



LOW CARBON PATHWAYS UNTIL 2050

DEEP DIVE ON HEAVY-DUTY TRANSPORTATION



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Executive Summary

The European Commission calls for a climate-neutral Europe by 2050 [European Commission, 2018a], which is in-line with the goals of the Paris Agreement [UNFCCC, 2015]. One element of reaching a carbon-neutral economy is to reduce greenhouse gas emissions. Within the economy, the transport sector accounted for 23% of greenhouse gas emissions in 2017, while heavy-duty trucks accounted for 25% of the greenhouse gas emissions in the transport sector [EEA, 2019]. Thus, heavy-duty trucks are important to achieve the greenhouse gas emission reduction.

Yet, it is unclear how heavy-duty vehicles can contribute to this reduction. There are three reasons for this: Firstly, the freight transport demand will likely increase. Secondly, size and weight of the vehicles limit the options to reduce their energy demand. Thirdly, many stakeholders need to be aligned to make change happen: authorities, fleet operators, vehicle manufacturers, technology suppliers and energy providers.

However, we conclude that low carbon pathways for heavy-duty trucks do exist. Figure I shows the pathways. We present three low carbon pathways, which achieve greenhouse gas emission reductions of 80% to 95% by 2050 compared to 1990.

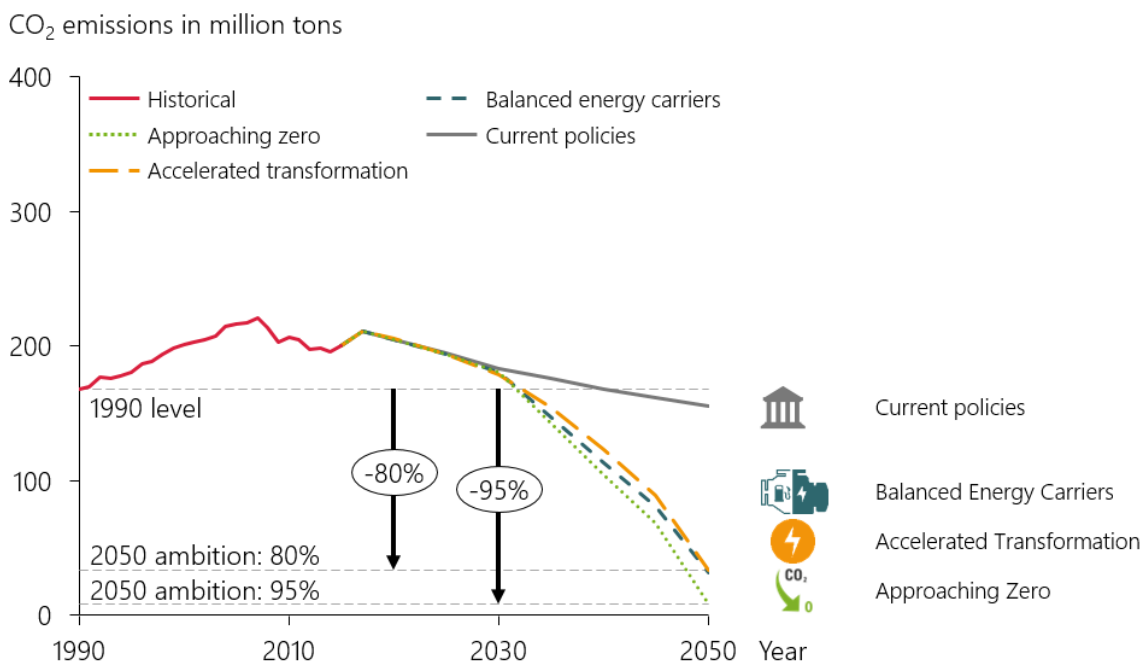


Figure I: Pathways of the four scenarios modeled in the extended tank-to-wheel balance. Please see chapter 1.2 for an explanation of the balances we applied.

All pathways apply four measures: optimization of usage, electrification of powertrains, efficiency increase of vehicles and adaptation of energy carriers. Our four key take-aways for the measures are:

1. Optimization of usage is an important aspect of the CO₂ emission reduction. It can mitigate the emissions added by the higher transport demand in the future. This is enabled by an uptake of connected and automated trucks which result in an increased truck utilization.
2. Electrification of powertrains includes hybrid, battery and fuel cell electric powertrains. It provides a small CO₂ emission reduction in the well-to-wheel balance. To increase this, more electricity and hydrogen – used in fuel cells – needs to come from renewable sources. All low carbon pathways use battery and fuel cell electric trucks at more than 25% of the vehicle stock.
3. Efficiency increase of the vehicles is a strong contributor to lower CO₂ emissions. This efficiency increase is enabled by improved gliders – reduction of aerodynamic drag, rolling resistance and weight – and improved powertrains – e.g. engine efficiency measures.
4. The adaptation of energy carriers is key. Only with high shares of energy from renewable sources, high CO₂ emission reduction can be achieved in the well-to-wheel balance.

Figure II also reflects this. It compares the CO₂ emission reduction and the impact of the four measures in the four scenarios. In the extended tank-to-wheel balance the adaptation of energy carriers contributes the most to the CO₂ emission reduction, followed by the electrification of powertrains. In the well-to-wheel balance the adaptation of energy carriers contributes even more to the CO₂ emission reduction than in the extended tank-to-wheel balance. The adaptation of energy carriers in the well-to-wheel balance also includes the increase of electricity generation by renewable sources. In this balance the impact of electrification of powertrain is low since 2018’s energy mix is considered. For more explanation on the methodology see chapter 3.

CO₂ emission reduction in million tons and breakdown by measures

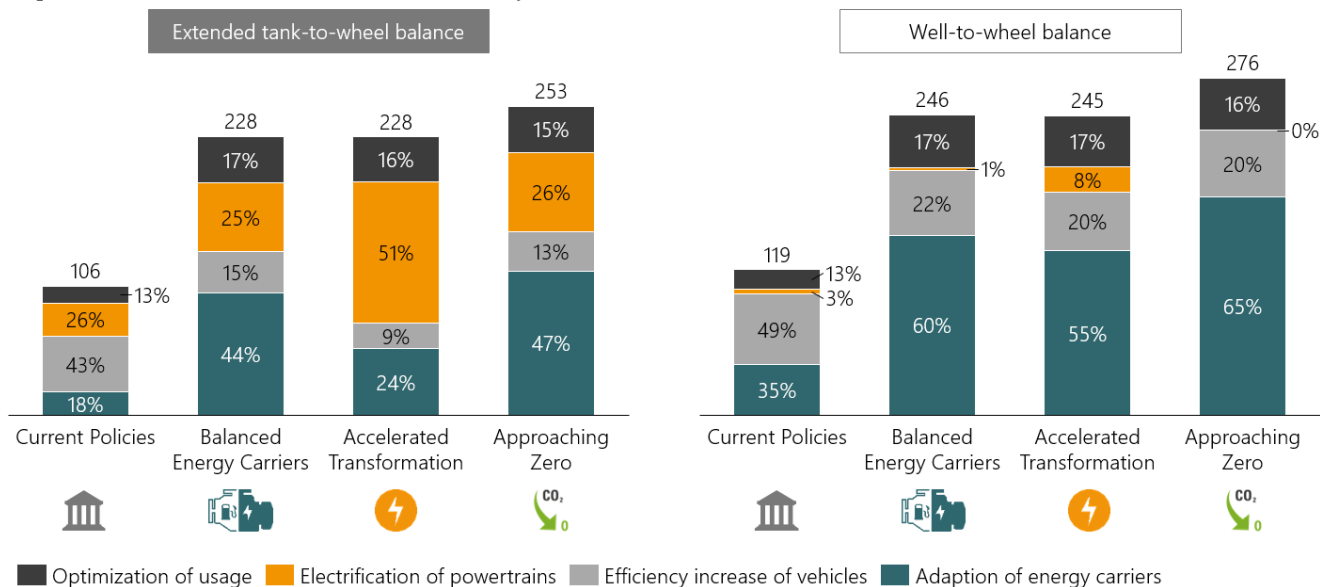


Figure II: Comparison of the CO₂ emission reduction in million tons in the four scenarios and breakdown by the four measures in the extended tank-to-wheel balance (left) and the well-to-wheel balance (right) by 2050 compared to 1990.

In all pathways, battery and fuel cell electric trucks as well as liquid and gaseous fuels from renewable sources are relevant. This requires huge investments and demands swift action. To ensure the measures are developed suited to the desired outcome, authorities need to provide a framework for fleet operators, vehicle manufacturers, technology suppliers and energy providers. Such frameworks could include incentive schemes, mandates, adaptation of taxation and review of CO₂ emission accounting.

The life-cycle CO₂ emissions reduce by about 70% for heavy-duty long-haul trucks sold in 2050 compared to such sold in 2018. This reduction is due to the higher share of energy from renewable sources.

Figure III shows the final energy demand of heavy-duty trucks. For reference, the energy demand of heavy-duty trucks in 1990 was about 2,300 PJ. In all scenarios the final energy demand reduces until 2050 compared to 2018 – at up to 37% in the Accelerated Transformation scenario. This is mostly due to optimized usage as well as more efficient vehicles and powertrains.

Final energy carrier demand in PJ

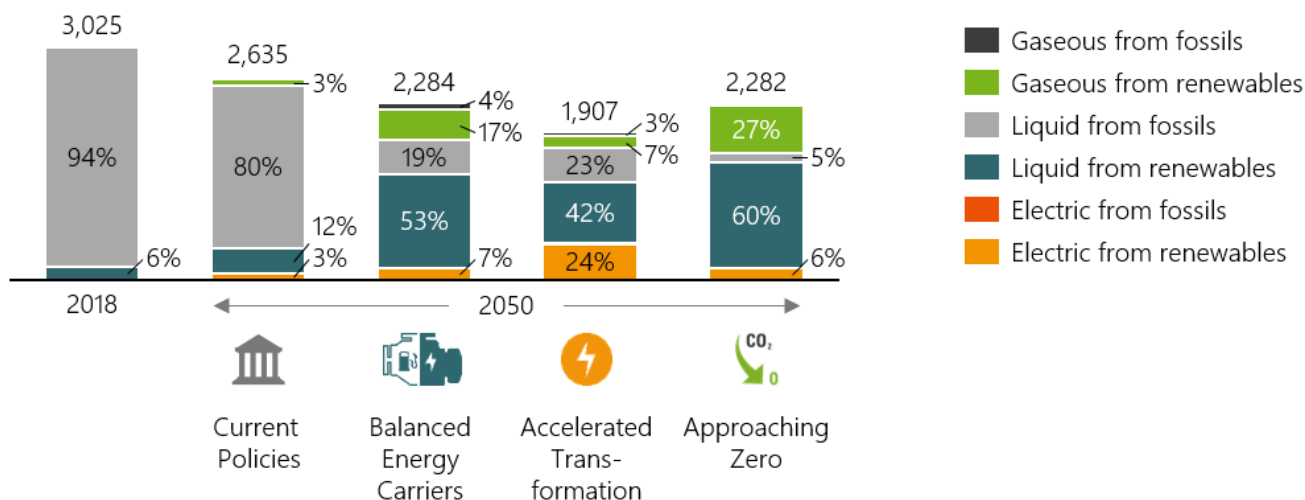


Figure III: Final energy demand of heavy-duty trucks in Europe in PJ, shown by energy carrier type and source in 2018 and 2050 in the four scenarios. The final energy demand does not include the energy to process the energy carriers.

Also, the source of energy provision moves towards increased use of renewable sources. In the three low carbon pathways – Balanced Energy Carriers, Accelerated Transformation and Approaching Zero – renewable sources account for more than 73% of the final energy demand. In the Approaching Zero scenario 93% of the energy is supplied from renewable sources. This results in 5 billion kg of gases from, 40 billion liters of liquids and 150 PJ of electricity – all from renewable sources.

Furthermore, the vehicle stock changes as shown in Figure IV. The stock size grows in the Current Policies scenario and reduces in the Accelerated Transformation scenario. In both, the Balanced Energy Carriers and Approaching Zero scenario, the vehicle stock size in 2050 is as in 2018.

Vehicle stock in million units

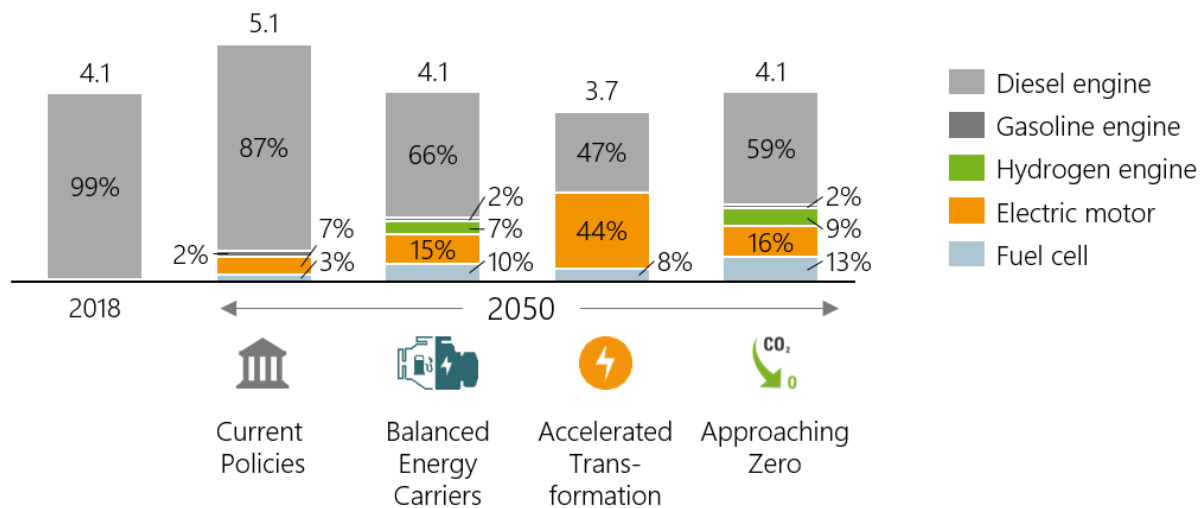


Figure IV: Heavy-duty vehicle stock in million units, shown by main energy conversion system in 2018 and 2050 in the four scenarios.

In all scenarios combustion engines stay relevant and represent at least 47% of the vehicle stock in 2050. Many of these combustion engines in the stock are hybridized: 23%-points in the Balanced Energy Carriers, 27%-points in the Accelerated transformation and 26%-points in the Approaching Zero scenario. Zero CO₂ emission powertrains represent a high share of the vehicle stock in 2050: 52% in the Accelerated Transformation, 38% in the Approaching Zero and 32% in the Balanced Energy Carriers scenario.

The total-cost of ownership for trucks with hydrogen combustion engine, battery and fuel cell electric powertrains reduce significantly until 2050. In the Balanced Energy Carriers scenario in 2050, a truck in a long-haul use-case incurs lower total cost of ownership with a fuel cell electric and hydrogen combustion engine powertrain than with a compression ignition powertrain. The total costs of ownership for battery electric and compression ignition powertrain are similar. In a regional-haul truck, battery electric powertrains are cheaper in total cost of ownership already in 2025 and extend this advantage throughout 2050. For a regional-haul truck, the total cost of ownership of a fuel cell electric and hydrogen combustion powertrain are similar to the compression ignition powertrain. In the Accelerated Transformation scenario, battery electric powertrains are cheaper in total cost of ownership than fuel cell electric, hydrogen combustion engines and compression ignition engines as well for long- as for regional-haul trucks.

Due to upgraded technology, all powertrains and gliders become more expensive. Therefore, the direct manufacturing costs of all vehicles sold are 9.3 billion € higher in 2045 than in 2018 in the Balanced Energy Carriers scenario and 8.8 billion € in the Accelerated Transformation scenario. This is an average increase of 39,000 € per vehicle in the Balanced Energy Carriers scenario and 44,000 € per vehicle in the Accelerated Transformation scenario compared to 2018's baseline vehicle.

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1. A pathway combines the ambition, boundary conditions, balances and modeling

1.1. The CO₂ emission reduction ambition focuses on complying with the Paris agreement

The decisions of authorities have an impact on pathways into the future by their influence on companies and consumers in their decisions that lead to greenhouse gas emissions. In recent years authorities enforced various strategies to reduce greenhouse gas emissions.

In November 2018, the European Commission communicated a strategic long-term vision for a climate neutral economy called “A Clean Planet for all” [European Commission, 2018a]. In this, the Commission defines the ambition of achieving net-zero greenhouse gas emissions by 2050. This level of ambition is in-line with the Paris Agreement to limit the global temperature increase to well below 2°C and pursue to limit it to 1.5°C [UNFCCC, 2015].

In “A Clean Planet for all” the European Commission mentions the need to prepare and align industry stakeholders so that the level of ambition can be met socially fair and cost efficient. In heavy-duty transportation the industry stakeholders are logistics fleet operators, vehicle manufacturers, technology suppliers and energy providers. Authorities should set-up a holistic framework for them to collaborate, as illustrated in Figure 1. This is especially important as the level of ambition is challenging and cannot be met by actions of any single stakeholder while pursuing economic growth.

