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Fuel cell electric tractor-trailers: Technology overview and fuel economy

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Introduction

Decarbonizing the transport sector is necessary to achieve a carbon-neutral economy in the European Union (EU) by 2050, in line with the EU's long-term climate goals. The decarbonization of passenger vehicles is well underway thanks to extensive regulatory efforts over the past decade. On the contrary, road freight transport—responsible for more than 19% of the transport sector's greenhouse gas emissions in the EU (European Environment Agency, 2020)—still lacks a clear, enforceable pathway to achieve full decarbonization. More regulatory intervention is thus warranted to curb the emissions of heavy-duty vehicles.

The CO_2 emission standards for heavy-duty vehicles (HDVs) adopted in 2019 provide a distinct regulatory framework to set road freight on a path to carbon neutrality. In their current form, the standards mandate a 15% reduction in the CO_2 emissions of newly registered HDVs in the EU by 2025 relative to 2019, increasing to at least 30% by 2030. A recently published ICCT study shows that these standards are not sufficient to meet the legally binding goals set by the European Climate Law, underscoring the pressing need to strengthen the reduction targets for 2030 and beyond (Mulholland et al., 2022).

The industrial landscape has changed dramatically since the HDV CO_2 standards were proposed in 2017, based solely on the CO_2 reduction potential of combustion engines. Several HDV manufacturers in the EU have made zero-emission (ZE) HDVs central to their long-term strategic planning. By 2030, most truck makers estimate that ZE-HDVs will constitute 30% – 50% of annual sales in the EU (Basma & Rodriguez, 2021).

By the end of 2022, the HDV CO_2 standards will be reviewed, providing an opportunity to increase the current CO_2 reduction targets and to set new goals beyond 2030 that will lock in the ambition of several HDV manufacturers to fully transition toward ZE-HDVs before 2040. As a result, the HDV CO_2 standards could become a central instrument in attaining the carbon neutrality targets of the European Climate Law.

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To inform the feasibility of this rapid transition toward ZE-HDVs, this study provides a vehicle technology analysis for fuel cell electric trucks (FCETs), focusing on the most energy-intensive truck segment in Europe: tractor-trailers (Delgado et al., 2017). A recently published ICCT study focused on the technology analysis of battery electric tractor-trailers in the EU (Basma et al., 2021). This paper analyzes FCET technologies, contextualized by selected critical findings from our previous publications.

In this analysis, we address the following main research questions:

1. What is the current state of technology for fuel cells in heavy-duty vehicle applications?
2. Under typical use profiles for current and future technologies, what is the hydrogen fuel consumption for fuel cell tractor-trailers?
3. How does the energy efficiency of fuel cell electric tractor-trailers compare with that of their battery-electric and diesel counterparts?
4. What is the impact of fuel-cell powertrain technology on the payload capacity of tractor-trailers?

These points are addressed through an in-depth review of fuel cell technology at the stack, system, and vehicle levels, highlighting the current state of technology and directions of future development. In addition, vehicle energy modeling and simulation are conducted to quantify the energy efficiency of tractor-trailers in the EU, focusing on vehicles in long-haul and regional delivery operations.

Technology review

This section presents a detailed review of the fuel cell system, hydrogen storage tank, and FCET vehicle technology. The main objective of this section is to identify the current state of technology while highlighting its main challenges and recent development trends.

Vehicle technology

Fuel cell electric trucks are hybrid trucks composed of two main energy carriers—hydrogen storage tanks and batteries—and various energy conversion devices, such as fuel cells and electric motors. The interactions among batteries, fuel cells, and the electric drive require careful calibration of the control strategy and are primarily driven by the sizing of the components. Figure 1 shows the fuel cell electric truck powertrain architecture.

