as steel, cement and chemicals, but also aviation and sea transport .

Within the road transport sector, personal vehicles, buses and light trucks tend not to be seen as hard-to-abate, but heavy-duty trucks are somewhat of a different category. The conventional view has long been that battery electrification would be challenging for heavy-duty trucks, mainly because the large weight of the batteries needed to mimic the range of diesel-powered trucks would mean that less load could be carried, thereby negatively impacting freight economics (e.g. Sripad and Viswanathan, 2017).

Recently, views on the electrification potential of heavy-duty vehicles have changed markedly. Several recently published studies have shown that battery electrification of heavy trucks is not only feasible, but also an option that soon could become economically competitive with diesel-powered options (Nykvist & Olsson, 2021; Phadke et al., 2021). These assessments tend to rest on some key boundary conditions, in particular the availability of high-capacity fast-charging stations.

In addition, there has been renewed interest in the use of fuel cell electric vehicles (FCEVs). These are at their core also electric vehicles, but with a much smaller onboard battery and instead using hydrogen fuel cells as a form of range extender. Compared to battery electric vehicles (BEVs), this combination allows for longer ranges between stops for charging, but FCEVs have the drawback of substantially poorer grid-to-wheel energy efficiency. This translates into higher energy use per driven distance and hence higher operational costs.

Earlier this year, the International Energy Agency (IEA) released a report presenting scenarios for how the global energy sector could transition to a setup that would entail a 50% chance of reaching the ambition of the Paris Agreement: to limit global warming to 1.5°C above pre-industrial levels (IEA, 2021). In the IEA’s roadmap report, “Net Zero by 2050”, global emissions from heavy-duty trucks are projected to decrease by 90% in the period 2020–2050. The increasing optimism around electrification is also clearly showcased, with 100% of heavy-duty trucks sold in 2050 being either BEVs or FCEVs, up from less than 0.1% in 2020.

The very small market share of electrified vehicles in the heavy-duty truck segment is, however, likely to change over coming years. Global manufacturers are launching electric options in more and more market segments, and plenty of demonstration projects are running in close-to-commercial applications (Einride, 2021; Moore, 2021; Smith, 2020). In the bus segment, BEV models have been available now for several years, and although their share of the European stock was still small overall (0.6%) in 2021, but there are countries with much higher deployment rates than the average for the EU, for example the Netherlands (7.6%), Sweden (1.8%), Austria (1.6%), Denmark (1.0%) and Luxemburg (5.0%; ACEA, 2021c).

Less hard-to-abate than thought, but on track?

Notwithstanding substantial recent advances around electrification of heavy-duty tvehicles, it will be a momentous challenge to transition the global heavy-duty truck sector to an emissions reduction pathway compatible with the Paris Agreement. Action will have to be immediate and forceful – less than three decades remain until 2050, and in this context, that is a very short time to transform the entire composition of global heavy-duty vehicle fleets. As soon as by 2030, global truck emissions have to decrease by 10% from 2020 levels, which is no small feat in light of the preceding decade’s **increase** in emissions of 20% (IEA, 2021).

Furthermore, both the reduction in 10% by 2030 and the 90% reduction by 2050 in the IEA's "Net Zero by 2050" report are **global averages**. A key principle in the Paris Agreement (United Nations, 2015) is one of common but differentiated responsibilities (CBDR), which among other things implies a responsibility for rich countries with large cumulative historical CO_2 emissions to accelerate their own decarbonization. For the EU, this implies that substantial acceleration is required to adhere to the principle of CBDR, by using its innovation capabilities and financial resources to support global efforts as well as efforts within the region. This is especially true in the heavy-duty sector, given that out of the 10 largest heavy-duty vehicle manufacturers globally, 5 (Daimler, Volvo, Iveco, MAN and Scania) are based in the EU.

The objective of this report is to analyse the current status of decarbonization of the heavy-duty transport sector in the EU. In an effort to shift the discussion to near-term action, our focus is particularly on developments until 2030, as the 2020s will be an absolutely crucial decade for global climate change mitigation efforts, with massive progress needed in the key markets to pave the way for global economy-wide implementation thereafter.

Our research questions are the following:

- What are the potential decarbonization pathways for heavy-duty vehicles in Europe to be compatible with the requirements under the Paris Agreement, by 2030, to eventually reach the 2050 goals?
- How much of the emissions reduction achievable by 2030 is projected to be from improving fleet efficiency, switching to other drivetrains, and using biofuels?

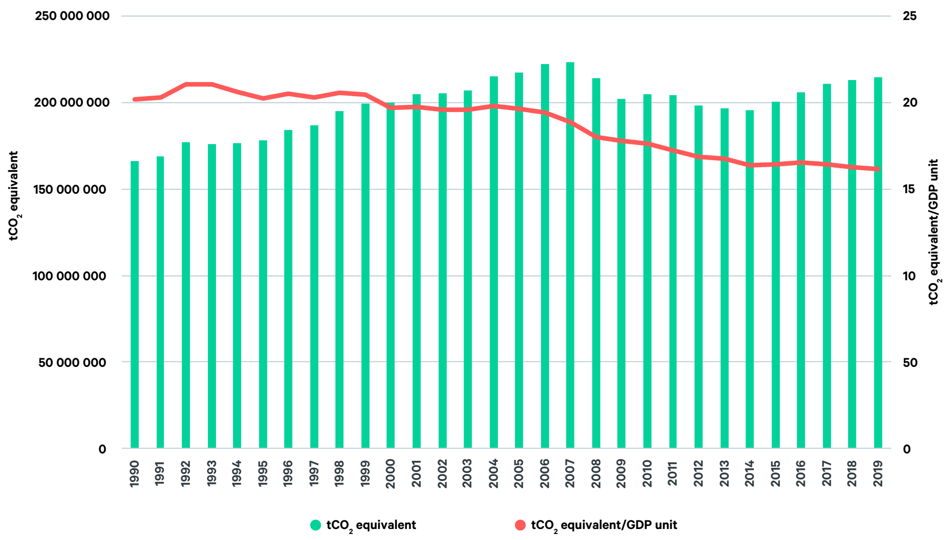
The remainder of the report is structured as follows. In section 2, we discuss what would be a reasonable EU target for heavy-duty vehicle emissions reduction by 2030. Section 3 presents an assessment of the level of emissions reduction possible from fleet renewal and gradually larger proportions of electrified trucks in fleets. Finally, section 4 presents a synthesis of the two research questions and discusses key findings.