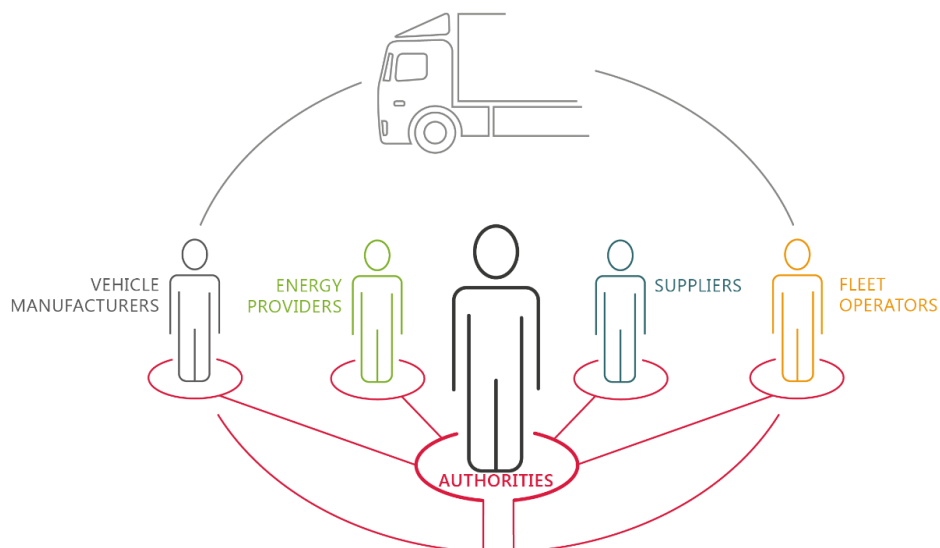


Figure 1: Authorities need to provide a framework for the industry stakeholders.

To achieve net-zero greenhouse gas emissions, there are two options: reduce emissions and increase sinks. Analysis carried out by the European Commission shows that a greenhouse gas emission reduction in the whole economy of 80% by 2050 compared to 1990 is in-line with limiting the temperature increase to well below 2°C and a reduction of 95% by 2050 compared to 1990 is in-line with limiting the temperature increase to 1.5°C compared to the pre-industrial era [European Commission, 2018a]. Therefore, the low carbon pathways for heavy-duty vehicles presented in this report achieve an 80% and 95% greenhouse gas emission reduction by 2050 compared to 1990 in an extended tank-to-wheel balance – please refer to chapter 1.2 for an explanation of the balance. This level of ambition for the transport sector is in part higher as in “A Clean Planet for all”, but we decided to explore these to understand their implications.

Since the data on greenhouse gas emissions the European Environment Agency publishes [EEA, 2019] covers EU-28, we will also do so in the following and refer to this as Europe.

1.2. We use three balances: extended tank-to-wheel, well-to-wheel and life-cycle analysis

Different greenhouse gas balances yield different results and thus different pathways. For this reason, we introduce the balances we consider.

Figure 2 shows three balances over five steps of an energy carrier’s value chain. The balances differ in which steps of the value chain they consider. We use three balances in this report: extended tank-to-wheel, well-to-wheel and life-cycle analysis.

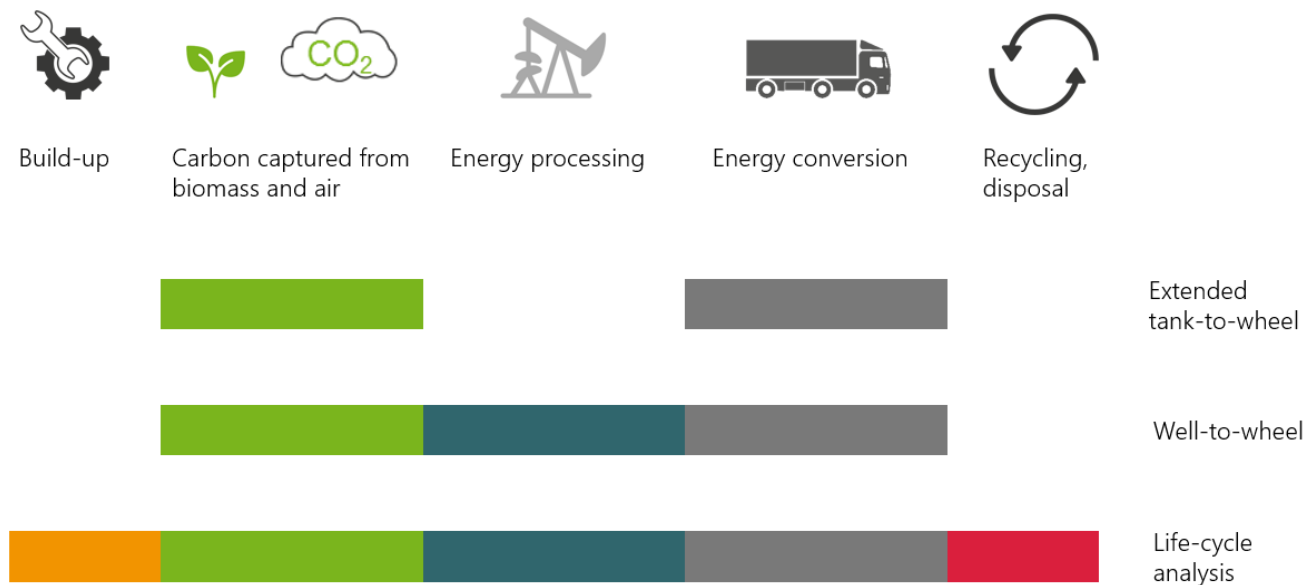


Figure 2: Overview of selected greenhouse gas emission balances.

The well-to-wheel balance considers three steps of the energy carrier’s value chain and the according emissions:

1. The carbon captured during plant growth for energy carriers from biomass or CO₂ capture for energy carriers from power-to-x processes.
2. Processing of the energy that is necessary to get from the raw materials to a final energy carrier.
3. Conversion of the final energy carrier in the vehicle to kinetic energy.

Analogously, the extended tank-to-wheel balance considers two steps of the energy carrier’s value chain: the carbon captured in point 1 and the conversion of the final energy carrier in point 3 of the list above.

Figure 3 illustrates the differences of the balances for four examples: for the two balances and for two fuels – diesel from a power-to-liquid process and diesel from fossil sources. We chose these four examples to explain the methodology.

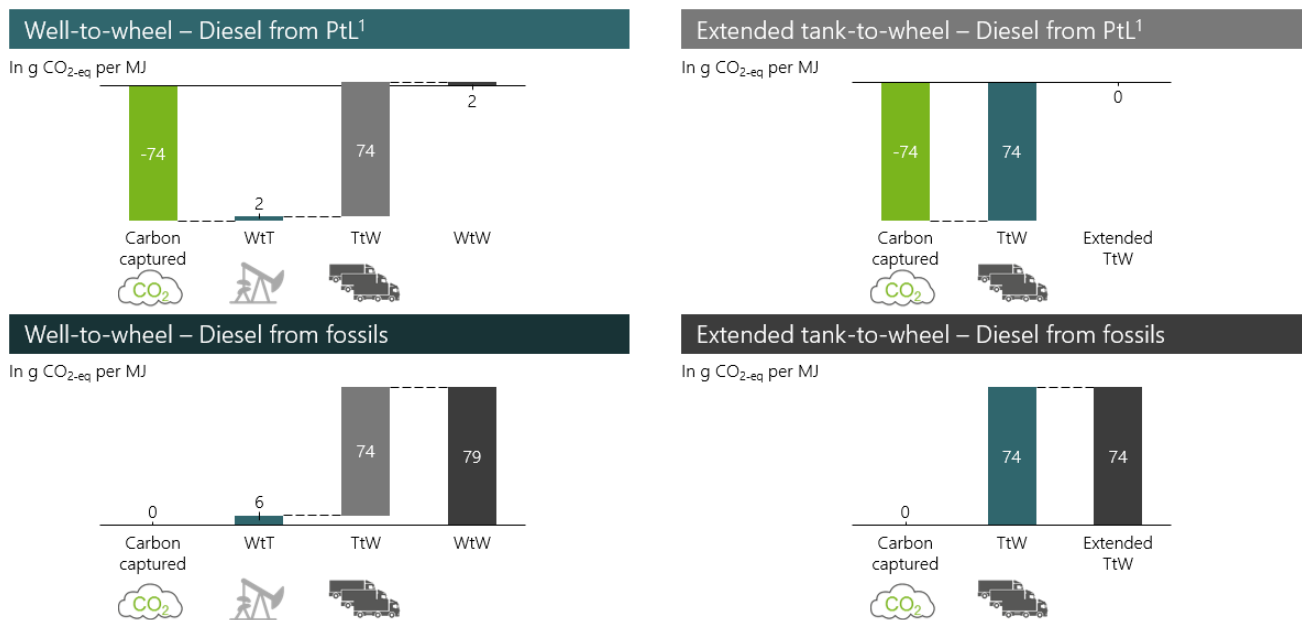


Figure 3: Exemplary calculation of CO₂ emissions for a diesel type fuel produced from renewable sources in a power-to-liquid process (upper) and from fossil sources (lower). Balanced in a well-to-wheel (left) and an extended tank-to-wheel balance (right). 1) Power-to-liquid process assessed with 98% electricity from low CO₂ emission sources and CO₂ from direct air capture as an input.

The top left diagram shows the well-to-wheel balance for the diesel from the power-to-liquid process. In this, the carbon captured refers to the 74 g CO₂ per MJ that are necessary to produce the fuel. Since this capturing removes CO₂ from the atmosphere the value is below zero. The next step – the processing of the fuel from well-to-tank – emits 2 g CO₂ per MJ. This is due to CO₂ emissions from electricity generation during the fuel production as well as the transportation to the filling station and

the dispensing of the fuel. This value is low since we consider 98% of the electricity to be supplied from low CO₂ emission sources. Now the fuel is in the tank of the vehicle. By combusting this fuel to deliver energy to the wheels, 74 g CO₂ per MJ enter the atmosphere through the tailpipe. In sum, the CO₂ emissions are 2 g per MJ.

The tank-to-wheel emissions equal the carbon captured since the tailpipe emissions are due to the carbon content of the fuel.

The three other examples can be computed analogously.

For fuels from fossil sources, the carbon captured equals zero since the process from capturing CO₂ in biomass and transforming it to fossil fuels takes millions of years. This is not sustainable in the timeframe discussed here.

We use the well-to-wheel balance to assess the greenhouse gas emissions of the economy. This is, because this balance includes emissions in all sectors of the economy to operate a vehicle. Consequently, it is a more comprehensive balance than the extended tank-to-wheel balance.

We use the extended tank-to-wheel balance to compare the greenhouse gas emissions to the level of ambition of the European Commission. The European Commission reports the greenhouse gas emissions in all industry sectors according to the IPCC guidelines [IPCC, 2006]. The balances in these guidelines for the transport sector resemble the extended tank-to-wheel balance. To ensure completeness, the emissions from energy processing are allocated in other sectors. Those reports date back to 1990 [EEA, 2019].

To establish a common baseline back to 1990, we calculated the corresponding emissions in a well-to-wheel balance. This is based on data that the European Environment Agency provides in the extended tank-to-wheel balance [EEA, 2019]. For the calculation we considered the well-to-tank emissions of the energy carriers and their blend rates.

Please note that the extended tank-to-wheel balance is different to the balance used to measure the CO₂ emissions from newly sold vehicles. The balance to measure the CO₂ emissions from newly sold vehicles is a tank-to-wheel balance and is measured with the certification fuel in defined test cycles. The CO₂ emission reduction targets for vehicle manufacturers are measured in this balance for newly sold vehicles. We do not use this balance in this study. We model the extended tank-to-wheel emissions in real-world driving under consideration of appropriate blend shares for each energy carrier.

1.3. We model pathways by integrating vehicles, energy demand and energy carriers

All pathways are results from our modeling. Therefore, we explain the methodology in the subsequent section.

We modeled CO₂ emissions since 99% of the greenhouse gas emissions were from CO₂ between 1990 and 2016 for heavy-duty vehicles [EEA, 2019].

We modeled the CO₂ emissions of the stock of heavy-duty vehicles in Europe. To do that we combined three groups of inputs as shown in Figure 4: vehicle, energy demand and energy carrier.

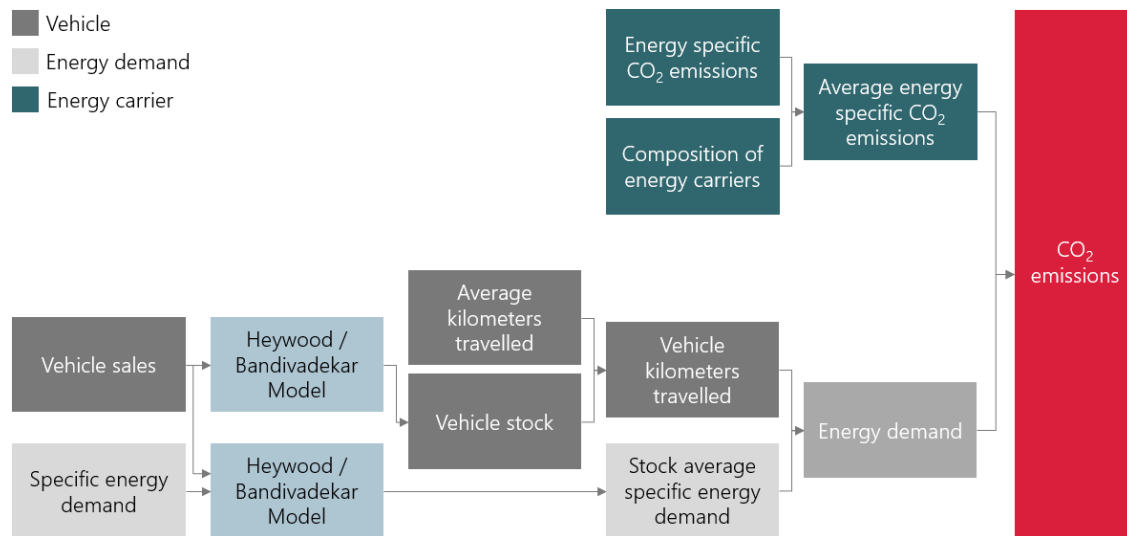


Figure 4: Structure to model the pathways

One vehicle specific input is the vehicle sales. We input the sales for each model year. Then, we use the Heywood/Bandivadekar Model to consider that vehicles stay in the market for a specific time. Thus, the result of the Heywood/Bandivadekar model is the vehicle stock. By multiplying the number of vehicles in use with the average kilometers travelled per vehicle we compute the vehicle kilometers travelled.

An energy demand input is the specific energy demand of the vehicles that are being sold. For example, the unit of the specific energy demand could be liter per 100 km or grams of CO₂ per km. By weighting the specific energy demand with vehicle sales and supplying this to the Heywood/Bandivadekar model, we compute the stock average specific energy consumption. The input of the specific energy demand considers the real-world energy demand at the average payload of the vehicle.

Now – by multiplying the vehicle kilometers travelled and the stock average specific energy demand – we compute the energy demand of the vehicle stock.

On the energy carrier side, we consider the energy specific CO₂ emissions and the composition of energy carriers as inputs to compute the average energy specific CO₂ emissions for each energy carrier group. We consider the energy specific CO₂ emissions in both balances: well-to-wheel and extended tank-to-wheel. The composition of energy carriers – for the example of liquid diesel-type fuel in 2018 – is approximately 94 volume-% from fossil sources and 6 volume-% from renewable sources.

Usually, energy carriers from fossil sources have higher CO₂ emissions than those from renewable sources. Thus, the composition affects the average energy specific CO₂ emissions.

Finally, by multiplying the average energy specific CO₂ emissions with the energy demand we compute the CO₂ emissions of the vehicle stock.

Since we calculate the energy the vehicles demand, we refer to this as the final energy demand. This does not include the energy to produce the energy carriers, while it does include the losses during the charging of batteries. Especially for power-to-liquid fuels it is important to note that we did not calculate the primary energy demand.

1.4. Boundary conditions include assumptions and limitations to the potential pathways

Several boundary conditions apply to the scenario modeling. Two boundary conditions of interest will be discussed here: the consideration of methane as an energy carrier and implications on air quality.

The combustion of methane is an option to reduce CO₂ emissions compared to the combustion of gasoline- and diesel-type fuel. It is a potentially important solution for heavy-duty trucks. Iveco and Volvo offer heavy-duty trucks with a methane combustion engine. Due to the more beneficial carbon-to-hydrogen ratio, the CO₂ emissions from the combustion of methane are lower compared to gasoline- and diesel-type fuels. Furthermore, production of methane from renewable sources is a viable option. Also, for a methane combustion powertrain lower total cost of ownership seem possible, as shown in Figure 14 and Figure 20. However, the methane slip from the vehicle and methane emissions through the whole value chain of the fuel can mitigate and offset the other savings. In the scenarios in this study methane is used in dedicated applications. Other scenarios with a higher use of methane are a valid option.

Air quality affects the health of everyone. Pollutant emissions reduce the quality of the air. The reduction of pollutant emissions by many combustion engine related measures has an impact on greenhouse gas emissions. Thus, we considered a reduction of pollutant emissions by 2050. However, this study focuses on greenhouse gas emissions and does not discuss implications on air quality in detail. We included a subchapter in the Appendix to cover key indications for the air quality within the scope of this study.

2. Four measures to achieve low carbon pathways

The four measures are: optimization of usage, electrification of powertrains, efficiency increase of vehicles and adaptation of energy carriers.

Main technologies for these measures are shown on the roadmap in Figure 5. In this, we only listed technologies we expect to be relevant in the given point in time. We suppose that more options will enter but are not widespread in the market.