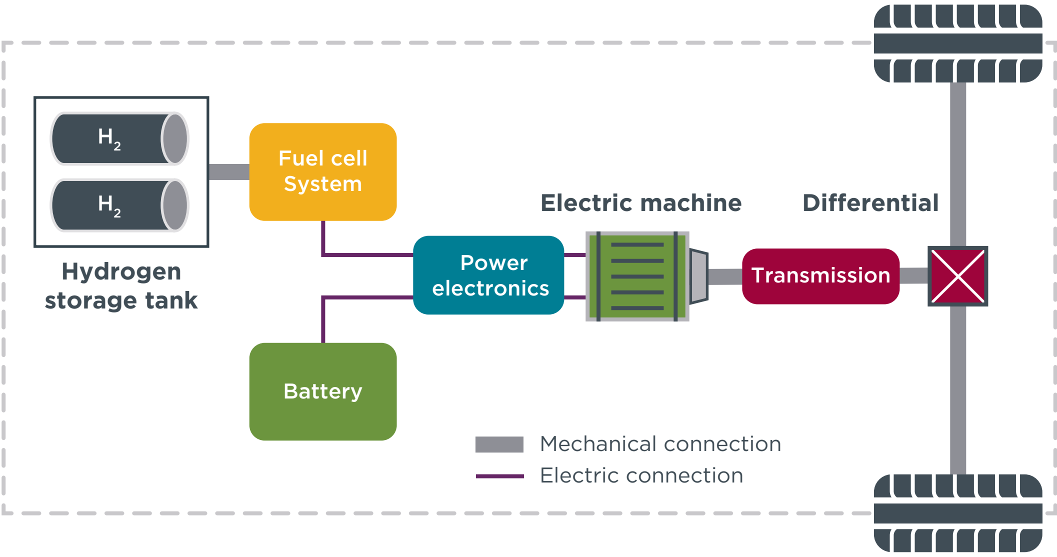

Figure 1. Fuel cell electric vehicle powertrain architecture

Compared with battery-electric powertrains, fuel cell electric powertrains require more complex designs and control strategies. Depending on the powertrain components' sizing, a fuel cell powertrain could be considered a **load follower** or a **range-extended fuel cell battery hybrid powertrain**. A **load follower** fuel cell powertrain features a large fuel cell stack providing most of the power to the electric machine, with a small power battery providing additional electric power during peak demand. Pure fuel cell powertrains —without a battery onboard—are not common as they would lead to oversized fuel cell stacks and miss on the opportunity of recovering vehicle kinetic energy during braking. On the other hand, a **range-extended powertrain** relies mainly on a battery as the energy source, with a smaller fuel cell unit providing additional extended driving range with an option for a DC charging socket to recharge the battery pack if needed.

The following modes of operation are achievable using fuel cell powertrains:

1. The fuel cell stack directly powers the electric motor.
2. The fuel cell stack powers the electric motor and simultaneously charges the battery.
3. The battery directly powers the electric motor.
4. Battery and the fuel cell stack power the electric motor jointly for maximum power.
5. The electric motor acts as a generator during regenerative braking.

Table 1 summarizes the main technical specifications of selected fuel cell electric truck models in Europe. Out of those models, only Daimler's GenH_2 is targeted at long-haul operation thanks to its 80 kg liquid hydrogen storage tank capable of achieving long driving ranges without the need for refueling during the day.

Based on the available fuel cell truck models, this paper will focus on quantifying the energy needs of a load follower fuel cell hybrid electric truck where the fuel cell unit primarily powers the electric motor.