2. EU pathways for decarbonization

The EU submitted its updated Nationally Determined Contribution (NDC) for the region and its member states at the end of last year, targeting emissions reduction of at least 55% by 2030 from 1990 levels (European Commission, 2020a). The goal serves as a stepping stone to climate neutrality by 2050, as agreed in the EU's "Fit for 55" package adopted in July 2021. According to the European Commission, the proposed legislative actions in this package are consistent with the Paris Agreement objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C (European Commission, 2020b). Meeting the Paris Agreement overall will require full decarbonization of road freight around 2050, particularly for advanced economies (Climate Action Tracker, 2018).

In 2019, heavy-duty trucks and buses represented 27% of all road transport-related emissions in the 27 countries that made up the EU (EU-27), and 6% of the total EU-27 emissions reported to the UNFCCC (EEA, 2021). Emissions from heavy-duty trucks and buses decreased between 2007 and 2014 but have been increasing since 2014 (see Figure 1). Notably, emissions from heavy-duty trucks and buses show signs of decoupling from European Gross Domestic Product (GDP) since at least 2007.

Figure 1: Emissions (t CO2eq) and emissions per gross domestic product (GDP) for heavy-duty trucks and buses in the EU-27, 1990–2019. Source: EEA 2021.

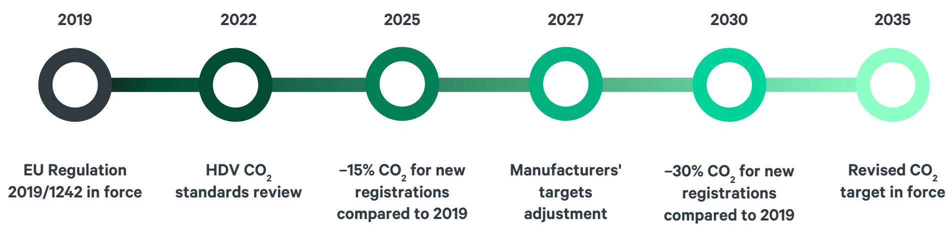


The EU adopted the first ever CO_2 emission standards for heavy-duty vehicles in 2019 with Regulation (EU) 2019/1242. The fleet-average type-approval targets imposed on manufacturers are expressed as emissions reduction for new truck registrations in a calendar year compared to EU average for a reference period (1 July 2019 to 30 June 2020) and are formulated as follows:

- from 2025 onwards: 15% reduction compared to the reference period;
- from 2030 onwards: 30% reduction compared to the reference period.

The EU regulation includes technology-neutral incentives for zero – and low-emission vehicles and initially covers large trucks. The 2022 review of the standards will assess a potential extension to cover other types of heavy-duty vehicles, such as smaller vans, buses, coaches and trailers (IEA, 2019). These revisions together with other policies are expected to pave the way for zero-emission road transport (Buysse, 2021). Figure 2 shows a timeline for the Regulation (EU) 2019/1242 target implementation and revision.

Figure 2: Indicative timeline for heavy-duty trucks regulation in the EU. Source: adapted from Serra (2020).



What would constitute a reasonable 2030 target for decarbonization of heavy-duty truck fleets in the EU, taking into account the goals of the Paris Agreement and the principle of CBDR? The EU has noted that regional assessments are missing: the UNEP Emissions Gap report evaluated consistency of pathways with the Paris Agreement but does not provide information regarding consistency at the regional level (European Commission, 2020).

We compare here three alternative pathways for heavy-duty transport emissions in the EU region. The contribution of negative emissions is not taken into account for the pathway construction.

The impact assessment of the EU 2030 climate target plan under the “Fit for 55” package is based on a number of different scenarios (European Commission, 2020):

- Scenario “REG”: a regulatory-based measures scenario that achieves around 55% greenhouse gas reductions;
- Scenario “CPRICE”: a carbon-pricing–based scenario that achieves around 55% greenhouse gas reductions;
- Scenario “MIX”: following a combined approach of REG and CPRICE, which achieves around 55% greenhouse gas reductions;
- Scenario “MIX-50”: a scenario achieving at least 50% greenhouse gas reductions, similar to MIX;
- Scenario “ALLBNK”: the most ambitious scenario in greenhouse gas emissions reduction, based on MIX and further intensifying fuel mandates for aviation and maritime sectors.

The four scenarios where 55% emissions reduction is achieved show an average cumulative emission decrease of 6% for heavy-duty trucks between the model’s baseline year of 2015 and 2030 (see Annex 9.4.2.6 of the impact assessment and supplementary data file). This can be translated to an annual emissions reduction rate of 0.4%. The share of electric and hydrogen drivetrains in the heavy-duty vehicle stock does not exceed 1% by 2030 in the scenarios, but it is within the range of 37% to 46% by 2050; the model results show a very steep increase of zero-emission trucks after 2030 (see Annex 9.4.2.6 of the impact assessment).