We arrived at these main technologies by a synthesis of a technology push and a market pull assessment under consideration of a total cost of ownership and life cycle assessment as well as insights from FEV Consulting’s industry network. An expert group of Concawe and its member companies was involved in the process. Nevertheless, this report reflects FEV Consulting’s view on the mainstream technologies included in this assessment.

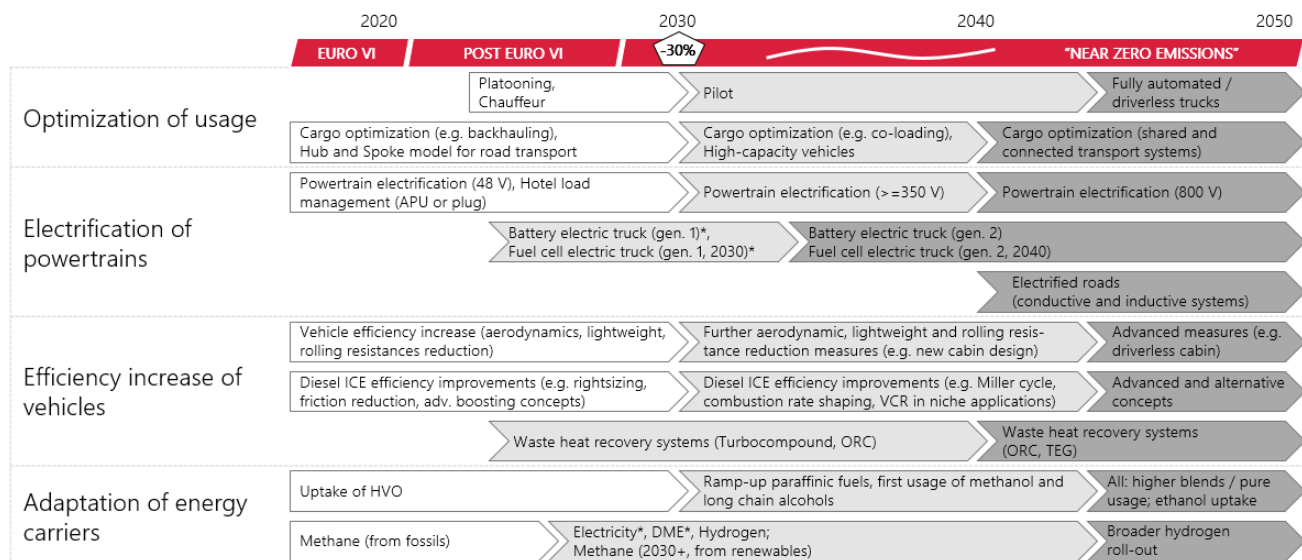


Figure 5: Roadmap of main greenhouse gas emission reduction technologies for heavy-duty trucks in Europe

*In dedicated use-cases

2.1. Optimization of usage considers modal and segment split as well as utilization

We consider the influence of the optimization of usage by three factors:

1. Modal split: How much of freight demand is transported on road?
2. Segment split: How much of road freight is transported with heavy-duty trucks?
3. Utilization: How much is the average payload of a heavy-duty truck?

As a baseline for all our scenarios, we take the overall freight demand in ton-kilometers in Europe. The European Commission expects this to increase by 36% between 2018 and 2050 [European Commission, 2016].

We determined the share of road transport by considering the modal split between road, rail, water and air transport. This depends mainly on infrastructure development, ease and cost of transportation in the competition between the modes. For the example of road transport, the infrastructure development considers the availability, congestion, condition and connectivity of the roads. Ease and cost of transportation on road benefit from high connectivity and automation.

Automation especially has the potential to reduce the costs of heavy-duty transport significantly. We determined a cost reduction of 54% for long-haul use-cases and 73% for regional-haul use-cases in 2045 between non-automated and automated trucks as shown in Figure 6. Driver costs dominate this cost reduction as they are the largest cost category at 52% for long-haul and 62% for regional-haul use-cases. The cost savings outweigh the additional depreciation an automated truck incurs since it requires – among others – more sensor systems.

Since the cost reduction is so significant, it is likely to influence the modal split towards road transport. Thus, emissions will be shifted from other segments of the transport sector towards the road. However, such a shift may lead to additional infrastructure costs for the society which we did not consider in this study.

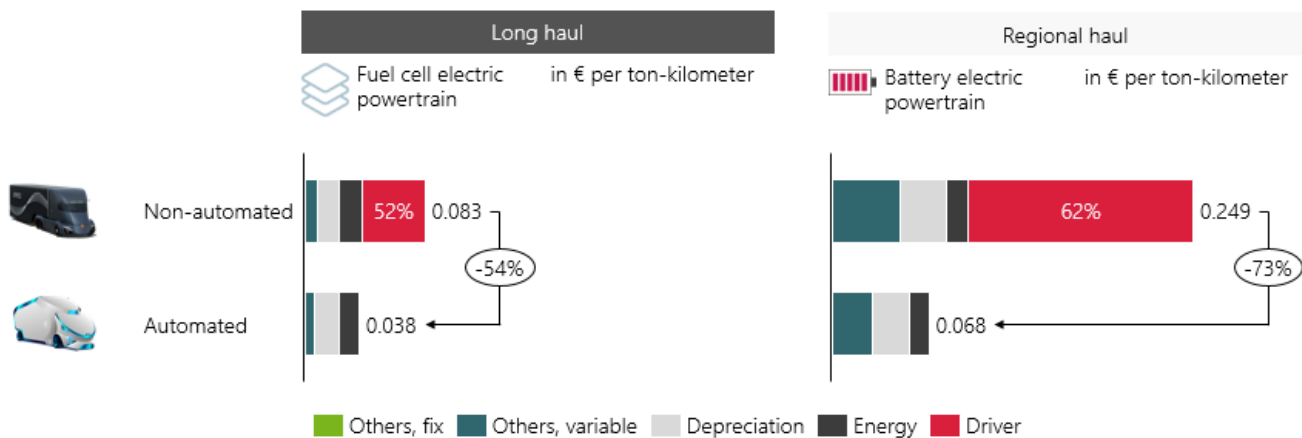


Figure 6: Cost breakdown of automated and non-automated use-cases in 2045.

The second influencing factor we considered is the segment split. Now that we know, which share of the freight demand is delivered on road, we can determine which share of this is covered by the segment of heavy-duty vehicles. Again, this share is influenced by several aspects including logistics concepts, additive manufacturing as well as connectivity and automation.

Logistics concepts such as the hub and spoke model or a different distribution of warehouses change the basis of today's truck purchasing decisions. Therefore, a shift from heavy-duty to medium- or light-

duty and the other way around is possible. The same effect is true for additive manufacturing: If rolled out widely, products can be created closer to the consumer and thus lead to a shift from heavy-duty towards lighter vehicles. Similarly, a fleet of connected and automated trucks could impact the share of transport carried out with heavy-duty trucks. This is due to more information about supply and demand of freight transport being available and the vehicles being more flexible to fulfill the demand.

As the third influencing factor on the optimization of usage, we consider utilization. A higher utilization at constant freight demand reduces emissions. We measure the utilization as the share of the average payload in the average capacity of the vehicles. Again, many factors influence the utilization including backhauling, co-loading and high capacity vehicles.

Backhauling refers to transporting goods on the way back of another trip. This is already done today, but may be increased in the future. The same applies to co-loading which is transporting goods from various customers in one trip. Connectivity and automation of trucks impact both trends since more information is available and the vehicles have a higher flexibility. High capacity vehicles refer to concepts which allow them to have more volumetric cargo space. An increase of the volumetric cargo space increases the utilization, since many transport tasks today are limited by the available cargo space rather than the permissible gross weight.

The optimization of usage reflects all of those influencing factors. In chapter 3, we will isolate the impact of this on the CO₂ emission reduction.

2.2. Electrification of powertrains comprises hybrid, battery and fuel cell electric

Electrification of powertrains starts with equipping today's combustion engine powertrains with a small battery and electric motor to build a hybrid powertrain. A next step is to increase the capacity of the battery and the power of the electric motor to strengthen the effect of the hybridization. An even larger step is the adoption of battery electric and fuel cell electric powertrains.

We expect hybrid powertrains in heavy-duty trucks mostly in a parallel architecture. One advantage of a hybrid over a conventional powertrain is the higher efficiency. This results from shifts of the load point of the combustion engine to higher efficiencies and more kinetic energy that can be recuperated. We consider the higher efficiency and thus fewer CO₂ emissions of hybrid trucks in this measure in the results presented in chapter 3. One disadvantage is the higher costs of the powertrain compared to a conventional powertrain. These accumulate since the battery, electric motor and power electronics cost more than the omission of other parts saves.

Battery electric trucks require large batteries to cover the high number of kilometers driven in one trip and the high energy demand of the vehicles. Since batteries are expensive, the costs for these vehicles depend largely on the battery.

Fuel cell electric trucks store pressurized hydrogen on board and use a fuel cell to generate electricity which in turn powers an electric motor. Additionally, the powertrain requires a small battery since the fuel cell usually does not provide power dynamically enough to cover all load points.

Battery and fuel cell electric powertrains use an electric motor as their single propulsion system. For most types of electric motors, their continuous power output is significantly lower than their peak power output. This is due to the cooling effect being lower than the heat generation at the peak power. When the materials get closer to their critical temperature, the power output needs to be reduced so that the cooling power matches the heat generation. Electric trucks need to match the continuous power output of combustion engine powered trucks to be competitive with these. Therefore, for electric trucks the peak power is usually higher than for combustion engine powered ones.

Electrified road systems support the electrification of powertrains. Those systems include conductive and inductive as well as road bound and overhead solutions. These solutions especially support hybrid and battery electric trucks. However, it is expensive to build up such an infrastructure and only a wide roll-out yields considerable effects.

Electrified powertrains reduce CO₂ emissions significantly in the extended tank-to-wheel balance. In this balance, the conversion from energy in the battery to kinetic energy does not emit CO₂. The same goes for the conversion of hydrogen to electricity and then to kinetic energy. On the contrary, in the well-to-wheel balance the CO₂ emissions of electrified powertrains depends on the generation of electricity and the production of hydrogen. By that, in a well-to-wheel balance the energy provision to the truck needs to be optimized. This implies a coupling of the transport and energy sector. To significantly reduce CO₂ emissions from electrified powertrains in the well-to-wheel balance, the provision of electricity and hydrogen needs to be based on renewable sources – the effect of this is included in the adaptation of energy carriers in chapter 2.4.

2.3. Efficiency increase of vehicles combines improvements of glider and powertrain

To account for the efficiency increase, we segment the truck into glider and powertrain. The powertrain includes the energy carrier storage, energy conversion system, gearbox and axles. The glider includes everything else, which is mostly the chassis and the cabin.

Improvements of the glider include reduction of aerodynamic drag, rolling resistance and weight reduction as well as improvements of auxiliaries. We expect the glider improvements in three steps and name those gliders:

1. Improved
2. New
3. Cabinless

The improved glider builds on today's body. It optimizes the aerodynamics mostly by covers and extenders. Advances in tires and axles reduce the rolling resistance. To reduce the weight, some parts are manufactured from aluminum instead of steel. An increase in the use of electrified auxiliaries helps to create the improved glider.

New gliders build on a new body-in-white. With the new body in white, aerodynamics improvements such as a backward raked windshield and a chassis integrated fuel tank can be realized. Moreover, we consider a wide use of active elements to optimize the aerodynamics of the truck to the driving conditions. To reduce the rolling resistance, we consider the optimization of the tire pressure. To reduce the weight, we apply composite materials.

Cabinless gliders are optimized for automated driving. A vehicle that does not need a driver, does not need a cabin. The absence of the cabin allows for more freedom in the design. This freedom can be used to reduce the aerodynamic drag. Since this shift is radical we expect aerodynamics to draw the focus of improvements. For rolling resistance and weight reduction as well as for improvement of auxiliaries we expect evolutionary improvements.

For the introduction of the gliders into the market we differentiate the heavy-duty vehicles between regional- and long-haul use-cases. In regional-haul trucks the improved glider prevails after 2030 and the new cabin glider after 2040. In long-haul trucks the improved gliders are introduced before 2030 and the new cabin glider before 2040. For both, a share of the automated trucks comes with cabinless gliders. The share differs in each scenario.

Improvements of the powertrain are different for each powertrain. For combustion engine powertrains those include general optimization and introduction of waste heat recovery.

We split combustion engine powertrains into compression and spark ignition. In compression ignition engines we consider the first step of optimization to include a stop/start function, rightsizing of the engine, an optimization of the injection system and an optimized crank train as well as the adoption of turbo compound waste heat recovery. In the second step we consider increased injection and peak firing pressure, Miller cycle and a variable compression ratio as well as organic Rankine cycle waste heat recovery. A third step includes further improvements of the measures named.

Today, spark ignition engines are only applied in very few heavy-duty trucks. Therefore, we expect different steps to increase the efficiency. Since many spark ignition engines for the use in heavy-duty trucks are based on compression ignition engines, the first step includes adaptations to the ignition, turbocharger, mixture preparation and engine management system. The second step includes base engine improvements, an increase of customized cylinder heads and an increase of waste heat recovery systems, especially for engines that run a stoichiometric combustion. The third step then considers further improvements following the compression ignition engine trends and improvements of the valvetrain as variable valve timing and lift as well as a potential application of lean combustion.

Electric powertrains can increase their efficiency in battery, power electronics and electric motor. The efficiency increase in the battery happens at cell and pack level: On cell level by advanced materials in anode, cathode and electrolyte and on pack level by optimization of the battery management system. In power electronics, two options are key: advances in IGBT (insulated-gate bipolar transistor) module design and a switch to MOSFET (metal-oxide semiconductor field-effect transistor) modules, which are based on silicon-carbide. In the electric motor, the optimization is driven by advanced magnetic field design and control.

Those measures increase the efficiency of hybrid, battery and fuel cell electric powertrains. Moreover, fuel cell electric powertrains can increase their efficiency by advances in the fuel cell stack and auxiliary system.

2.4. Adaptation of energy carriers is driven by energy from renewable sources

The adaptation of energy carriers contains two aspects: aggregate state and source of the energy carrier. Regarding the state, we differentiate between gaseous, liquid and electric energy carriers. Regarding the source, we differentiate between energy carriers from fossil sources and from renewable sources. As renewable sources we consider sunlight, wind, geothermal heat and biomass.

One option to reduce CO₂ emissions from fossil sources is to apply carbon capturing in the processing of the fuel. We considered such technologies. With these, the CO₂ intensity of energy carriers from fossil sources reduces.

Energy carriers from renewable sources achieve near zero CO₂ emissions in a well-to-wheel balance. These can be provided based on biomass and electric power. For gaseous and liquid fuels, the electric power is used in a power-to-gas and power-to-liquid process to produce a gaseous or liquid energy carrier. While the power-to-x process achieves a lower efficiency from well-to-tank compared to many alternatives, it yields two main benefits: higher energy densities compared to other energy carriers and omitting the need to adapt the powertrain [FEV Consulting, 2019]. Yet, power-to-x processes are still immature today and need further development. Therefore, we model a low contribution of energy carriers from power-to-x processes until 2030.

Liquids are today's most important energy carrier in the transport sector. The most promising candidates for a production from renewable sources considered in this study are: paraffinic fuels as well as short and long chain alcohols.

Paraffinic fuels are chains of carbon and hydrogen. From renewable sources, they can be produced from biomass- and power-to-liquid using the Fischer-Tropsch process for the fuel synthesis. We expect an uptake of paraffinic fuels from biomass before 2030 and an overall ramp-up of paraffinic fuels after 2030. Towards 2050, high blend shares up to pure usage of paraffinic fuels can be realized.

The most important short chain alcohols are methanol and ethanol. Both can be produced from biomass and for methanol a power-to-liquid process seems promising. We consider first usage of methanol in heavy-duty trucks in considerable quantities around 2030 and increasing blend shares towards 2050. Using ethanol in heavy-duty trucks is expected later than methanol. These can be used in compression and spark ignition engines, but would come at significant development effort.

Here, long chain alcohols begin with a chain length of seven carbon atoms. They can be produced via the biomass- and power-to-liquid process. For these, we expect the first usage after 2030 and a further ramp-up towards 2050. Blends of paraffins and long chain alcohols seem very promising – also when blended with diesel from fossil sources and FAME.

Gaseous fuels have low importance in heavy-duty trucks today, but promise high potential for the future. They include methane, DME and hydrogen – which can all be produced from renewable sources.

Methane is a niche energy carrier in commercial vehicles today and we expect it will be applied in dedicated use-cases in the future. This applies to compressed natural gas (CNG) as well as to liquefied natural gas (LNG). Until 2030 methane is expected to be mostly produced from fossil sources. After 2030 the production of methane from renewable sources is expected to increase. DME is a gaseous fuel that can be used in compression ignition engines. We expect it will be applied in dedicated applications around 2030. The production of DME can be based on a biomass- and power-to-gas process using the methanol route.

Hydrogen can power a fuel cell or a combustion engine. A hydrogen combustion engine can be an enabler for the market entry of hydrogen as an energy carrier: With a hydrogen combustion engine there is a change of the energy carrier, but the energy conversion system stays a combustion engine. Many fleet operators trust the combustion engine due to the experience they have with it. Due to the expensive tank, it is challenging to establish a hydrogen combustion engine competitive with a diesel powertrain. Yet, a hydrogen combustion engine emits zero CO₂.