Table 1. Selected hydrogen electric truck models in Europe

Maker-model	Type	Fuel cell power	Battery size	E-drive power [a]	H_2 tank size and technology	Range [f]
Hyundai-Xcient [b]	4	190 kW	72 kWh	350 kW	31 kg - 350 bars	400 km
Daimler-GenH$_2$ [c]	4/5/9/10	300 kW	70 kWh	460 kW	80 kg - Liquid	1,000 km
DAF-VDL [d]	5	60 kW	85 kWh	-	40 kg - 350 bars	350 km
DAF-VDL [d]	9	60 kW	82 kWh	-	40 kg - 350 bars	400 km
MAN [d]	4	100 kW	120 kWh	-	34 kg - 350 bars	400 km
Scania [e]	9	90 kW	56 kWh	210 kW	33 kg - 350 bars	500 km

a) Continuous power

b) Hyundai (2021)

c) Daimler (2021)

d) FCH JU & Roland Berger (2020)

e) Scania (2020)

f) Driving range reported by the truck manufacturers under very specific driving and weather conditions.

Fuel cell system

A fuel cell system comprises two main subsystems, a fuel cell stack and a balance of plant. While the fuel cell stack is responsible for generating electric power, the balance of plant is fundamental for ensuring the proper management of the inputs and outputs of the fuel cell stack. Figure 2 provides a component-by-component breakdown of both subsystems. These are further described below.