A comparison of pathways in the EU 2030 climate plan Impact Assessment Annex 9.10.6 stated that the “MIX” and “ALLBKN” scenarios appear “to be in line with EU results for global 1.5°C scenarios” and therefore consistent with the Paris Agreement (European Commission, 2020). However, European Parliament members suggested that the ambition for emissions reduction in the EU should be higher (60%) in order to be consistent with the Paris Agreement (European Parliament, 2020). Defining what is a “fair share” of contribution for the EU is complicated and related to the progress and responsibilities of other regions of the world. Recent research highlights that there is risk of oversimplification when trying to quantify the fair share among countries, and the complex political and ethical dimensions of this context should be explored in a transparent fashion (Dooley et al., 2021).

IEA’s Net Zero by 2050 Roadmap

The global net-zero emissions scenario of the IEA assumes at least a 50% chance of limiting warming to 1.5°C, and thus emissions reduction of at least 90% are required (IEA 2021). Trucks are included in the pathway with a Compound Annualized Average Growth Rate of –0.6% between 2020 and 2030 and –6.9% between 2020 and 2050. The IEA pathway does not make a distinction between buses and trucks, nor does it differentiate between emerging and advanced economies. Since the EU is an advanced economy with net-zero targets already in place, a faster rate can be assumed.

It should be noted that only CO_2 emissions are documented in the pathways presented above, but for simplicity we assume in this analysis that CO_2 equivalent emissions (all greenhouse gases) follow the same trend. In reality, changes in the fuel mix impact the total greenhouse gases in CO_2 equivalents differently, since a decreased deployment of diesel, for example, would mean lower NO_x and black carbon emissions. Additionally, buses are not explicitly modelled in the scenario, but we assume the same emissions reduction trends apply even for buses.

A linear emissions reduction pathway for net zero by 2050

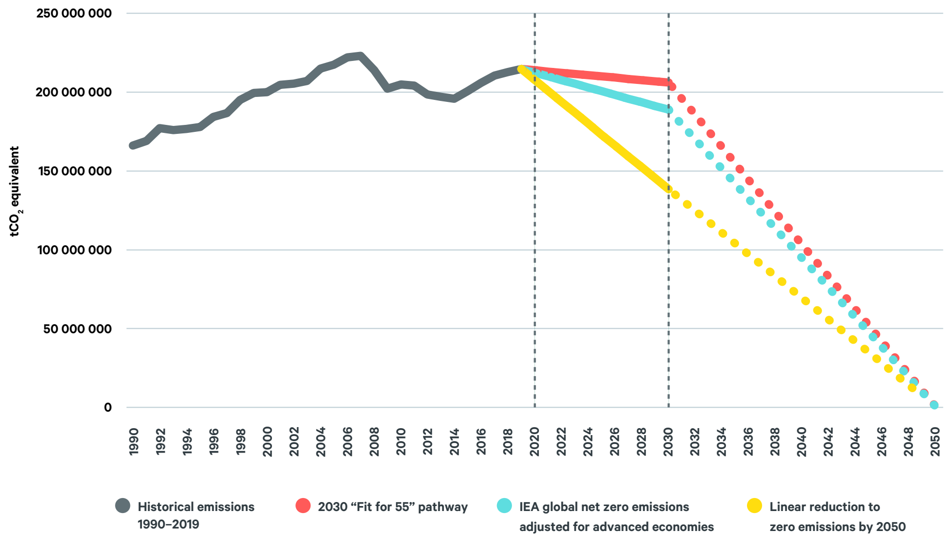
The pathways presented by the European Commission and the IEA assume a much slower pace for emissions reduction between 2020 and 2030 compared to between 2030 and 2050. Essentially, the major emissions reduction for heavy-duty vehicles are expected to happen after 2030. However, an alternative trajectory could be assumed behave linearly all the way to 2050 and, therefore, show larger reductions before 2030. Such a pathway would lead to an emissions reduction of 35% by 2030, before reaching full decarbonization in 2050.

Based on the above, we construct the three indicative pathways showcasing different trajectories to reach the 2050 net-zero target (see Table 1 and Figure 3). These trajectories are based on the assumption that emissions reduction is linear. This process would not entirely be linear in reality, but this approximation helps highlight the differences in the three pathways up to 2030 that could all still result in net zero by 2050.

Table 1: Indicative emissions reduction pathways for the EU-27: aligned with with the “Fit for 55” 2030 climate target plan, the adjusted IEA net-zero emissions scenario, and a linear pathway to zero emissions by 2050.

	Emissions reduction heavy duty trucks and buses, 2020–2030	Comments	Source
2030 “Fit for 55” pathway	4%	In line with the "MIX", "CPRICE", and "REG" scenarios of the impact assessment of the 2030 climate target plan. An average annual emissions reduction rate of 0.4% is assumed.	European Commission, 2020
IEA global net-zero emissions scenario – adjusted for advanced economies	12%	Annual decrease rate of 0.6% is assumed globally for heavy-duty trucks between 2020 and 2030. Here we assume a double decrease rate (1.2%) for the EU as an advanced economy.	Adjusted from IEA, 2021, with authors’ assumption for double emissions decrease rate for advanced economies compared to IEA’s global decrease rate.
Linear reductions to zero emissions in 2050	35%	Linear pathway to zero emissions by 2050, which implies a faster emissions decrease up to 2030.	Authors’ estimation

Figure 3: Estimated emissions reduction by 2030 for heavy-duty trucks and buses in the EU-27, as per the indicative pathways presented in Table 1.