Hydrogen can be produced from renewable sources with electrolysis, which is the first step of a power-to-x process. In the electrolysis, electricity from renewable sources is fed to an electrolyzer to split water into hydrogen and oxygen. An increased ramp-up of hydrogen is expected towards 2050.

Electricity is both a primary and a final energy carrier in heavy-duty vehicles: primary, if the final energy carrier is produced in a power-to-x process, final in electric vehicles that can connect to the electricity grid via a charger or an electrified road system. For both, the provision of electricity from renewable sources is key to emit few CO₂ in the well-to-wheel balance. Moreover, the electricity generation industry has its own ambition to reduce CO₂ emissions [European Commission, 2018a]. The CO₂ intensity of electricity generation in 2018 was about 134 g/MJ, for 2030 we expect 90 g/MJ and until 2050 the ambition is to generate electricity at net 0 g/MJ of CO₂ emissions. The realization of that has a great importance to achieve low CO₂ emissions in Europe. To generate electricity from renewable sources, solar and wind are the main sources.

For all energy carriers produced from renewable sources, scaling the production is challenging. This is due to high investments, necessary technology developments and for biomass due to a lack of availability and competition with nutrition.

With this, we have multiple options to reduce the CO₂ emissions from heavy-duty vehicles: many energy carriers that can be produced from renewable sources at low CO₂ emissions, many opportunities to raise the efficiency of vehicles, many steps to electrify the powertrain and many ways to improve the usage of vehicles. In chapter 3 we will combine these according to each scenario and present the impact of each of the four measures: optimization of usage, electrification of powertrains, efficiency increase of vehicles, and adaptation of energy carriers.

3. Result: 80%-95% of CO₂ emission reduction by combination of these measures

The composition of policy frameworks as well as the development and deployment of technologies define the pathway towards 2050. We present four scenarios: Current Policies, Balanced Energy Carriers, Accelerated Transformation and Approaching Zero. The latter three are on a low carbon pathway.

The Balanced Energy Carriers and Accelerated Transformation scenarios achieve 80% lower CO₂ emissions, while the Approaching Zero scenario achieves 95% lower CO₂ emissions in 2050 compared to 1990. For reference, in the Current Policies scenario only a 7% reduction can be achieved. These figures refer to an extended tank-to-wheel balance.

In each scenario we outline the impact of the four measures for the CO₂ emission reduction by 2050. Therefore, we set a reference to a development stop. The development stop is a common baseline to all the scenarios. In this, technology does not develop further after 2018: Throughout the years only 2018 model year vehicles are sold at the current share of powertrains. Only the number of vehicles sold increases to match the expected 36% increase in freight demand by 2050 compared to 2018. To isolate the effect of each, we then subsequently add the measures in four steps:

1. Optimized usage of the trucks
2. Electrification of powertrains
3. Efficiency increase of the vehicles
4. Adaptation of energy carriers

Please note that the resulting impact of each measure depends on the order of their application.

In the first step, to identify the impact of optimized usage we only consider changes of the modal split, share of road transport performed by heavy-duty trucks and their utilization. Doing that, we adapt the number of vehicles sold in each model year to satisfy the freight demand. We do not change the share of the powertrains being sold, nor do we consider efficiency improvements of the vehicle or adaptations of the energy carriers. All that stays in 2018's condition.

In the second step we add the electrification of powertrains by considering the share of hybrid, battery electric and fuel cell powertrains that we expect to be sold in each model year. Again, we do not change the efficiency of the vehicles and do not adapt the energy carriers. Thus, in the line named electrification in the well-to-wheel balance in Figure 8 (right), the impact of electrification is low since 2018's energy mix is considered.

In the third step, we account for the efficiency increase of the vehicles by introducing vehicles of the respective model year. As the vehicles get more efficient over time, they demand less energy. Now, only the energy carriers are still in 2018's condition.

In the fourth step – finally – the energy carriers are adapted. We consider blend shares of renewable sources according to each year. The effect of increasing the share of electricity from renewable sources is allocated in the measure adoption of energy carriers.

We apply this approach in all scenarios.

3.1. Each scenario results in its own combination of measures

Figure 7 compares the CO₂ emission reduction in the four scenarios and the four measures in the extended tank-to-wheel and the well-to-wheel balance.

In the extended tank-to-wheel balance the electrification of powertrains and adaptation of energy carriers are the most important measures. The electrification of powertrain is especially strong in the Accelerated Transformation scenario at 51% of the CO₂ emission reduction. The adaptation of energy carriers is in both – the Balanced Energy Carriers and the Approaching Zero scenario – the biggest contributor to the CO₂ emission reduction at 44% and 47%. In the Accelerated Transformation scenario, the adaptation of energy carriers is also important at 24%.

In the well-to-wheel balance the adaptation of energy carriers contributes to more than 50% of the CO₂ emission reduction in all three low carbon pathways: 60% in the Balanced Energy Carriers, 55% in the Accelerated Transformation and 65% in the Approaching Zero scenario. The contribution of the adaptation of energy carriers is higher in the well-to-wheel balance than in the extended tank-to-wheel balance because the effect of generating more electricity from renewables is recognized.

CO₂ emission reduction in million tons and breakdown by measures

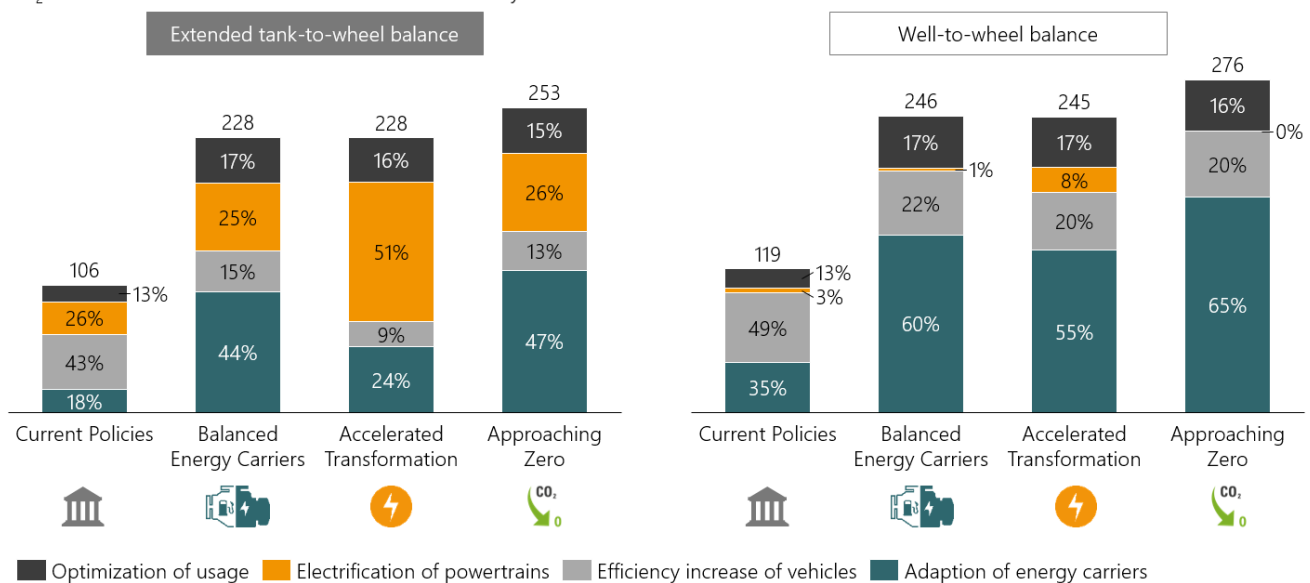


Figure 7: Comparison of the CO₂ emission reduction in million tons in the four scenarios and breakdown by the four measures in the extended tank-to-wheel balance (left) and the well-to-wheel balance (right) by 2050 compared to 1990.

3.1.1. The underlying assumptions of the scenarios influence the combination of measures

The level of the CO₂ emission reduction ambition is not defined for the Current Policies scenario. For the Balanced Energy Carrier scenario it is 80% as well as for the Accelerated Transformation scenario, for the Approaching Zero scenario it is 95% – each measured in the extended tank-to-wheel balance and to be achieved by 2050 compared to 1990. Figure 23 in the Appendix shows a comparison of details for the developed scenarios.

The fundamental assumption for the Current Policies scenario is that the announced policies are considered and above that some market driven improvements. In the Balanced Energy Carriers and Approaching Zero scenario the world evolves as we expect it – alternative powertrains are introduced where they are the best solution. The Accelerated Transformation scenario assumes an earlier and more intense uptake of electrification, automation, connectivity and the according infrastructure.

The Current Policies scenario applies some usage optimization, has 7% battery and fuel cell electric vehicles in the stock in 2050 and increases the usage of renewable sources at up to 14 volume-% in liquids, 30 mass-% in gases. In electricity we considered nearly 100 energy-% from low CO₂ emission sources. The efficiency increase of vehicles is high in relative terms, driven by the customer demand for lower total cost of ownership.

As the Balanced Energy Carriers and Accelerated Transformation scenario fulfills the same level of CO₂ emission reduction ambition, we can compare the combination of measures by comparing their impact in Figure 11 and Figure 18. The optimization of usage plays an equally important role in both.

3.1.2. Energy carriers are adapted more in the Balanced Energy Carrier, electrification is stronger in the Accelerated Transformation scenario

The optimization of usage considers the share of freight transported on the road and within that, the share of freight transported with heavy-duty trucks as well as the average truck utilization. All those factors impact the number of vehicles sold in each scenario. In 2018 about 300,000 heavy-duty trucks have been sold, while 71% of the ton-kilometers of freight transport were transported on the road and 86% of these were transported in heavy-duty trucks at an average truck utilization of 65%. In the Current Policies scenario in 2050 we model sales of 325,000 vehicles considering the increased freight demand and a modal split of 70% for road transport, the share of heavy-duty vehicles in that reduces to 84% while the average truck utilization increases to 67%. In the Balanced Energy Carriers and Approaching Zero scenario in 2050 we model 225,000 vehicles sold with a modal split of 74% on the road, 80% of the freight on the road transported in heavy-duty trucks and 70% average truck utilization. In the Accelerated Transformation scenario in 2050 we model 170,000 vehicles sold and a modal split of 76% on the road, 75% of the on-road freight transported in heavy-duty vehicles and an

average truck utilization of 70%. The main drivers for the differences are the level of automation, connectivity and different forms of logistics concepts.

The impact of electrification is much stronger in the Accelerated Transformation scenario at 51% of the CO₂ emission reduction by 2050 compared to 25% in the Balanced Energy Carriers scenario in the extended tank-to-wheel balance. This is due to the fundamental assumption of the Accelerated Transformation scenario that the uptake of electrification happens earlier and more intense than in the other scenarios. This is mirrored by the assumption of lower battery costs in the total cost of ownership analysis – shown in Figure 14 and Figure 20. This leads to battery electric trucks being favorable in many use-cases in this scenario by 2050. In the Accelerated Transformation scenario 44% of the vehicle stock has a battery electric and 8% a fuel cell electric powertrain by 2050, compared to 15% and 10% respectively in the Balanced Energy Carriers scenario. The results of the Accelerated Transformation scenario are hard to achieve since therefore multiple aspects need to develop favorably: charging infrastructure, electrified road systems, battery energy density and battery costs.

For the efficiency increase, we assumed the same measures to be applied to gliders and powertrains in both scenarios – yet we receive different results at 15% contribution in the Balanced Energy Carriers and 9% in the Accelerated Transformation scenario in the extended tank-to-wheel balance. We assume the same measures to be applied since the customers demand efficient vehicles and the manufacturers supply these when the improvements are mature in technology and costs. The results are different due to the order in which we apply the measures. We account for the uptake of electrification first, and there is a fewer share of combustion engine powered vehicles in the stock in the Accelerated Transformation than in the Balanced Energy Carriers scenario. As electric vehicles have a lower efficiency improvement potential than combustion engine powered ones, the impact of the same measures is lower.

The adaptation of energy carriers has a higher impact in the Balanced Energy Carriers scenario than in the Accelerated Transformation scenario. In the extended tank-to-wheel balance this is due to electric vehicles being accounted with zero CO₂ and the fact that there are more of these vehicles in stock in the Accelerated Transformation scenario. In the well-to-wheel balance this is due to electric vehicles having a higher efficiency than combustion engine powered ones and thus reduce the CO₂ emissions and mitigating the need for an adoption of energy carriers. In the Balanced Energy Carriers scenario renewable sources are blended at 75 volume-% to liquid and 80 mass-% to gaseous fuels compared to 65 volume-% for liquid and 70 mass-% for gaseous fuels in the Accelerated Transformation scenario. In both scenarios electricity comes at nearly 100 energy-% from low CO₂ emission sources.

The Approaching Zero scenario sets out the same fundamental assumptions as the Balanced Energy Carriers scenario, but it achieves the more demanding 95% reduction of CO₂ emissions. To achieve this, electrification and adaptation of energy carriers are stronger in the Approaching Zero than in the Balanced Energy Carriers scenario. By 2050 the vehicle stock consists of 16% battery and 13% fuel cell

electric trucks in the Approaching Zero scenario compared to the 13% and 10% respectively in the Balanced Energy Carriers scenario. At the same time, the blend rates of renewable sources are 93 volume-% in liquid and 95 mass-% in gaseous fuels compared to 75 volume-% and 80 mass-% respectively in the Balanced Energy Carriers scenario.

After this comparison of the results, we now present the details of the four scenarios. We walk through the scenarios one by one. Starting with the Current Policies, then the Balanced Energy Carriers and Accelerated Transformation and finally the Approaching Zero scenario.

3.2. Under the Current Policies CO₂ emission reduction is effective until 2030

Within the Current Policies scenario, we consider the policies announced by early 2019. This includes the Renewable Energy Directive II [European Commission, 2018b] and the CO₂ emission targets for the heavy-duty vehicle manufacturers sales fleet. The four measures – optimized usage, electrification of powertrains, efficiency increase of vehicles and adaptation of energy carriers – are introduced as needed. Apart from that and especially after 2030, improvements are only introduced if they yield a clear competitive advantage for the vehicle manufacturers and fleet operators. In this sense, the Current Policies scenario reflects a business-as-usual mindset.

Figure 8 shows the CO₂ emission reduction in the Current Policies scenario. In both balances the CO₂ emissions are only 7% lower by 2050 than in 1990, which is insufficient to achieve the European level of ambition. As Figure I shows, the Current Policies scenario achieves nearly the same CO₂ emission reduction as the other scenarios until 2030. This is because the whole industry needs to take high efforts to comply with the targets for 2030. Only after 2030 the Current Policies scenario lacks further CO₂ emission reduction to achieve a sufficient reduction.

Relative to the development stop, the CO₂ emission reduction in the extended tank-to-wheel balance splits into 13% optimization of usage, 26% electrification of powertrains, 43% efficiency increase of the vehicles and 18% adoption of energy carriers.

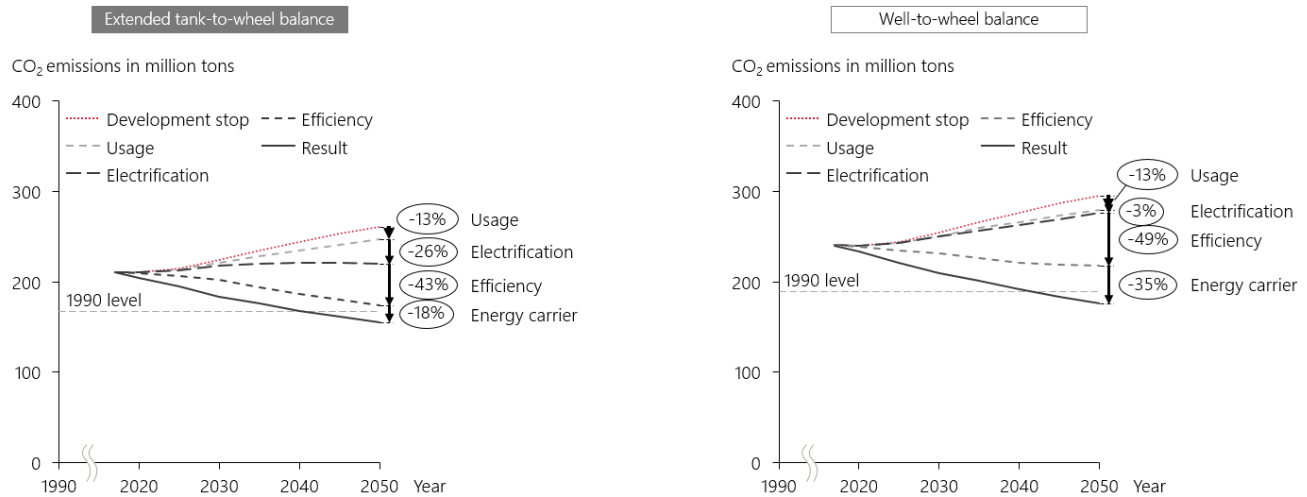


Figure 8: Current policies – CO₂ emission reduction in an extended tank-to-wheel balance (left) and a well-to-wheel balance (right). Both break the reduction down to the four measures.

3.2.1. All four measures contribute to the CO₂ emission reduction but the impact is low

The CO₂ emission reduction from the optimized usage comes from three factors:

1. Modal split between road, rail, water and air
2. Share of on-road transport performed by heavy-duty vehicles
3. The average truck utilization

We considered a small modal split shift away from the road as the European Commission plans [European Commission, 2016]. In 2018, approximately 71% of freight is transported on roads, in the Current Policies scenario this reduces to 70% by 2050. The strong upgrade in the rail infrastructure and the automated usage of trucks is balanced. In this scenario we expect automated trucks at 20% of the vehicle stock in 2050. With this, we expect a market introduction of automated trucks after 2030 and an uptake only in few use-cases. However, in these use-cases the automated trucks dominate due to their cost advantage as shown in Figure 6. The uptake of automated trucks is later and less intense than in the other scenarios due to an assumed lack of guiding frameworks.