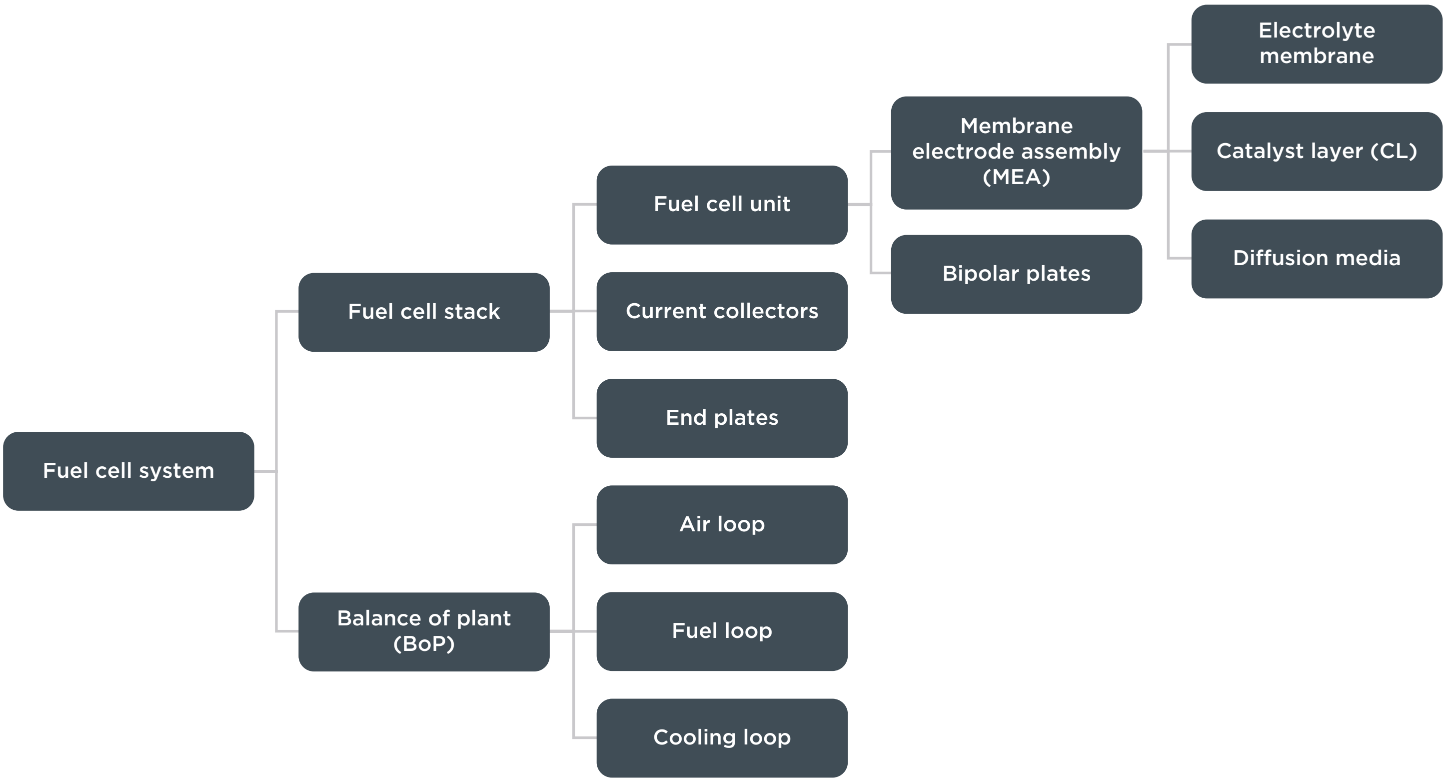

Figure 2. Fuel cell system components

Fuel cell stack

There are several fuel cell technologies depending on the application. Of them, polymer electrolyte membrane (PEM) is the most common for transport applications (U.S. Department of Energy, 2016). As discussed later, the main differences between fuel cell technologies lie in their electrolyte membranes. Fuel cell units, which form a fuel cell stack when connected, are mainly composed of two major components: (1) **membrane electrode assembly** and (2) **bipolar plates**. Figure 3 shows a schematic of a fuel cell stack highlighting the main components.

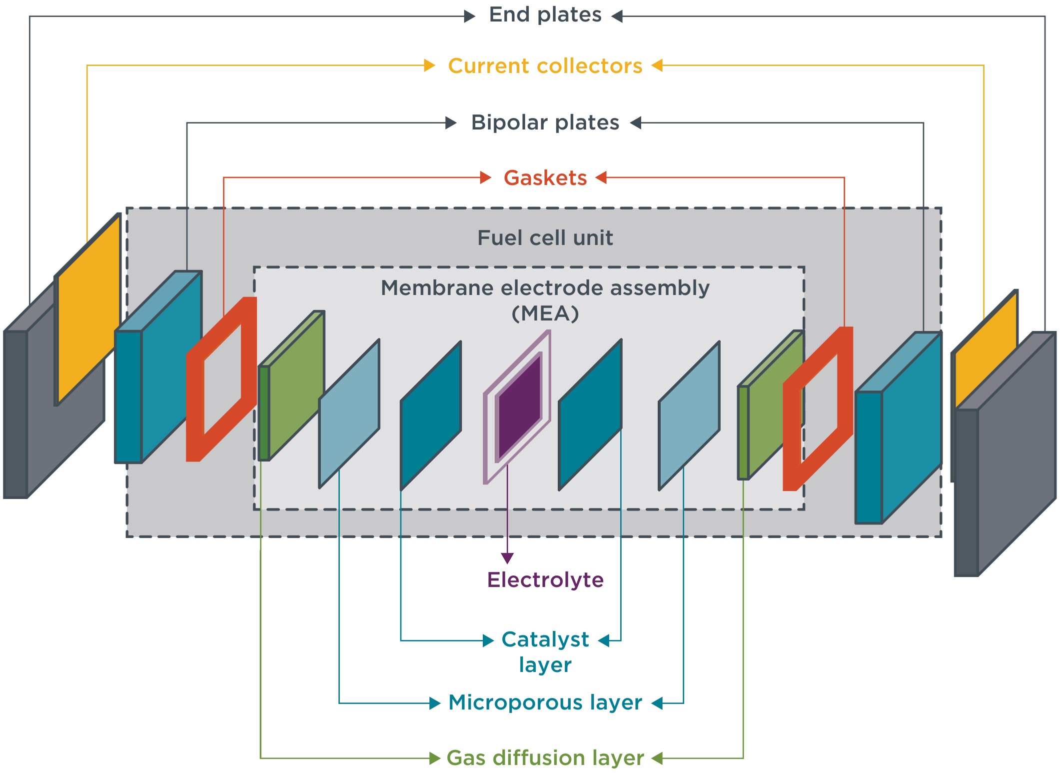

Figure 3. Schematic of a fuel cell stack

The **membrane electrode assembly (MEA)** is the core component of a fuel cell unit where the oxidation-reduction reactions occur. Three main components constitute the MEA: (1) **electrolyte membrane**, (2) **catalyst layer**, and (3) **diffusion media**.