3. Alternatives for reducing heavy-duty transport emissions by 2030

This section explores the various alternatives for reducing emissions of heavy-duty trucks and buses in the EU. The main alternatives here are energy efficiency improvements, electrification with battery or fuel cell–driven vehicles, and switching to biofuels or electrofuel, such as e-diesel, e-methane, e-methanol, e-hydrogen, and e-ammonia, which are produced using electrolysis.

We estimate the potential emissions reduction based on fleet projections up to 2030, the gradual change of fuels and electricity emission factors, and potential internal combustion engine efficiency improvements.

The European classification of heavy-duty trucks is "motor vehicles with at least four wheels, used for the carriage of goods", with a total weight of more than 3.5 metric tons. Trucks are either classified under the N2 category (medium duty, weighing more than 3.5 t) or the N3 category (heavy duty, weighing more than 16 t; ACEA, 2021b). The European association of vehicle manufacturers, ACEA, gathers vehicle stock and new registration statistics for medium- and heavy-duty vehicles combined (ACEA, 2021c). We use this aggregated data in this section.

Vehicle stock and transport demand assumptions

Heavy-duty trucks are estimated to make up 53% of the total number of medium and heavy commercial vehicles in use in a previous study (Roland Berger, 2016). The corresponding distribution between city buses and coaches is assumed to be half each of the total number of buses in use. We further assumed that the annual distance driven for a city bus is 60 000 km, for a coach 75 000 km, and for a long-haul heavy-duty truck 100 000 km (personal communications, Scania, 2021).

The trends for the annual vehicle stock growth and the share of new registrations up to 2030 are projected using historical data from ACEA. The annual vehicle stock growth is thus 2%, and the new registrations represent 5% of the total medium- and heavy-duty vehicle stock and 5% of the total bus stock.

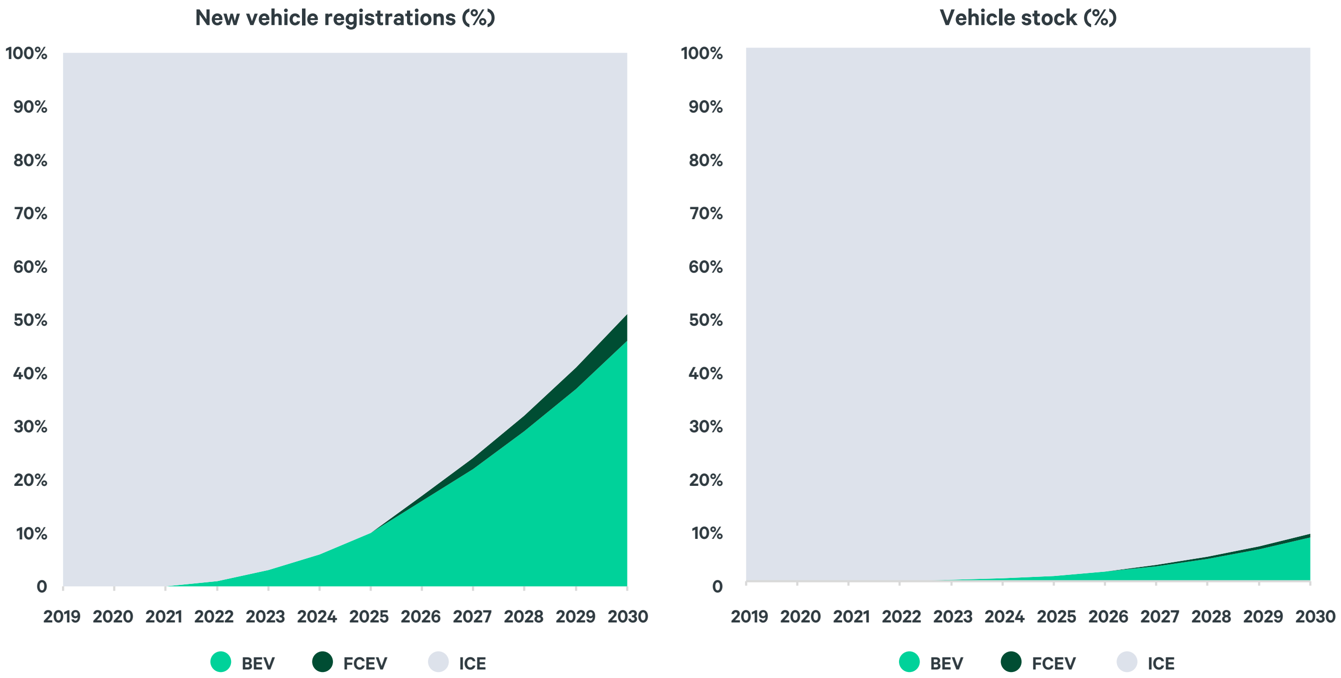
How fast will vehicle fleets change?

For trucks, the share of electric vehicles in the new registrations is assumed to reach 50% by 2030, which is in line with the ambitions expressed by several European vehicle manufacturers (ACEA, 2021a; Sennder, 2021). Most of these new electric vehicle registrations will be BEVs, with sales starting from 2021. We assume that only a smaller share (5% by 2030) is FCEVs, with sales starting from 2025.