For the share of on-road transport that is performed by heavy-duty vehicles there is a small reduction from 86% in 2018 to 84% in this scenario. This is due to a mild uptake of advanced logistics concepts and a shift towards lighter vehicles by automated and connected trucks.

The average truck utilization increases in this scenario from 65% in 2018 to 67% in 2050. An increase in co-loading and backhauling by a higher connectivity and automation of trucks yields this effect.

Electrification of powertrains has a different impact in the two balances. In the extended tank-to-wheel balance the 7% of the vehicle stock which are battery electric and 3% which are fuel cell electric have

zero CO₂ emissions. While in the well-to-wheel balance they emit CO₂ at 2018's energy mix. Battery electric trucks emit somewhat less CO₂ and fuel cell electric trucks powered with hydrogen produced from steam methane reforming emit significantly more CO₂ per kilometer than compression ignition powertrains fueled with standard diesel.

The efficiency increase combines the effect of the advanced gliders and upgraded powertrains sold throughout the years. On average a new truck sold in 2050 demands 35% less energy than a truck from 2018. The new gliders dominate the vehicle stock in 2050, followed by the improved and cabinless gliders. The improved gliders are mainly in regional-haul use-cases and the cabinless gliders mainly in long-haul use-cases.

Energy carriers from renewable sources contribute to the CO₂ emission reduction. We considered a blend share of renewable sources of 14 volume-% in liquid fuels, 30 mass-% in gaseous fuels by 2050. In electricity we considered nearly 100 energy-% of low CO₂ emission sources by 2050. As explained above, the effect of applying electricity from renewable sources is recognized only in the well-to-wheel balance. The blend shares of renewable sources in liquid fuels are ramped up to meet the Renewable Energy Directive II by 2030. After 2030 there is no considerable uptake of liquids from renewable sources since they are more expensive than liquid fuels from fossil sources. The high share of electricity from renewable sources is in-line with the European ambition to achieve a CO₂ neutral electricity generation.

The 35% CO₂ emission reduction from energy carriers comes at 26%-points from liquid fuels, 19%-points from electricity and 2%-points from gaseous fuels.

3.2.2. Energy demand and vehicle stock change less than in other scenarios

Results from this combination of measures are the final energy demand and the composition of the vehicle stock. As shown in Figure 9 (left), the final energy demand of heavy-duty vehicles is 13% lower in 2050 than in 2018.

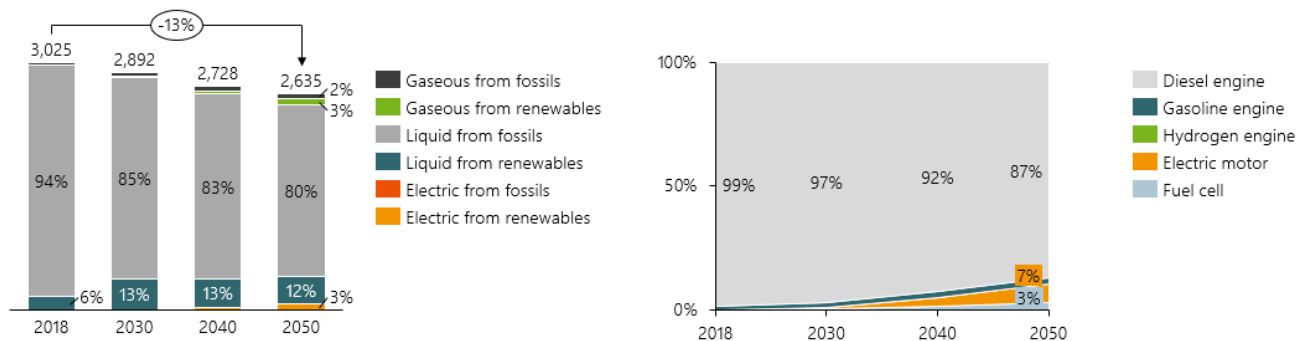


Figure 9: Current policies – Final energy carrier demand in PJ including a breakdown to state and source of the energy carriers (left). Breakdown of the vehicle stock by main energy conversion system (right).

The reduction is a result of more efficient vehicles and powertrains as well as the increased transport demand. In 2050, fossils supply more than 80% of the final energy demand. Liquid fuels from fossil sources are the biggest segment at 80% of the energy demand which is nearly all diesel-type fuel. The 12% liquid fuels from renewable sources equal 10 billion liters which is nearly double of today's demand. Gaseous fuels include methane and hydrogen. The demand of the vehicle stock for methane adds-up to 1 billion kg and for hydrogen to 0.70 billion kg in 2050. Although the amount is much larger than today, we expect the supply of this amount to be a comparably low challenge: first, because other industries process larger amounts, second because the production of liquids from renewable sources requires related technology. Finally, the electricity demand rises to 65 PJ by 2050. This equals the production of 103 km² solar panels or 1,900 wind turbines. For reference, the number of newly installed wind turbines in Europe in 2018 was about 2,500 [Wind Europe, 2019].

Figure 9 (right) shows the composition of the vehicle stock by main energy conversion systems. In 2050, 87% of these still apply a diesel engine. 7% apply an electric motor as the main energy conversion system and thus operate a battery electric powertrain. 3% apply a fuel cell as the main energy conversion system. Of the 87% diesel engines, 23%-points are hybrids. Hydrogen combustion engines are not expected to enter the market in this scenario. Overall, 5.1 million vehicles are in the stock which is considerably more than today's 4.1 million. The larger stock is a result of the increased transport demand and the optimization of usage as stated above.

3.3. In the Balanced Energy Carriers scenario all four measures unfold

In the Balanced Energy Carriers scenario, the world evolves as we currently expect it – alternative powertrains are introduced where they are the best solution. An 80% CO₂ emission reduction ambition is met in the transport sector in the extended tank-to-wheel balance by 2050 compared to 1990. Battery electric vehicles are introduced where they are the best solution. The same goes for hydrogen combustion engines, fuel cell and diesel trucks.

In the well-to-wheel balance, the CO₂ emission reduction is 74% between 2050 and 1990. This is, in relative terms, less than in the extended tank-to-wheel balance because in the well-to-wheel balance emissions from electricity and fuels from renewable sources are considered. In absolute terms the CO₂ emission reduction in the well-to-wheel balance is higher than in the extended tank-to-wheel balance – the difference between the two balances reduces between 1990 and 2050, as shown in Figure 10. This is, because the energy provision from well-to-tank gets more efficient over time. This trend is

supported by the uptake of electricity from renewable sources and power-to-x fuels from renewable sources that nearly emit no CO₂ from well-to-tank.

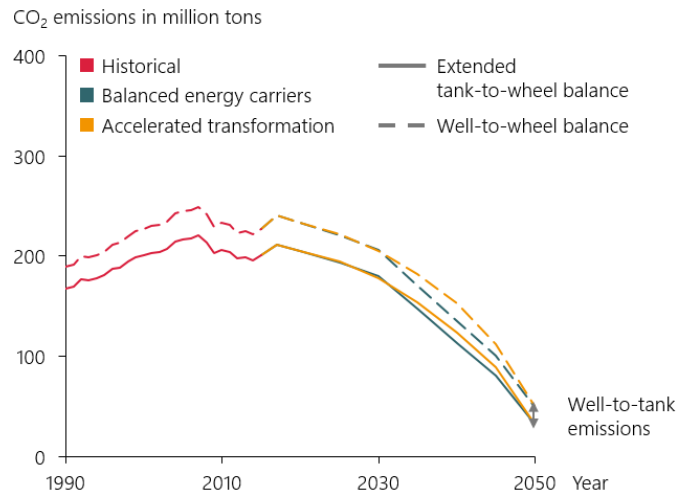


Figure 10: Comparison of emissions in the two balances well-to-wheel (dashed) and extended tank-to-wheel (solid)

As shown in Figure 11, relative to the development stop, the CO₂ emission reduction in the extended tank-to-wheel balance in 2050 splits into 17% optimization of usage, 25% electrification of powertrains, 15% efficiency increase of the vehicles and 44% adaptation of energy carriers.

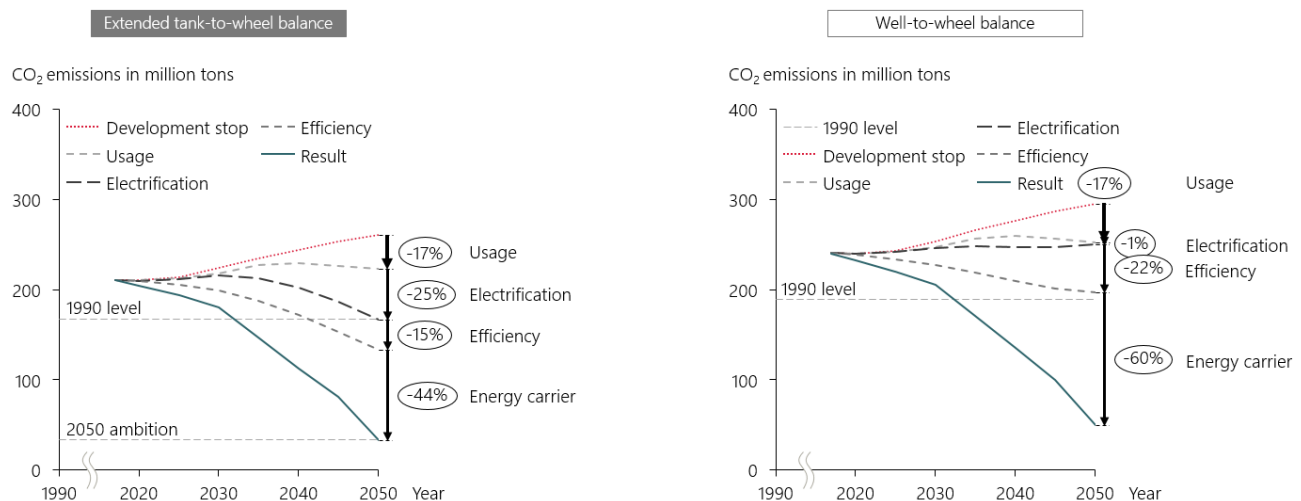


Figure 11: Balanced Energy Carriers – CO₂ emission reduction in an extended tank-to-wheel balance (left) and a well-to-wheel balance (right). Both break the reduction down to the four measures.

3.3.1. Energy carriers and electrification drive the CO₂ emission reduction while usage and efficiency have a considerable contribution

The CO₂ emission reduction from the optimized usage originates from the modal split, the share of road transport performed by heavy-duty vehicles and the average truck utilization.

In this scenario, we expect a modal split shift towards the road from 71% in 2018 to 74% in 2050. With this, CO₂ emissions from other transport modes are shifted into the road transport. This is because we expect an earlier and more intense uptake of automated trucks than in the Current Policies scenario: 33% of the trucks in stock can drive automated in 2050. As shown in Figure 6, automated trucks are much cheaper than non-automated ones. Adding on that is the higher flexibility and connectivity of these vehicles. In sum of these aspects we shift 3%-points of transport activity towards the road.

Contrary to this, we modeled the share of road transport performed by heavy-duty trucks to reduce from 86% in 2018 to 80% in 2050. As in the Current Policies scenario this is due to a mild uptake of advanced logistics concepts, while the shift towards automated and connected trucks is even stronger than in the Current Policies scenario.

We expect the average truck utilization to increase from 65% in 2018 to 70% in 2050 in this scenario. This is realized by an increase in co-loading and backhauling, which itself are enabled by connected and automated trucks.

The electrification of powertrains reduces the CO₂ emissions in the extended tank-to-wheel balance at 25% and in the well-to-wheel balance only by 1%. Again the 1% is only a low contribution since this only considers the effect of electrifying the powertrain and still uses the energy mix of 2018. The shift towards more electricity and hydrogen from renewable sources is included in the adaptation of energy carriers.

The 25% CO₂ emission reduction from electrification in the extended tank-to-wheel balance can be attributed mostly to battery and fuel cell electric vehicles: battery electric vehicles account for 14%-points of the reduction, fuel cell electric vehicles for 10%-points and hybrids for 1%-point. Figure 13 (right) shows the composition of the vehicle stock that leads to this CO₂ emission reduction of electrified powertrains.

Efficiency increase of the vehicles accounts for 15% of the CO₂ emission reduction in the extended tank-to-wheel and 22% in the well-to-wheel balance.

In 2050 the stock of trucks with a new cabin glider and a hybrid powertrain demands on average 35% less energy for the same task than the stock of trucks with a baseline glider and compression ignition powertrain in 2018. Analogously, the stock of trucks in 2050 with a battery electric powertrain demands 20% less energy than the trucks that are expected to enter the market around 2020. For the stock of fuel cell electric trucks this figure is 25%. The values for battery and fuel cell electric powertrains are lower than for the combustion engine powertrains for two reasons: Firstly, battery and fuel cell electric powertrains have a higher efficiency and less potential for optimization than compression ignition and hybrid powertrains. Secondly, battery electric and fuel cell powertrains are introduced into the market later and with more advanced gliders compared to the stock of trucks with a compression ignition powertrain in 2018 which is on average about ten years old.

The improvement of gliders dominates the efficiency increase: More than 60% of the efficiency increase comes from the glider and less than 40% from the powertrain. For hybrid, battery and fuel cell electric powertrains the influence of gliders is especially high, since these powertrains have a high efficiency. With the improvements of the compression ignition engine a maximum brake thermal efficiency of around 55% can be achieved.

The adaptation of energy carriers is the most important measure for the CO₂ emission reduction in this scenario at 44% and 60% in the respective balances. For this, we modeled blend shares of energy carriers from renewable sources at 75 volume-% in liquids, 80 mass-% in gases by 2050. In electricity we considered 100 energy-% from low CO₂ emission sources. The 60% CO₂ emission reduction in the well-to-wheel balance distributes to 44%-points to liquids, 8%-points to gases and 8%-points to electricity.

3.3.2. Life-cycle CO₂ emissions reduce due to use of energy from renewable sources

As shown in Figure 2, the life-cycle analysis is the most comprehensive balance to account CO₂ emissions. It includes carbon captured, well-to-tank and tank-to-wheel emissions as well as the emission from build-up, recycling and disposal of all related components.

We modeled the life-cycle CO₂ emissions for long- and regional-haul use-cases, compression ignition, battery and fuel cell electric powertrains, each if the truck is sold in 2018 and 2050. For all vehicles we considered a usage over eleven years to represent the average time a vehicle stays in the European market. We considered a yearly driving distance of 110,000 km for long-haul trucks and 50,000 km for regional-haul trucks. We set-out to isolate the influence of the energy carrier. Therefore, the energy demand and emission intensity from maintenance, production and materials are assumed to be constant at 2018's values.

In the long-haul use-case the trucks have a peak power of 330 kW in the combustion engines and the fuel cell as well as 550 kW in the electric powertrain. The peak power in the electric powertrain is higher to match the maximum continuous power output of the combustion engine powertrains – for an explanation see chapter 2.2. The hydrogen tank capacity is 80 kg for the vehicle with a hydrogen combustion engine and 50 kg for the vehicle with a fuel cell. The battery electric powertrain comes in two battery capacities: small with 500 kWh and large with 900 kWh. We apply the small battery capacity until 2035 and afterwards the large one. If the truck runs eleven years, no battery replacement is necessary but the fuel cell stack needs to be replaced one time. Starting from 2025 we modeled the improved glider, and from 2035 the new glider.

In the regional-haul use-case the peak power of combustion engines and the fuel cell is 240 kW and 400 kW in the electric powertrain. The hydrogen tank capacity is 40 kg in the vehicle with the hydrogen combustion engine and 25 kg in the vehicle with the fuel cell. Again, the battery electric powertrain

comes in two battery capacities: 300 kWh and 400 kWh. Until 2035 we specified the small battery and afterwards the large one. If the truck runs eleven years, no battery replacement is necessary but the fuel cell stack needs to be replaced one time. Until 2025 we modeled the baseline glider, in 2035 the improved one and starting from 2045 the new one.