The **electrolyte membrane** is mainly involved in separating the reactant gases—that is, hydrogen and oxygen—and transporting the electric charges between anode and cathode, as illustrated in Figure 4. Thus, the electrolyte membrane design should respect several competing properties, including conductivity, gas impermeability, electron insulation, chemical, mechanical, and thermal stability (Wang et al., 2021).

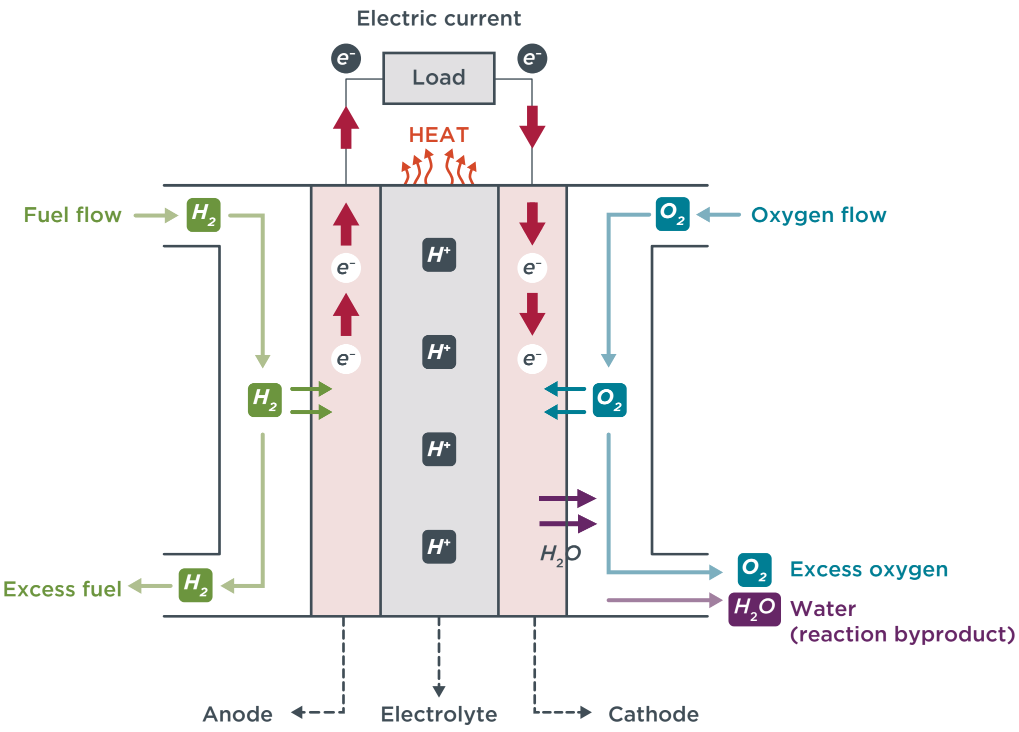

Figure 4. Working principle of a fuel cell unit

PEM fuel cells use as an electrolyte either perfluoro sulfonic acid (known as the brand Nafion) or sulfonated hydrocarbon polymers. Alkaline fuel cells typically use potassium hydroxide membranes.

Nafion-PEM is the most common technology for vehicular applications because of its high conductivity, durability, and chemical stability (Rath et al., 2019). Table 2 summarizes the different properties of electrolyte membrane materials.