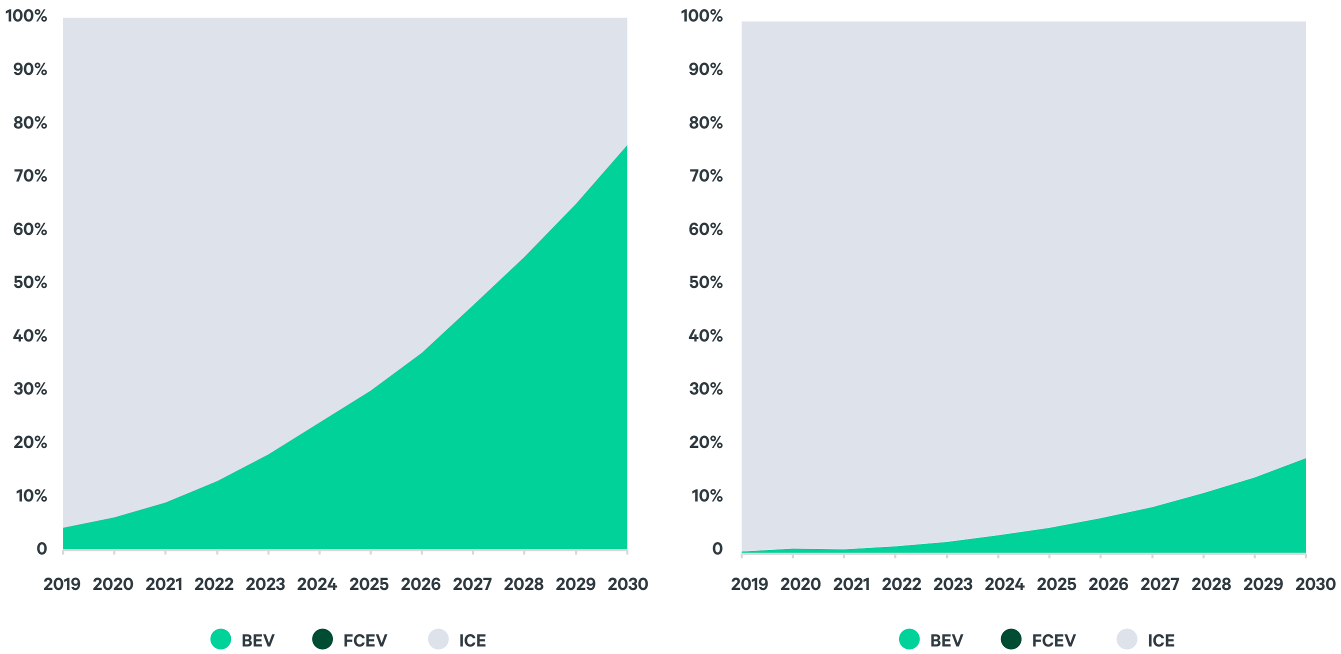
For buses, the share of BEVs in new registrations is assumed to reach 100% for city buses and 50% for coaches by 2030, resulting in an overall electric bus registration rate of 75% by 2030, compared to 4% in 2020. Buses that are FCEVs are assumed to play a minimal role and therefore not modelled in detail. Hybrid electric vehicles are included in the share of internal combustion engines (ICEs) and plug-in hybrids in the share of BEVs. The estimations for the vehicle stock and new registrations up to 2030 is shown in Figure 4.

Figure 4: Estimated share of new vehicle registrations and vehicle stock, 2019–2030. Historical data from ACEA's statistics and polynomial growth (order=2) is assumed for new registrations. Hybrid electric and plug-in hybrids are included in the share of BEVs.

Heavy-duty trucks (over 16 t)



Buses (over 3.5 t)



Even with very ambitious targets for new registrations, the projections show that effects on the vehicle stock take a long time to appear. The assumed targets for new registrations of electric vehicles are 50% for heavy-duty trucks and 75% for buses, of which all city buses and half of all coaches are electric. The electric vehicle stock represents approximately 10% of the total truck stock and approximately 20% of the total bus stock by 2030. In other words, the vehicle stock renewal cycles are long and changes take time to become prominent even when assuming very optimistic development trends.

According to ACEA, the average lifetime of a truck in the EU is 13 years and that of a bus is 11.7 years, so a non-electric truck or a bus purchased today will be in use at least until a bit beyond 2030. Further research is needed to gain better understanding of driving patterns with regards to vehicle type and age, e.g. whether older vehicles might contribute less to the overall transport volume and, therefore, to heavy-duty transport emissions. Here, we do not account for the likely effect of newer vehicles contributing more to the total transport volume, due to lack of data. However, it is probable that a newly purchased BEV will be used more than an older ICE vehicle and therefore the turnover rate of vehicles might not be directly proportional to transport volumes because of engine technology.

Meanwhile, electrification can be complemented with other emission reducing alternatives. These can be higher biofuel deployment rates and general improvements to the efficiency of ICEs. The individual effects in terms of emissions reduction by each alternative are calculated in the sections below and compared against a business-as-usual baseline. In this way, we estimate the potential emissions reduction by each individual measure as percentage decreased compared to this baseline.

How do the various alternatives contribute to reducing emissions?

Efficiency improvements of ICE vehicles

The emissions intensity of heavy-duty transport in the EU has decreased over the past few decades. However, this positive development has been counteracted by an increase in total road freight traffic, resulting in overall increased heavy-duty road transport emissions in the EU (European Commission, 2019b). However, this offset does not imply that efficiency improvements are pointless – they can still be an important component in the overall emissions reduction toolbox, especially when combined with measures for more effective transport demand management.

Here, we assume an annual ICE efficiency improvement of 2% for trucks and buses, combining the results from previous studies (for more information, see the Appendix). The assumed improvements include, for example, “best in class” technology adoption, engine technology improvements, driveline efficiency improvements, low rolling resistance tires, trailer aerodynamic devices and turbo-compound engines. This assumption is based on average stock; it should be noted that some of the vehicle stock might be ahead or lagging behind the baseline assumption. These assumptions result in reducing emissions from heavy-duty ICE trucks and buses by 6% in the time period 2019–2030. The WTW emission factors for all energy carriers are provided in Table 4 of the Appendix.