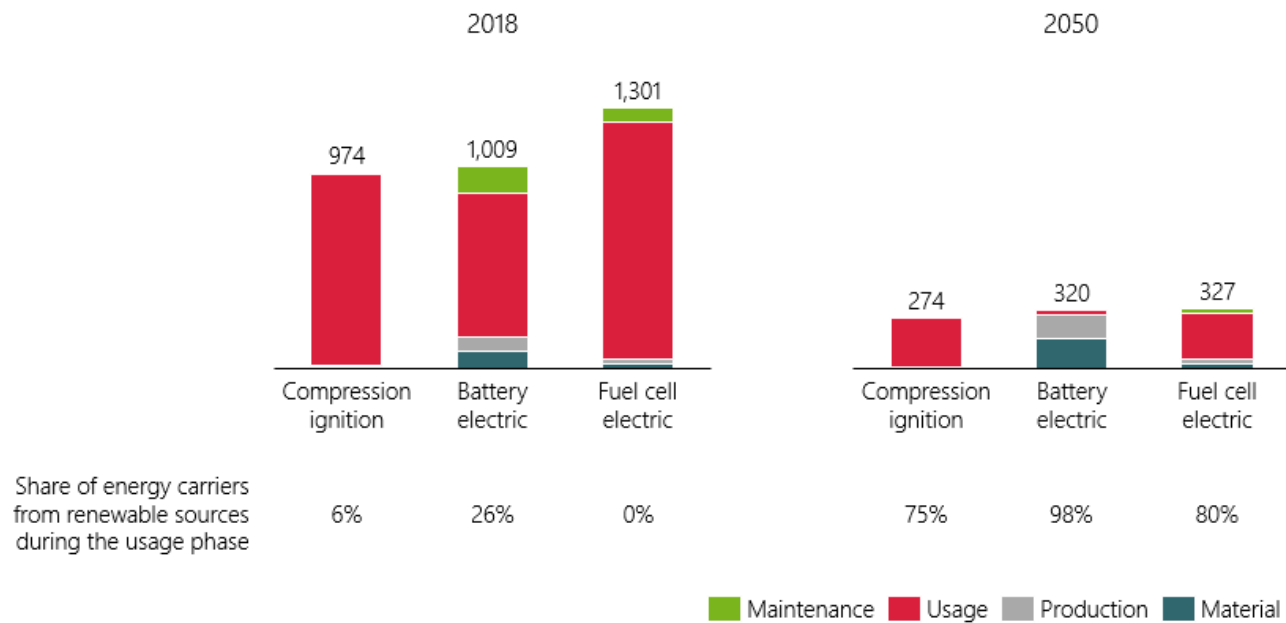


Figure 12: Balanced Energy Carriers – Life-cycle CO₂ emissions in the first eleven years of a heavy-duty long-haul trucks life if it is sold in 2018 (left) and 2050 (right).

As Figure 12 shows, with these boundary conditions, a truck sold in 2018 with a compression ignition powertrain emits the least CO₂ over their life-cycle. These are 4% lower than for the battery electric powertrain and 26% lower than for the fuel cell electric powertrain. For the battery electric powertrain, the emissions related to built-up and recycling account for nearly 30% of the emissions – compared to less than 2% in the compression ignition powertrain. This is especially due to the high energy demand related to the battery cell production. The fuel cell electric powertrain emits so much CO₂ because in 2018 still most of the hydrogen is produced from steam methane reforming which comes at high well-to-tank emissions.

If a truck is sold in 2050 at the share of energy carriers from renewable sources as in this scenario, the life-cycle CO₂ emissions of all powertrains are on average 72% lower than for a truck sold in 2018. Compression ignition powertrains have the lowest life-cycle CO₂ emissions in this scenario and under the assumptions taken. The emissions from a battery electric powertrain are 17% and from a fuel cell electric powertrain are 19% higher. For the battery electric powertrain, the CO₂ emissions from the usage are lowest – which is due to the high share of energy from CO₂-free sources at 98%. If for the production and material a higher share of renewable energy would be considered, the life-cycle CO₂ emissions from the battery electric truck would be lowest.

These results are similar for regional-haul trucks. Also in the other scenarios, the results are similar. The differences depend only on the emissions in the usage phase. Those depend on the share of energy carriers from renewable sources.

3.3.3. Energy demand reduces and more energy comes from renewable sources while the vehicle stock differentiates

Closely linked to the adaptation of energy carriers is the final energy demand shown in Figure 13 (left). In 2050 the heavy-duty trucks demand 25% fewer energy than in 2018. This is due to more efficient gliders and powertrains. More efficient powertrains include upgraded combustion engines, hybrid and battery electric powertrains. Battery electric powertrains are more energy efficient than the other powertrains modeled. Therefore, the share of vehicles in stock Figure 13 (right) is higher than the share of final energy demand for electricity.

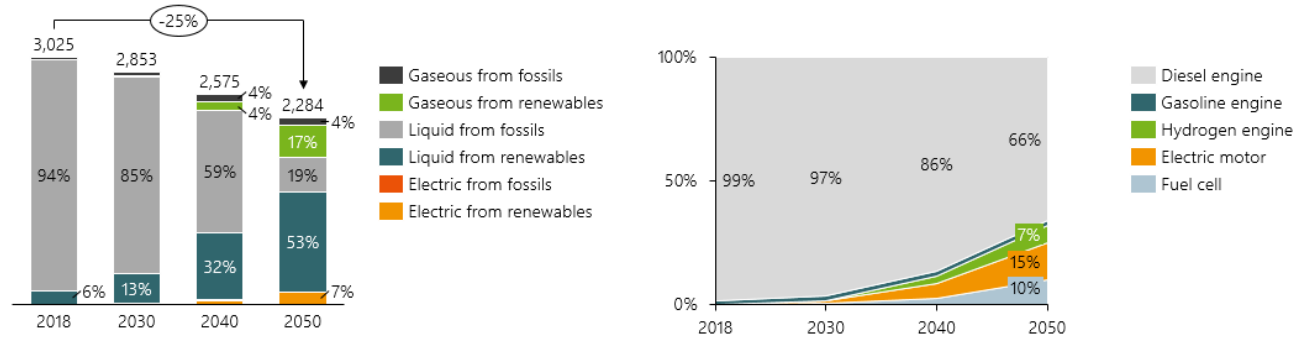


Figure 13: Balanced Energy Carriers – Final energy carrier demand in PJ including a breakdown to state and source of the energy carriers (left). Breakdown of the vehicle stock by main energy conversion system (right).

Besides the reduction of energy demand, also the composition of energy carriers changes significantly between 2018 and 2050. In 2050, 21% of the energy is supplied by gaseous fuels, of which 17%-points are from renewable sources. This is dominated by a demand for 4 billion kg of hydrogen, the demand for methane adds up to 0.85 billion kg. Also, liquid fuels from renewable sources account for 53% of the final energy demand, which equals 35 billion liters in 2050. The demand for electricity from low CO₂ emission sources is 154 PJ. To supply these energy carriers from renewable sources, profound changes in the energy provision are required. To achieve these, authorities need to provide frameworks that enable competitiveness of energy carriers from renewable sources. So, planning security and high demand is established to enable the huge investments that are required.

The vehicle stock that demands this energy, is shown in Figure 13 (right) and is broken down by main energy conversion system. Overall 4.1 million vehicles are in stock, which is nearly the same as in 2018. 66% of these still apply diesel engines in 2050 – of which 27%-points are hybridized. 7% of the vehicle stock apply a hydrogen combustion engine, 15% apply an electric motor as the main energy conversion

system and thus a battery electric powertrain. 10% of the vehicle stock converts the energy first in a fuel cell.

In this scenario, we expect an uptake of hydrogen combustion engines around 2030. For long-haul trucks, we expect this to happen before the uptake of battery and fuel cell electric trucks. This is for the reasons: ease of use, customer sentiment and costs.

A hydrogen combustion powertrain will be easier to use than a battery electric powertrain, because it has a higher range and energy can be restored faster. Compared to a fuel cell electric powertrain, there is no need for refurbishment of components with the hydrogen combustion engine – we expect exchanges of the fuel cell stack will be necessary in this timeframe. The customer sentiment will be in favor of a hydrogen combustion powertrain, since only the energy carrier changes. The energy conversion system is still an engine, which the truck drivers trust already today. In investment costs the hydrogen combustion powertrain is expected to be cheaper around 2030 than the battery and fuel cell electric powertrain, which can favor buying decisions.

3.3.4. Total cost of ownership of zero CO₂ emission powertrains become competitive with compression ignition until 2050

These figures on stock level are a result of the sales of each year. In turn, the total cost of ownership influences the sales of commercial vehicles. Figure 14 shows the total cost of ownership of eight powertrains of a heavy-duty truck in a long-haul and regional-haul use-case.

The total cost of ownership considers the vehicle price, its resale value and operational costs as well as taxes. In the operational costs we considered energy, maintenance, repair, tires, insurance, imputed depreciation interest, cleaning, handling and labor costs for the driver. If applicable, we considered costs for oil and diesel exhaust fluid. We did not consider tolls. Also, infrastructure and societal costs are excluded. To cover the most important trends of each decade we modeled the total cost of ownership in the middle of each decade: in 2025, 2035 and 2045.

For the specifications of the vehicle, please refer to chapter 3.3.2. For the batteries we considered costs of 160 € per kWh in 2025, 120 € per kWh in 2035 and 100 € per kWh in 2045 and a usable share of the battery capacity of 80% in 2025, 85% in 2035 and 90% in 2045. We assumed the batteries to be usable until they reach 2,500 cycles in 2025, 3,000 cycles in 2035 and 4,000 cycles in 2045. For the fuel cell stack, we considered costs of 110 € per kW in 2025, 70 € per kW in 2035 and 60 € per kW in 2045. We exchanged the stack after it ran 8,000 hours in 2025, 10,000 hours in 2035 and 12,000 hours in 2045.

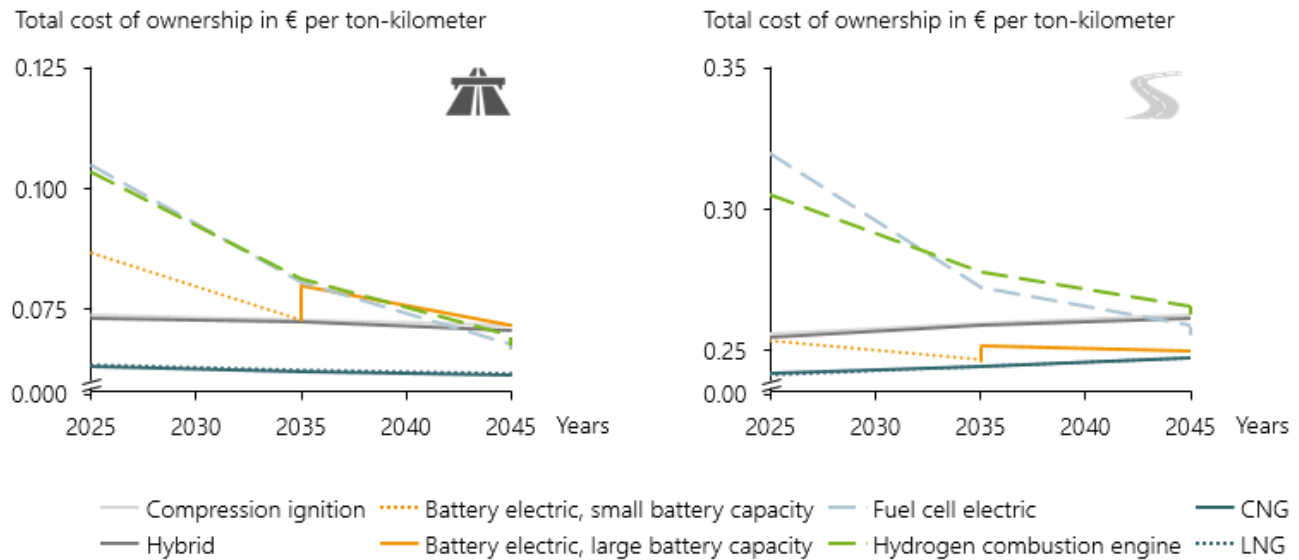


Figure 14: Balanced Energy Carriers – Comparison of the total cost of ownership in € per ton-kilometer for heavy-duty trucks in a long-haul use-case with 110,000 km driving distance per year (left) and in a regional-haul use-case with 50,000 km driving distance per year (right).

As a result, the battery electric powertrain with the small battery capacity achieves cost parity with the compression ignition powertrain in 2035. After the upgrade to the large battery the cost parity can be nearly established again in 2045. The total cost of ownership for fuel cell electric and hydrogen combustion engine powertrains, decreases strongly. Both become cheaper than the compression ignition powertrain before 2045.

Due to these results, we expect sales of hydrogen combustion engine, battery and fuel cell electric powertrains to be comparably low before 2040 and accelerate afterwards. The battery electric powertrain with the small battery capacity already increases in sales before 2040.

For vehicles in regional-haul use-cases that drive 50,000 km per year, the battery electric powertrain is cheaper in total cost of ownership before 2030 and therefore increases significantly in sales. However, infrastructure costs and the total costs for society have not been considered in this study.

Moreover, the analysis hints to the fact that total cost of ownership is not the only buying criteria. For example, CNG and LNG powertrains are significantly cheaper in the total cost of ownership, yet the sales shares stay low. In the balance of all effects, we expect CNG and LNG in dedicated use-cases where they can unfold their potential.

3.3.5. Direct Manufacturing Costs of the vehicles increase by about 9 billion € until 2050 compared to 2018

One influencing factor on the total cost of ownership is the investment to buy the vehicle. This investment is determined by the direct manufacturing costs (DMC) and overheads. The direct

manufacturing costs are set to increase in the long term. Figure 15 shows the delta of the direct manufacturing costs between 2018 and 2045 of the vehicles sold in those years. The left column shows the Balanced Energy Carriers scenario and the right the Accelerated Transformation scenario which we describe in chapter 3.4.

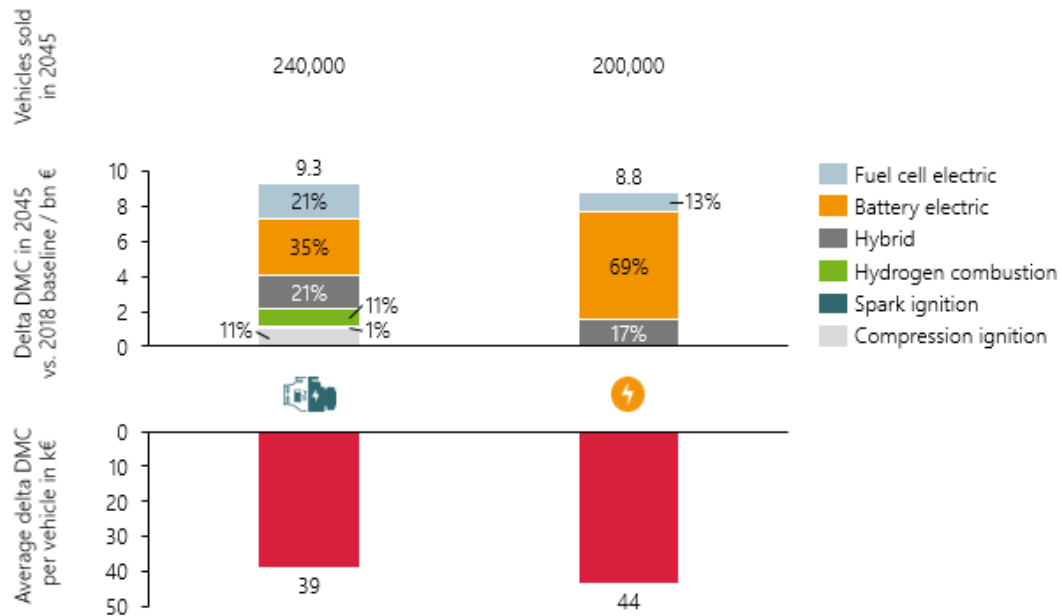


Figure 15: Balanced Energy Carriers and Accelerated Transformation scenario – Additional direct manufacturing costs of the vehicles sold in 2045 compared to 2018

In the Balanced Energy Carriers scenario in 2045, 240,000 vehicles are sold. This is less than the 300,000 in 2018 due to the optimization of usage. Despite there being 60,000 fewer vehicles, the additional direct manufacturing costs for the vehicles are 9.3 billion €. This equals an average of 39,000 € of additional direct manufacturing costs per vehicle. This increase is significant and comes from the advanced technologies in the vehicles. These advances include upgraded gliders and powertrains. The battery electric powertrain increases the direct manufacturing costs, which is due to the high costs of the battery that are still expected in the long term.

The significant increase of direct manufacturing costs of 39,000 € per vehicle will lead to an even higher increase of the buying price for such a vehicle. This could be a burden to companies that buy these vehicles since they would need to increase their investments. This burden can be relieved by the lower total cost of ownership.

Figure 16 shows the underlying assumption for long-haul trucks and Figure 17 for regional haul trucks. Both show the additional Direct Manufacturing Costs and the CO₂ emission reduction. The CO₂ emission reduction is stated in the tank-to-wheel balance with the certification fuel. Therefore, it does not include the shift towards energy carriers from renewable sources. For the specifications of the vehicle, please refer to chapter 3.3.2.

Long-haul

	2020-2030				2030-2040				2040-2050			
Compression ignition	5.6	6.1%	15.9	16.6%	16.9	18.0%	20.3	22.1%	20.0	23.8%	Not existing	
Spark ignition	7.6	12.0%	17.9	25.2%	18.1	25.2%	21.4	31.8%	20.8	31.7%		
Hybrid	6.6	6.2%	17.9	17.3%	18.3	18.2%	22.8	23.0%	27.1	27.2%		
Battery electric	70.3	100%	79.9	100%	96.2	100%	99.0	100%	88.6	100%	92.2	100%
H ₂ combustion	Not existing		77.2	100%	63.7	100%	66.5	100%	49.0	100%	52.6	100%
Fuel cell electric	94.6	100%	104.2	100%	73.2	100%	76.0	100%	57.3	100%	60.9	100%
	€	CO ₂	€	CO ₂	€	CO ₂	€	CO ₂	€	CO ₂	€	CO ₂

€ Cost values are additional Direct Manufacturing Costs (DMC) and are shown in 000 EUR compared to the 2018 Diesel baseline

CO₂ CO₂ decrease in the tank-to-wheel balance with certification fuel, compared to the 2018 Diesel baseline

Figure 16: Balanced Energy Carriers – Underlying assumptions for long-haul trucks regarding the additional Direct Manufacturing Costs and the CO₂ emission reduction. All values are an average of multiple vehicle specifications. The columns show decades and the four glider types: baseline, improved, new and cabinless. The lines show the different powertrains.

Regional-haul

	2020-2030				2030-2040				2040-2050			
Compression ignition	5.6	4.8%	15.9	12.0%	16.9	13.7%	20.3	17.4%	20.0	18.5%	Not existing	
Spark ignition	9.6	12.0%	19.9	21.7%	20.2	21.7%	23.6	27.7%	22.8	27.7%		
Hybrid	6.6	7.0%	17.9	14.7%	17.3	18.3%	21.8	22.4%	26.5	26.3%		
Battery electric	41.6	100%	51.2	100%	45.1	100%	47.9	100%	42.8	100%	46.4	100%
H ₂ combustion	Not existing		36.4	100%	36.9	100%	39.7	100%	30.6	100%	34.2	100%
Fuel cell electric	54.1	100%	63.8	100%	48.7	100%	51.5	100%	40.2	100%	43.8	100%
	€	CO ₂	€	CO ₂	€	CO ₂	€	CO ₂	€	CO ₂	€	CO ₂

€ Cost values are additional Direct Manufacturing Costs (DMC) and are shown in 000 EUR compared to the 2018 Diesel baseline

CO₂ CO₂ decrease in the tank-to-wheel balance with certification fuel, compared to the 2018 Diesel baseline

Figure 17: Balanced Energy Carriers – Underlying assumptions for regional-haul trucks regarding the additional Direct Manufacturing Costs and the CO₂ emission reduction. All values are an average of multiple vehicle specifications. The columns show decades and the four glider types: baseline, improved, new and cabinless. The lines show the different powertrains.

Cost drivers are the additional glider and powertrain technologies. For the battery electric powertrain, the costs are driven by the battery, for the hydrogen combustion powertrain by the hydrogen tank and for the fuel cell by the fuel cell stack and the hydrogen tank.

The additional Direct Manufacturing Costs for the battery electric, hydrogen combustion and fuel cell electric powertrain are significantly higher than for the compression and spark ignition as well as for the hybrid powertrain. Therefore, the investment of vehicle operators to buy these vehicles are higher while the operating costs are lower. The higher investment can be a burden for vehicle operators.

3.4. The Accelerated Transformation scenario has a high electrification of powertrains

Accelerated Transformation means earlier and more intense change of the heavy-duty transport sector. Electrification, automation, connectivity and infrastructure built-up disrupt the current way of freight forwarding. With this, an 80% CO₂ emission reduction ambition is met in 2050 compared to 1990 – just as in the Balanced Energy Carriers scenario.

In the well-to-wheel balance, the CO₂ emission reduction is 73% between 2050 and 1990. This is, in relative terms, less than in the extended tank-to-wheel balance. The reason for that is the consideration of the well-to-tank emissions from electricity and fuels from renewable sources. In absolute terms, the CO₂ emission reduction in the well-to-wheel balance is higher than in the extended tank-to-wheel balance. This is because the energy provision from well-to-tank gets more efficient, as explained above.

Figure 18 shows the breakdown of the CO₂ emission reduction to the four measures in this scenario relative to the development stop in 2050.

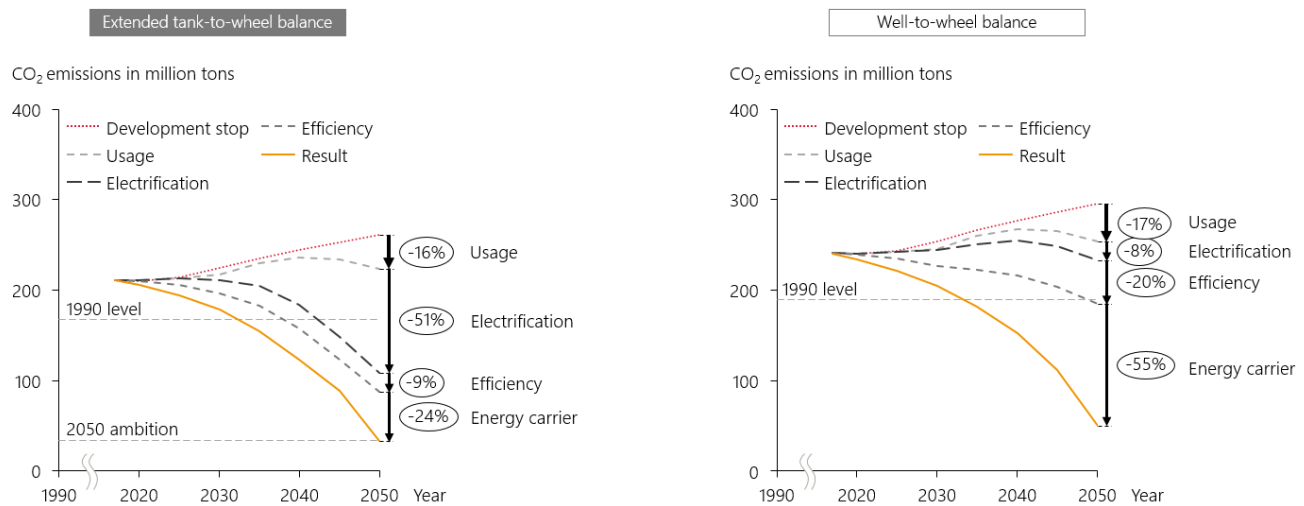


Figure 18: Accelerated Transformation – CO₂ emission reduction in an extended tank-to-wheel balance (left) and a well-to-wheel balance (right). Both break the reduction down to the four measures.

In the extended tank-to-wheel balance, 16% splits into the optimization of usage and 51% electrification of powertrains. In this scenario the electrification of powertrains has a significantly higher impact than in all other scenarios. 9% of the CO₂ emission reduction originates from efficiency increase of vehicles and 24% of the adaptation of energy carriers.

3.4.1. Electrification dominates the CO₂ emission reduction in the extended tank-to-wheel balance, energy carrier in the well-to-wheel balance

The effect of the optimization of usage again comes from modal split, the share of road transport performed by heavy-duty trucks and the average utilization of these trucks.

In this scenario, the modal split shift towards road is the strongest of all scenarios: From 71% in 2018 to 76% in 2050. The reason for the stronger shift is the earlier and more intense adoption of automated trucks. Those make up 56% of the vehicle stock in 2050. Due to their cost advantage, they shift transport demand and the according CO₂ emissions to the road.

Yet, for the same reason the share of road transport performed by heavy-duty vehicles is the lowest of all scenarios at 75% in 2050, compared to 86% in 2018. Another factor contributing to this is a more intense roll-out of advanced logistics concepts enabled by the high level of connectivity and automation in this scenario.

Accordingly, the average truck utilization is high at 70% in 2050 compared to 65% in 2018. Also here, connectivity and automation help to increase co-loading and backhauling which in turn increase the utilization.

The strong electrification of powertrains is represented in the extended tank-to-wheel balance by the 51% contribution to the CO₂ emission reduction. The 8% contribution in the well-to-wheel balance only reflect the higher efficiency of electric powertrains and is computed with 2018's energy mix. The effect of providing more electricity from renewable sources is allocated in the 55% for the adoption of the energy carrier.

Battery electric trucks dominate the 51% CO₂ emission reduction from electrification in the extended tank-to-wheel balance: battery electric vehicles account for 41%-points of the reduction, fuel cell electric vehicles for 9%-points and hybrids for 1%-point. Figure 19 (right) shows the composition of the vehicle stock that leads to this CO₂ emission reduction of electrified powertrains.

Efficiency increase of the vehicles accounts for 9% of the CO₂ emission reduction in the extended tank-to-wheel and 20% in the well-to-wheel balance. Those values are lower than in the Balanced Energy Carriers scenarios since in the Accelerated Transformation scenario a higher share of the vehicles is electrified and these have already a high efficiency and lower potential for improvement.

The origin of the efficiency increase is similar to the Balanced Energy Carriers scenario. We considered similar efficiency measures to be implemented, since with increasing efficiency the vehicle

manufacturer increases its competitive position. The small difference in the numbers between the scenarios is mostly explained by the lower sales volume in the Accelerated Transformation scenario compared to the Balanced Energy Carriers scenario. This lower sales volume is attribute to the higher share of automated vehicles in the stock in the Accelerated Transformation scenario.

By 2050 the stock of trucks with a new cabin glider and a hybrid powertrain demands on average 34% less energy for the same task than the stock of trucks with a baseline glider and compression ignition powertrain in 2018. Analogously, the stock of trucks by 2050 with a battery electric powertrain demands 19% less energy than the trucks that are expected to enter the market around 2020. For the stock of fuel cell electric trucks this figure is 23%. The values for battery and fuel cell electric powertrains are lower than for the combustion engine powertrains for two reasons: Firstly, battery and fuel cell electric powertrains have a higher efficiency and less potential for optimization than compression ignition and hybrid powertrains. Secondly, battery electric and fuel cell powertrains are introduced into the market later and with more advanced gliders compared to the stock of trucks with a compression ignition powertrain in 2018 which is on average about ten years old.

Also in this scenario, the improvement of gliders dominates the efficiency increase: More than 60% of the efficiency increase comes from the glider and less than 40% from the powertrain. For hybrid, battery and fuel cell electric powertrains the influence of gliders is especially high, since these powertrains have a high efficiency.

The adoption of energy carriers is a strong factor in this low carbon pathway, especially in the well-to-wheel balance. For this, we modeled blend shares of renewable sources at 65 volume-% in liquids, 70 mass-% in gases. In electricity we considered nearly 100 energy-% of low CO₂ emission sources. The 55% contribution to the CO₂ emission reduction in the well-to-wheel balance distributes to 24%-points to electricity, 24%-points to liquid and 7%-points to gaseous fuels.

3.4.2. Energy demand reduces more than in the other scenarios, while the vehicle stock holds the highest share of battery electric vehicles

Resulting from this is the final energy demand as shown in Figure 19 (left). Between 2050 and 2018 the final energy demand reduces by 37% since gliders and powertrains get more efficient. Especially in this scenario the higher efficiency of battery electric powertrains reduces the final energy demand.

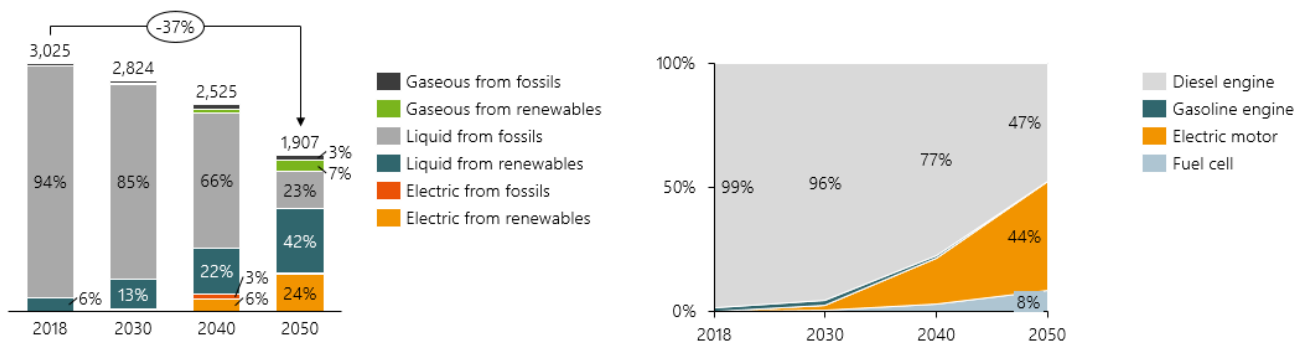


Figure 19: Accelerated Transformation – Final energy carrier demand in PJ including a breakdown to state and source of the energy carriers (left). Breakdown of the vehicle stock by main energy conversion system (right).

By 2050 a significant share of final energy demand is supplied by renewable sources. At 7% in gaseous fuels, which are dominated by hydrogen. The demand for hydrogen adds-up to 2 billion kg in 2050, the demand for methane is about 0.15 billion kg. This is low since the high advantages of battery electric powertrains gain market shares from methane combustion powertrains. The contribution of liquid fuels from renewable sources is high at 42% which equals 12 billion liters in 2050. The electricity demand amounts to 500 PJ. In this scenario the amount of electricity supplied through electrified road systems is higher than in the other scenarios. As in the Balanced Energy Carriers scenario, the underlying changes in the energy provision are fundamental. Therefore, it requires collective action organized by political frameworks to enable this supply of energy.

The vehicle stock shown in Figure 19 (right) also resembles the fundamental changes in the heavy-duty industry in this scenario. Only 47% of vehicles apply a diesel engine – of which 30%-points are hybrids – while 44% of the vehicle stock apply an electric motor as the main energy conversion system and thus operate a battery electric powertrain. Still, 8% of the vehicles are equipped with a fuel cell.

3.4.3. Battery electric vehicles get advantageous over compression ignition engines in both long- and regional haul before 2040

The vehicle stock is the result of vehicle sales and the vehicle scrappage. The vehicle sales in turn are largely influenced by the total cost of ownership. Figure 20 shows the total cost of ownership for different powertrains for heavy-duty trucks in a long-haul and regional-haul use-case. For the specifications of the vehicles, please refer to chapter 3.3.2.

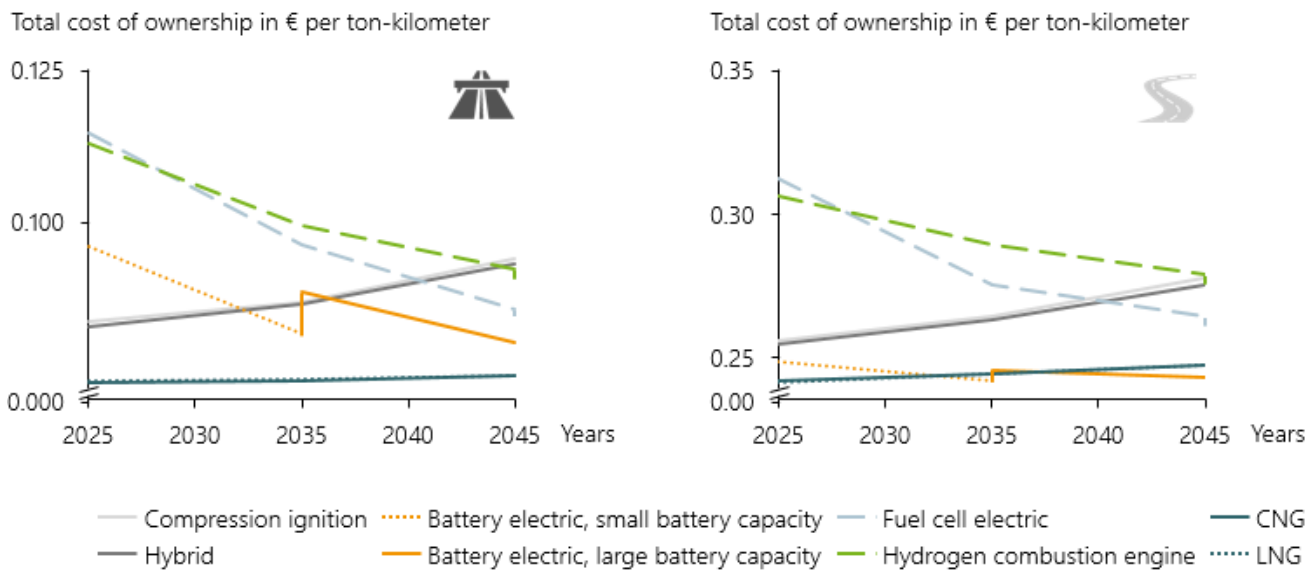


Figure 20: Accelerated Transformation – Comparison of the total cost of ownership in € per ton-kilometer for heavy-duty trucks in a long-haul use-case with 110,000 km driving distance per year (left) and in a regional-haul use-case with 50,000 km driving distance per year (right).

For the batteries we considered costs of 130 € per kWh in 2025, 95 € per kWh in 2035 and 75 € per kWh in 2045 and a usable share of the battery capacity of 80% in 2025, 85% in 2035 and 90% in 2045. We assumed that the batteries will be usable until they reach 2,500 cycles in 2025, 3,000 cycles in 2035 and 4,000 cycles in 2045. For the fuel cell stack, we considered costs of 95 € per kW in 2025, 50 € per kW in 2035 and 45 € per kW in 2045. We exchanged the stack after it ran 8,000 hours in 2025, 10,000 hours in 2035 and 12,000 hours in 2045.

In this scenario, the battery electric powertrains get cheaper than compression ignition powertrains around 2035 and are significantly cheaper than compression ignition, fuel cell and hydrogen combustion engine powertrains in 2045. Fuel cell electric trucks get cheaper than compression ignition powered ones shortly after 2040. The hydrogen combustion engine powertrain only reaches price parity with the compression ignition powertrain in 2045. For this reason, the expected sales figures would be low and therefore the investment to offer this powertrain option is not considered in this scenario.

Since in the regional-haul use-case the battery electric powertrain is the cheapest already before 2030 and has an even higher cost advantage than in the long-haul use-case, the regional-haul use-case is dominated by battery electric trucks. Together those effects lead to the 44% of the vehicle stock with a battery electric powertrain in 2050.

Strategic factors lead to sales of other powertrains than battery electric ones. These strategic factors include the potential to cover extremely long distances without refueling as well as the ease and speed of refueling.