Battery electric trucks

The potential reduction of CO_2 emissions associated with BEVs is calculated based on the average carbon intensity of EU-27 electricity generation. With the projections of the annual vehicle stock growth and market introductions of BEVs in consideration, we estimate the contribution from BEVs to the overall reduction of heavy-duty transport emissions to be 8%. Using a less carbon intensive electricity mix, such as the Nordic electricity mix, would lead to even larger reductions compared to the baseline. The time of charging can also play an important role in the emission intensity of the electricity, especially under peak demand conditions, but this aspect is not explored in detail in this study.

Fuel cell electric trucks

The FCEV fuel consumption is assumed to decrease linearly from 2019 to 2030, and electricity produced from wind is assumed to be used for hydrogen production. Under these assumptions, the potential contribution from FCEVs amounts to a 1% reduction of CO_2 emissions compared to the baseline. It should be noted that the use of more carbon intensive electricity mixes for hydrogen production would lead to emissions associated with FCEV operation being higher than the assumed ICE baseline (see the Appendix).

Biofuels

The revised Renewable Energy Directive (RED II) sets an overall target of 14% renewable energy in transport (road and rail) by 2030. The directive also defines the sustainability criteria and default greenhouse gas emission values of various biofuels. The threshold for emissions reduction from transport biofuels compared to the fossil fuel comparator baseline according to RED II is 65% (European Commission, 2019a).

We use the above as a starting point and assume that the ambition is to have a 14% biofuel blend by 2030 for all ICE trucks and buses, up from the current share of 7%. This target also includes renewable electricity and hydrogen, but in order to estimate the full possible effect of various measures, it is assumed the target will be exclusively achieved by biofuels in this case. The biofuels used towards the 2030 target should reduce emissions by 65% (the minimum reduction threshold according to the RED II criteria for transport biofuels; see above). This would lead to an emissions reduction of 9% compared to a fossil fuel baseline.

Advanced biofuels that could become commercially available in the future could provide emissions reduction of up to 90%. In such a case, emission reduction from biofuels would reach 13% according to our model results.

Additionally, the assumption of a 14% blend is in accordance with the RED II targets, but it is not the maximum possible blending with regards to current technologies, which is 20% (Climate Action Tracker, 2018). “Drop-in” biofuels, for example, which are used without modifications to the engine, can be deployed even beyond the limits for blending mentioned above. Therefore, biofuels could have an even larger contribution to emissions reduction in the future, depending on commercial developments and their availability in the EU.

Electrofuels

Electrofuels could be another complementary solution. These fuels can be used with minor adaptations to internal combustion engines but are still in development and may not be a commercial alternative before 2030 (Grinsven et al., 2021).

The estimated emissions reduction from the various measures discussed above are summarized in Table 2. All measures together would mean an emissions reduction of 24% by 2030 compared to the 2019 baseline, equivalent to approximately 52 million t CO_2eq. About 163 million t CO_2eq of fossil-based fuel would remain unaccounted for in the push to get to net-zero emissions. This corresponds to a transport volume of 151 billion vehicle-kilometres on a heavy-duty ICE truck, equivalent to the annual distance driven by 1.5 million long-haul trucks.

Table 2: Estimated emissions reduction by 2030 from electrification, energy efficiency, and biofuel blending for heavy trucks and buses.

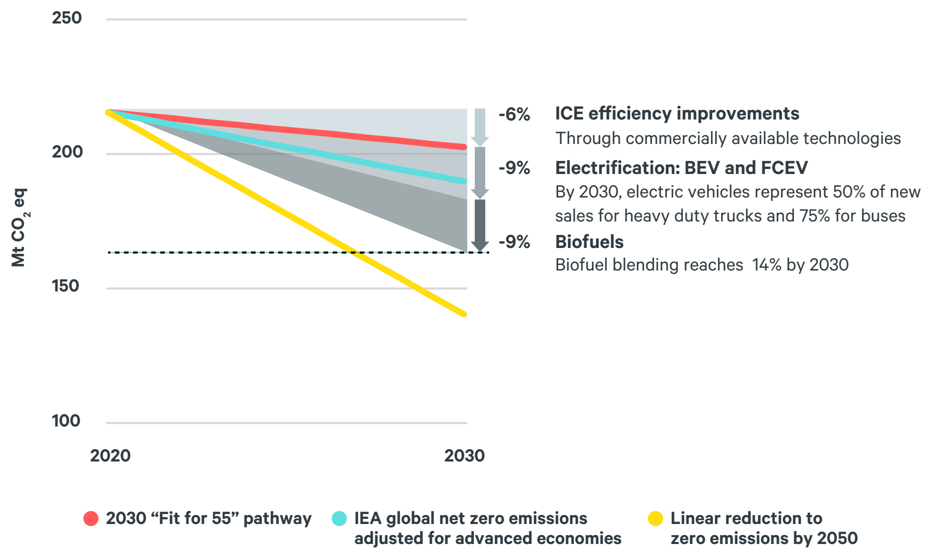
Emissions reduction measure	Greenhouse gas emissions reduction, 2030, compared to 2019 baseline
Energy efficiency	6%
Electrification – BEV	8%
Electrification – FCEV	1%
Biofuels	9%
Total	24%

4. The path to take

Figure 1 compares the potential emissions reduction estimated in Section 3 to the indicative pathways to net zero presented in Section 2. In this way, we illustrate the magnitude of emissions reduction that each option could achieve in relation to the previously defined pathways.