Another aspect are the direct manufacturing costs shown in Figure 15. In the Accelerated Transformation scenario shown in the right column, those are 44,000 € per vehicle higher in 2045 than in 2018. This results in an even higher increase of the buying price for such a truck. It can be a burden for truck buyers to increase their investments so significantly. Yet, for battery electric trucks the burden can be relieved by similar total cost of ownership in 2045 to a compression ignition truck today.

Furthermore, societal costs for charging infrastructure and electrified road system need to be considered. To build up the whole charging infrastructure in Europe high costs are expected. If 25% of roughly 200 million vehicles in Europe have a plug by 2050, and we consider one charger for two vehicles with a plug and a charger costs on average 3,000 €, this sums up to 75 billion €. To equip one kilometer of motorway with an electrified road system, 1 million € is currently an estimation. Therefore, it costs 10 billion € to equip 10,000 km of motorways – which is 12% of the motorways in Europe – with such a system.

3.5. Approaching Zero requires an especially strong adaptation of energy carriers

Approaching zero CO₂ emissions is the imperative of this scenario: 95% CO₂ emission reduction in 2050 compared to 1990 is the level of ambition. In this scenario, most of the boundary conditions are the same as in the Balanced Energy Carriers scenario. To meet the higher level of ambition in this scenario, further efforts need to be taken. Those are introduced in balance of technology push and market pull and result in stronger electrification and more energy carriers from renewable sources.

Figure 21 breaks the 95% CO₂ emission reduction down to the four measures. In this scenario in the extended tank-to-wheel balance, 15% of the reduction comes from the optimization of usage, 26% from the electrification of powertrains, 13% from increased efficiency of the vehicles and 47% from the adaptation of energy carriers.

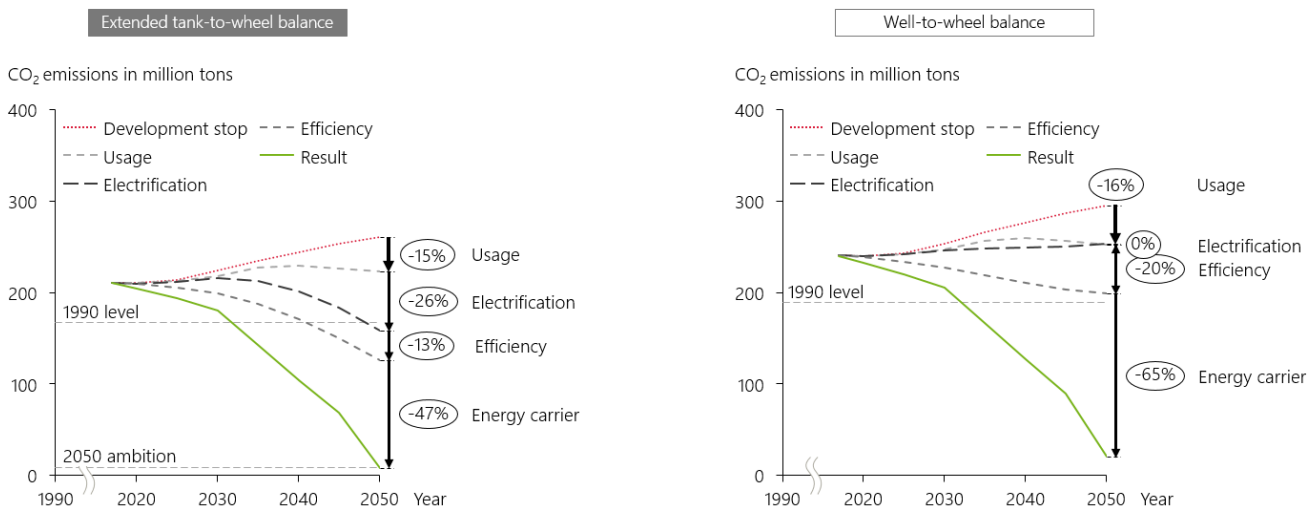


Figure 21: Approaching Zero – CO₂ emission reduction in an extended tank-to-wheel balance (left) and a well-to-wheel balance (right). Both break the reduction down to the four measures.

3.5.1. Energy carriers are key to achieve the 95% CO₂ emission reduction

The optimization of usage is just the same as in the balanced energy carrier scenario: The modal split increases to 74% on road, heavy-duty trucks perform 86% of the road transport and the average truck utilization increases to 70% in 2050.

Electrification of powertrains has a similar relative impact with 26% as in the Balanced Energy Carriers scenario with 26%. Yet, since the absolute CO₂ emission reduction is higher in this scenario, more electrified vehicles are in the stock, as shown in Figure 22 (right).

The adaptation of energy carriers is the most important measure in this scenario. Its relative contribution of 47% is only somewhat higher than in the Balanced Energy Carriers scenario at 44%. The higher absolute CO₂ emission reduction comes from blend rates of renewable sources at 93% in liquids, 95% in gases. In electricity we considered nearly 100% of low CO₂ emission sources. In this scenario, liquids are the most important factor in the adoption of energy carriers: The overall 47% contribution of the adaptation of energy carriers is to 33%-points from liquids, 10%-points by gases and 4%-points by electricity.

3.5.2. Energy needs to be nearly completely from renewable sources, the vehicle stock gets more differentiated

Resulting from this is the final energy demand, shown in Figure 22 (left). The overall reduction of energy demand is 25% and very similar to the Balanced Energy Carriers scenario. What is different between the two scenarios, is the composition of energy carriers. In the Approaching Zero scenario, there is significantly more energy from renewable sources in the market: 27% of the final energy demand in 2050 are covered by gaseous fuels from renewable sources. Those gaseous fuels are dominated by hydrogen, for which the demand is at 5 billion kg, demand for methane is at 0.85 billion kg. 60% of the final energy demand in 2050 are from liquid fuels from renewable sources – almost all diesel-type. This equals 40 billion liters. 6% of the final energy demand in 2050 are for electricity from low CO₂ emission sources, which adds-up to 150 PJ.

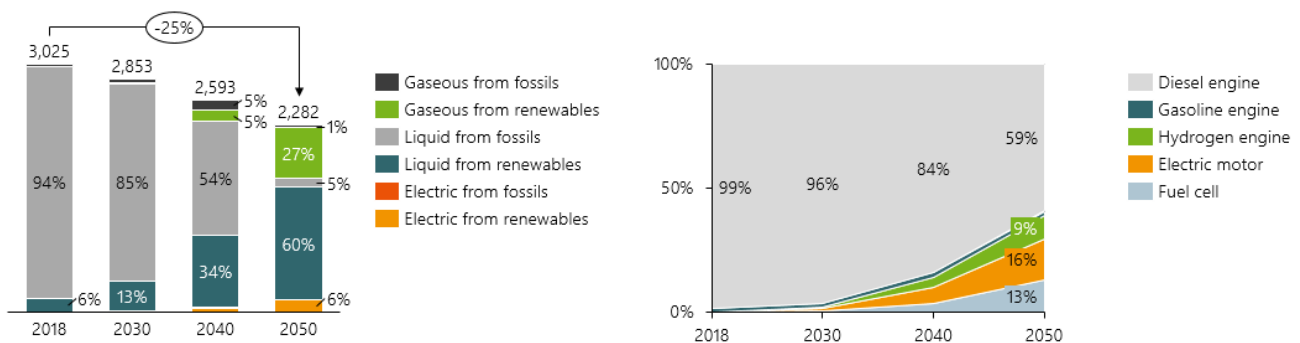


Figure 22: Approaching Zero – Final energy carrier demand in PJ including a breakdown to state and source of the energy carriers (left). Breakdown of the vehicle stock by main energy conversion system (right).

To make this happen, the core of energy provision needs to change. High investments in electricity generation from renewable sources, electrolysis of hydrogen and fuel synthesis are necessary. To enable these investments, investors need to be sure that there is sufficient demand. This can be achieved by suitable policies.

In the same way, policies are necessary to enable the change of the vehicle stock shown in Figure 22 (right). In this scenario, in 2050 59% of the vehicle stock have a diesel engine – of which 26%-points are hybrid. 9% of the vehicles in stock operate a hydrogen engine, 16% have an electric motor as the main energy conversion system and thus operate a battery electric powertrain. 13% of the vehicles have a fuel cell on board.

All figures of zero emission powertrains – hydrogen engine, battery and fuel cell electric – are somewhat higher than in the Balanced Energy Carriers scenario, although the boundary conditions and resulting total cost of ownership are the same as in the Balanced Energy Carriers scenario shown in Figure 14. But since in the Approaching Zero scenario the CO₂ emission reduction needs to be higher than in the Balanced Energy Carriers scenario, the whole industry needs to spend more to achieve the CO₂ emission reduction.

4. What's next? Identify which scenario is best for society – then, align to realize it

With the four scenarios we show that there are multiple options to follow a low carbon pathway by 2050.

The next step is to analyze which of the scenarios we should pursue. One metric to measure this is the costs for the society. This includes the built-up of infrastructure, impacts on taxation, spending by fleet operators for modern trucks and low carbon energy carriers.

Further, strategic factors need to be considered – for example independence from limited fossil resources, dependence on energy imports and localization of value generation.

Also, an integrated perspective on the road transport sector is necessary. On the one hand, to account for the shifts between vehicle segments and transport modes. On the other hand, to consider the overall energy demand for transport and the roles of biomass and power-to-x in this.

By these analyses, the necessary policies could be determined and the required technologies for fleet operators, vehicle manufacturers, technology suppliers and energy providers could be outlined. Then the players could align and make it happen: bring the European heavy-duty transportation on a low carbon pathway and thus mitigate climate change.

Appendix

Overview of scenarios and identified technologies

	Current policies				Balanced energy carriers				Accelerated transformation				Approaching zero			
	2018	2030	2040	2050	2018	2030	2040	2050	2018	2030	2040	2050	2018	2030	2040	2050
CO ₂ emission reduction ambition	None				80% in 2050 compared to 1990				80% in 2050 compared to 1990				95% in 2050 compared to 1990			
Freight transport demand, billion ton-km	2018: 5,380; 2050: 7,311; Total Increase = 36%; CAGR ₂₀₁₈₋₂₀₅₀ ~1%															
Usage of trucks (key points only)	Similar as today: minor utilization increase, minor shift to rail, few automated trucks				Minor shift to road by automated trucks, minor shift from HD to MD/LD, increase in utilization				Some shift to road by automated trucks, some shift from HD to MD/LD, increase in utilization				Shift towards road by automated trucks, minor shift from HD to MD/LD, increase in utilization			
E-charging infrastructure availability	Limited dedicated public charging points; mainly charging at depots				Dedicated charging points on main freight arteries in Europe; new specific CV standard (350-500 kW charging power)				High power alongside motorways (>500 kW) and other roads (350-500 kW); Electrified road systems available on main arteries				Dedicated charging points on main freight arteries in Europe; new specific CV standard (350-500 kW charging power)			
Hydrogen infrastructure availability	No dedicated public truck refueling pumps; mainly refueling at depot				Dedicated public truck refueling pumps, ~2045 also liquefied hydrogen				No dedicated public truck refueling pumps; mainly refueling at depot				Dedicated public truck refueling pumps, ~2045 also liquefied hydrogen			

Figure 23: Comparison of details for the developed scenarios.

Technology area	2020-2030	2030-2040	2040-2050
Optimization of usage	<ul style="list-style-type: none"> Platooning Chauffeur Driver behavior optimization Cargo optimization (step 1) Hub and Spoke model 	<ul style="list-style-type: none"> Pilot High-capacity vehicles Cargo optimization (step 2) 	<ul style="list-style-type: none"> Fully automated / driverless trucks Cargo optimization (step 3)
Electrification of powertrains	<ul style="list-style-type: none"> Powertrain electrification (step 1) Hotel load management 	<ul style="list-style-type: none"> Powertrain electrification (step 2) Battery electric truck (gen. 1) Fuel cell truck (gen. 1) 	<ul style="list-style-type: none"> Powertrain electrification (step 3) Battery electric truck (gen. 2) Fuel cell truck (gen. 2) Conductive road systems Inductive road systems
Efficiency increase of the vehicles	<ul style="list-style-type: none"> Demand controlled auxiliaries Lightweight measures (step 1) Aerodynamic measures (step 1) Rolling resistance reduction measures (step 1) ICE's internal efficiency improvements (step 1) 	<ul style="list-style-type: none"> Lightweight measures (step 2) Aerodynamic measures (step 2) Rolling resistance reduction measures (step 2) ICE's internal efficiency improvements (step 2) Waste heat recovery systems 	<ul style="list-style-type: none"> Lightweight measures (step 3) Aerodynamic measures (step 3) Rolling resistance reduction measures (step 3) ICE's internal efficiency improvements (step 3)
Adaptation of energy carriers	<ul style="list-style-type: none"> Methane Paraffinic fuels 	<ul style="list-style-type: none"> Methanol Hydrogen DME Electricity 	<ul style="list-style-type: none"> Long chain alcohols Ethanol

Figure 24: List of technologies by the four measures (lines) and decades (columns).

Further technologies were considered on a qualitative level

One technology to mitigate CO₂ emissions is carbon capture and storage. This technology could be fitted to a vehicle. In this case, it captures part of the emissions in the exhaust and thus reduces the emissions released to the atmosphere. Yet, the technology maturity is still low and storage issues remain to be solved.

One specific concept for the combustion of methane is high-pressure direct injection, short HPDI. HPDI uses compression ignition with a diesel pilot injection to start the combustion. With this concept, an efficiency increase and thus CO₂ emission reduction can be achieved. With a liquefied natural gas tank, it is an attractive option for long-haul heavy-duty trucks. Yet, due to the low expected uptake of methane combustion engines, the HPDI concept was not considered in detail.

Naphtha-like fuels are another option to reduce CO₂ emissions. Naphtha is a crude petrol and one product of the distillation of crude oil. By using Naphtha as a fuel, a refinery emits less CO₂ per unit of usable output. However, for three reasons this option was not considered in detail

1. To combust Naphtha-like fuels, changes to existing engines or dedicated developments seem necessary. Such investments are unlikely for vehicle manufacturers in the competition with investments into electrification, automation, connectivity and new gliders.
2. Naphtha-like fuels are more likely to be combusted in spark ignition engines, which are used at low shares in heavy-duty vehicles.
3. The CO₂ emission reduction is low compared to the other adaptations of energy carriers considered, e.g. the usage of biomass and power-to-x processes.

Air quality will improve – by regulation, energy demand and energy carriers

Air quality affects the health of everyone. Pollutant emissions reduce the quality of the air. These emissions include carbon mono-oxides, nitrogen oxides, particulates and hydrocarbons. However, the reduction of pollutant and CO₂ counteract for many combustion engine related optimizations: If pollutant emissions are reduced, greenhouse gas emissions tend to increase. And if greenhouse gas emissions are reduced, pollutant emissions tend to increase.

Therefore, we considered a reduction of pollutant emissions. This comes from three drivers: dedicated regulation, reduction of energy demand and adaptation of energy carriers.

Dedicated regulation for pollutant emissions are expected to increase significantly by 2050. For this timeframe we consider all vehicles to have near zero emissions – of pollutants and greenhouse gases. By that, the air quality increases significantly.

The reduction of energy demand in all four scenarios leads to a reduction of pollutant emissions. The reduction of pollutant emissions is especially from measures to reduce aerodynamic drag, rolling

resistance and weight of the vehicles since those do not imply higher specific pollutant emissions per unit of energy.

The adaptation of energy carriers contributes to a reduction of pollutant emission. This is strong for the shift in electricity generation from coal and gas to wind and solar. Moreover, the adaptation of liquid fuels from fossil sources to renewable sources reduces pollutant emissions. For example, the combustion of HVO – which is a paraffinic diesel-type fuel produced from biomass – emits significantly less particulates than standard diesel. This effect can then be used to reduce particulates in the exhaust gas or swap the effect for lower nitrogen oxide emissions. Similar effects appear for many liquid and gaseous fuels from renewable sources.

Indicative energy usage share of a heavy-duty truck on the highway

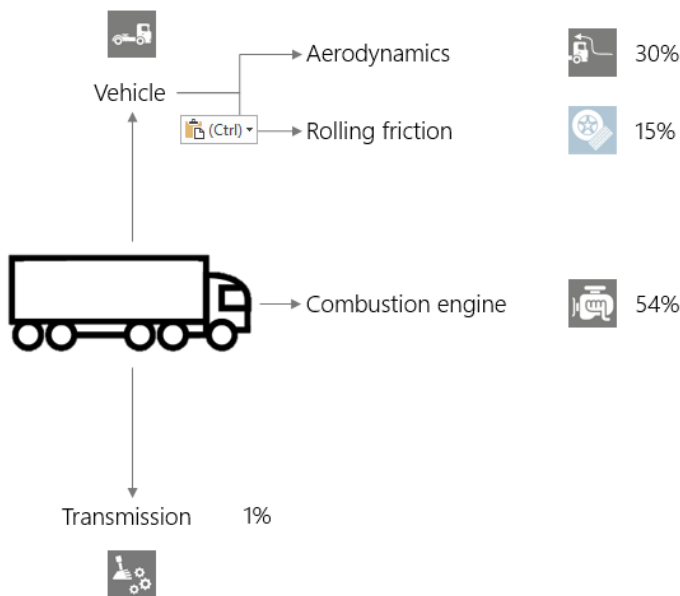


Figure 25: Indicative energy usage shares of a heavy-duty truck on the highway in a steady-state operation point.

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