The estimated total reduction when all options are combined would equal 24% and would eventually fall short of the steepest of the three pathways, i.e. the pathway that starts today with a linear decrease of emissions to net zero in 2050. No alternative on its own is sufficient for being consistent with two of the three pathways (the steeper ones), so all alternatives – energy efficiency improvement, electrification and biofuels – need to be combined under most circumstances.

Figure 5: Estimated potential emissions reduction between 2019 and 2030 for heavy duty trucks and buses in relation to indicative alternative pathways to net zero by 2050.



If one option underperforms, higher requirements are placed on the others to reach the net-zero targets. For example, if the estimated emissions reduction from energy efficiency improvements is not realized in practice, and biofuel availability is limited, then electrification needs to be deployed even faster than assumed. Similar effects should be expected if the transport volumes increase at faster paces than assumed. Policymakers should be aware of the need to balance between options while striving for net zero and be prepared through detailed policy impact assessments.

The estimations in this study are based on generally conservative assumptions of what could be commercially available by 2030 on the side of FCEVs and electrofuels, but rather optimistic ambitions on the share of electric vehicles in new registrations. Such optimistic targets have been set by some vehicle manufacturers (Daimler, 2021; Scania, 2021; Traton, 2021; Volvo, 2021) and should be considered necessary – and possible under certain conditions and prerequisites – for a rapid shift to carbon neutral solutions.

Heavy-duty vehicles' emissions reduction contribute very little to the EU 2030 climate plan for the "Fit for 55" package. With the latest technological developments and infrastructure deployed at the right place and time, heavy-duty vehicles could contribute far more to reducing European emissions to meet the Paris Agreement targets, as shown in this study. Even a pathway based on an initially slower pace could still be in line with the Paris Agreement if the pace is assumed to rapidly accelerate after 2030.

The concept of carbon budgets as such is translated in alternative pathways and gives room for delayed action. So when is it the right time to act? Timing should be defined by what can be done from the point of view of market structures and constraints, by what should be done in terms of political priorities, and by the relative cost-effectiveness of existing options.

The lifetime of heavy-duty vehicles and slow fleet renewal rates result in a situation where even very high shares of zero-carbon solutions in new registrations take time to make a difference to the vehicle stock composition. Assuming a pathway where the vehicle stock and its emissions change slowly in the beginning (e.g. up to 2030) and accelerate afterwards is theoretically not an issue from an end-result perspective, i.e. achieving net-zero emissions, but poses risks for lock-ins and sunk costs connected to short-term solutions. These risks make the transition to carbon neutrality harder to accelerate in the long term.

Comparing the options for transforming the heavy-duty transport sector, the contribution of fuel cells is rather modest up to 2030 due to a late market introduction and long vehicle stock renewal cycles. However, looking over a longer timeframe, fuel cells could have greater importance, as could electrofuels.

The emission factors assumed for the electricity mix are, naturally, key when discussing the effects of BEVs and FCEVs. Especially for the case of fuel cells, assuming the average EU-27 electricity mix for hydrogen production would not improve emissions compared to a fossil fuel–based baseline. Therefore, we assume renewable electricity is used for producing the hydrogen needed by FCEVs. For BEVs, our calculations are based on the development of the average EU electricity mix in line with the EU targets for renewables. Of course, using exclusively renewably sourced electricity would have positive impacts on the emissions reduction from BEVs, but this contribution would not be very significant because their overall share in the fleet is still relatively small by 2030.

Higher blending rates as well as extended use of drop-in fuels should be considered a priority when discussing short-term action with high impact, but fuel availability and policy mechanisms will define future limits of ambition. Gaining a deeper understanding of transport service providers' options and motives is necessary. The wider potential co-benefits for the development of the global bioeconomy from advanced biofuels and integrated land and biomass systems should also be considered in analysing comparisons across different pathways.

Detailed statistics are lacking on historical road freight transport volumes for light-, medium- and heavy-duty vehicle classes, including classification by age, daily distances and type of freight. Manufacturers, industry associations, and European and national bodies use various definitions and methods that need to be harmonized to produce more granular estimations of the sector's strategic development, especially when it comes to defining which segments could be easiest and hardest to electrify.

Further analysis focusing on detailed decarbonization pathways for the various segments, taking into account the distribution of transport volume per segment, vehicle age groups and regions, would be an appropriate next step for assisting policy design for heavy-duty vehicle decarbonization, harmonized with Paris Agreement targets.

As we have found in our explorations above, aligning short-term and long-term EU policy for decarbonization of heavy-duty trucks is challenging. All three indicative pathways we illustrate are designed to lead eventually to net-zero emissions by 2050. The start and end point of each pathway is the same, but the pace at which we reach the end point of net zero also matters, since every accumulated ton of carbon in the atmosphere influences climate.

We show the potential for heavy-duty vehicles to contribute more to emissions reduction within the EU than envisioned in the 2030 Fit for 55 package. However, in order to achieve this, efforts should accelerate at all fronts: energy efficiency improvements, electrification via BEVs, and commercialization of FCEVs and electrofuels, as well as higher deployment rates for advanced biofuels.

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Appendix

Methodological considerations

Estimation of the vehicle stock by 2030

- The annual vehicle stock growth is 2% and the new registrations represent 5% of the heavy-duty vehicle stock.
- For trucks, the share of electric vehicles in new registrations is assumed to reach 50% by 2030, while this share is 75% for buses by the same year.
- The growth of new registrations of electric vehicles is assumed to follow a polynomial growth curve (order=2).
- Hybrid electric vehicles are included in the share of internal combustion engines (ICEs) and plug-in hybrids are included in the share of battery electric vehicles (BEVs).
- Data are lacking at the European level regarding the share of electric and non-electric operation of plug-in hybrid models. For the sake of simplicity, this aspect is not modelled in detail in this study.

ICE efficiency improvement

Previous studies have reviewed the literature and analysed energy efficiency potentials for ICE vehicles in a European context. Through engine improvements and commercially available technologies, such as low rolling resistance tires, trailer aerodynamic devices and turbo-compound engines, the fuel consumption of newly registered long-haul tractor-trailer trucks can decrease by roughly 27% by 2025 compared to the 2015 fleet average vehicle according to a study by Delgado et al. (2017). Nevertheless, a 35% fuel savings potential without trailer optimization measures has been estimated for diesel engines in an EU context by Breed et al. (2021), although without a specific time horizon when these improvements could be fully realized. The potential is estimated compared to a baseline where no fuel saving technology package is applied at all and a 4% efficiency improvement is attributed to hybridization.

Combining the results of the two studies above and assuming a 10-year horizon leads to an average annual improvement rate of 2.9%, excluding hybridization and trailer optimization measures. Another study published in 2021 assumes a less ambitious annual rate for ICE efficiency improvements at 1.1% (Holmgren et al., 2021).

We assume an average pathway between the more and less ambitious estimations presented above, which can be translated to an average annual energy efficiency improvement rate for ICEs at 2%. The potential for ICE energy efficiency improvements is closely linked to the fleet's age structure across the EU, which could vary a lot depending on the country and specific transport uses.

For buses, Buysse (2021) estimated the remaining technical potential for ICE vehicle efficiency improvements to be similar to that of medium-duty vehicles. In a European context, Delgado et al. (2017) estimates this potential to be roughly 22% for 12-t rigid trucks in urban and regional delivery cycles. The same potential is applied to buses in this study for the period 2019–2030, leading to a 2% annual improvement rate. The baseline fuel consumption for the ICE heavy-duty vehicles is shown in Table 3. We assume an average energy consumption of 1.5 kWh/km for BEVs.

Table 3: The 2019 baseline fuel consumption of ICE vehicles.

Vehicle type	Fuel consumption, 2019 [litres/kilometre]	Source
Truck (long-haul)	0.33	Delgado et al., 2017
City bus	0.42	Xylia & Silveira, 2017
Coach	0.36	Xylia & Silveira, 2017

Fuel cell electric trucks

The potential emissions reduction from FCEVs are estimated based on an energy consumption of 9.5 MJ/km for heavy-duty freight vehicles for the 2019 baseline (Moultak et al., 2017). Following the work of Moultak et al. (2017), FCEV fuel consumption is assumed to decrease linearly to 7.6 MJ/km by 2030.

A recent study exploring decarbonization of heavy-duty transport in the Netherlands found well-to-wheel (WTW) emissions for hydrogen produced from the Dutch average electricity mix to be about 2.3 times higher than for BEVs fuelled by the same average electricity mix (Otten et al., 2020). Applying the same factor to the average carbon intensity of EU-27 electricity generation would lead to a higher emission factor for hydrogen than for diesel. As a result, the FCEVs are estimated to increase the heavy-duty vehicle emissions by 1% compared to a baseline with solely ICE vehicles.

Emissions reduction of CO_2 associated with FCEVs are further explored by applying a less carbon intensive WTW emission factor for hydrogen. The revised RED nevertheless prioritizes the use of renewable-based hydrogen in the transport sector (European Commission, 2021). In their study, Otten et al. (2020) identified a value of roughly 22 g CO_2eq/kWh for hydrogen produced from Dutch wind energy, which we use for estimating potential emissions reduction from FCEVs in this study.

Fuel and electricity emission factors

We apply a constant WTW emission intensity for diesel. The WTW emission factors for all energy carriers are provided in Table 4.

Table 4: The 2019 baseline emission factor for each energy carrier and their assumed development to 2030.

Energy carrier	2019 baseline WTW emission factor [gCO2eq/kWh]	Comment	Source
Fossil comparator[a]	338.4	Assumed to remain constant	Searle, 2021
EU-27 electricity generation	235.0	Linear reduction by 46% by 2030	Buysse, 2021
FCEV (hydrogen produced from wind)	21.6	Assumed to remain constant	Otten et al., 2020

[a] In line with the revised Renewable Energy Directive (RED II) requirements, the same emission factor is assumed for all liquid and gaseous fossil fuels. This is to discount changes in emissions when shifting between gasoline, diesel, and natural gas consumption (Searle, 2021).

Battery electric trucks

The potential reduction of CO2 emissions associated with BEVs is calculated based on the 2019 average carbon intensity of EU-27 electricity generation. Following Buysse (2021), the average carbon intensity for electricity generation is expected to reduce by 46% by 2030 compared to 2020 levels, based on the Vision Scenario for the EU. A linear decrease from 2019 to 2030 is assumed. With the projections of the annual vehicle stock growth and market introductions of BEVs in consideration, the contribution from BEVs can be estimated. This is compared to a baseline where the entire heavy-duty vehicle fleet consists entirely of ICE trucks and where the number of BEV buses in use remains constant from 2019 to 2030.

It should be noted that emissions reduction potential for BEVs is based on the average EU-27 electricity generation mix. The Nordic electricity mix is estimated to have an emissions factor of 90.4 g CO2eq/kWh, according to Sandgren & Nilsson (2021), which is 61.5% lower than the average emission factor for the EU-27 electricity mix and therefore would lead to further emissions reduction, for example.

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