Table 2. Summary of electrolyte membrane materials (SHP: sulfonated hydrocarbon polymers, KOH: potassium hydroxide)

	Nafion, PEM	SHP, PEM	KOH, AFC
Advantages	• Chemical stability • High conductivity • High durability	• Low cost • No humidification	• Cost effective • Quick start • Fast reactions
Drawbacks	• Expensive fabrication • Requires humidification	• Low conductivity	• Low conductivity • Sensitive to CO_2

The electrochemical reactions take place at the **electrodes' catalyst layers**. The catalyst layer is a three-phase structure—including ionomer, pore, and metal-carbon networks—transporting electric charges, reactants, and waste products (Ko & Ju, 2013; Molaeimanesh & Akbari, 2015). The main difference among the catalyst layer technologies lies in the choice of the conductive metal in the metal-carbon network. Platinum is the most common metal in use due to its high catalytic activity and stability; however, its cost, scarcity, and sensitivity to carbon monoxide poisoning limit its potential (Wang et al., 2020). Several other technologies are under investigation, relying on other precious metals such as ruthenium and palladium, providing a less expensive solution compared with the platinum-based catalyst layers (Bai et al., 2015). Other technologies rely on nonprecious metal catalysts—iron, cobalt, and magnesium—but these catalysts exhibit less chemical stability (Wu, 2017). The properties are summarized in Table 3.

Table 3. Summary of cathode catalytic layer materials

	Platinum	Palladium/Ruthenium	Nonprecious metals
Advantages	• High catalytic activity • High chemical stability in acidic and alkaline media	• Lower cost than platinum	• Low cost • Good catalytic activity
Drawbacks	• High cost • Carbon monoxide poisoning	• Immature	• Chemical stability in acidic mediums

The **diffusion media** are mainly composed of two layers, the **gas diffusion layer (GDL)** and **microporous layer (MPL)**. The GDL has several functions, including electrical conductivity, structural support, heat removal, and protection against corrosion and erosion (Wang et al., 2020). The most common GDL material is carbon fiber papers. However, this technology requires complex manufacturing and incurs limited electrical and thermal conductivity. On the other hand, metallic GDLs are easier to manufacture and realize higher thermal and electrical conductivity, although they are corrosion-prone (Jayakumar et al., 2017). The MPL's primary function is to separate the GDL from the catalyst layer to limit the loss of catalyst to the GDL.

The other main components of a fuel cell unit are the **bipolar plates**. These are the backbone of a fuel cell, separating the fuel cell units and providing the needed mechanical support, heat removal, and electrical current collection. The bipolar plates are separated from the MEA using gaskets that would ensure no fuel leakage from the MEA. Bipolar plates are also responsible for distributing the reactant gases and evacuating reaction products through dedicated flow channels (Wang et al., 2021).

The most common bipolar plate material is graphite due to its high electrical conductivity, gas impermeability, and corrosion resistance. However, graphite is naturally brittle, imposing several manufacturing challenges (Jin et al., 2014). Carbon composite bipolar plates exhibit good thermal and electrical conductivity but face trade-offs between conductivity and mechanical robustness (Wang et al., 2020). Metallic bipolar plates such as aluminum, titanium, and stainless steel are easier to manufacture and have good mechanical robustness and conductivity. However, metallic bipolar plates require anti-corrosion coating, resulting in defects on the bipolar plate's surface, leading to membrane contamination, and can have shorter lifetimes (Longo et al., 2017).

Table 4. Summary of bipolar plate technology materials

	Graphite	Carbon composites	Metals
Advantages	• Electrical conductivity • Gas impermeability	• Electrical conductivity • Thermal conductivity	• High conductivity • Easy machining
Drawbacks	• Manufacturing	• Mechanical robustness	• Corrosion prone

Moreover, the design of the bipolar plate flow field directly impacts the performance of the fuel cell, transport of reactants, and water balance. The different flow field designs, shown in Figure 5, face several trade-offs, including pressure drop, water removal, and reactants distribution. Table 5 summarizes the main drawbacks and advantages of each flow field design.

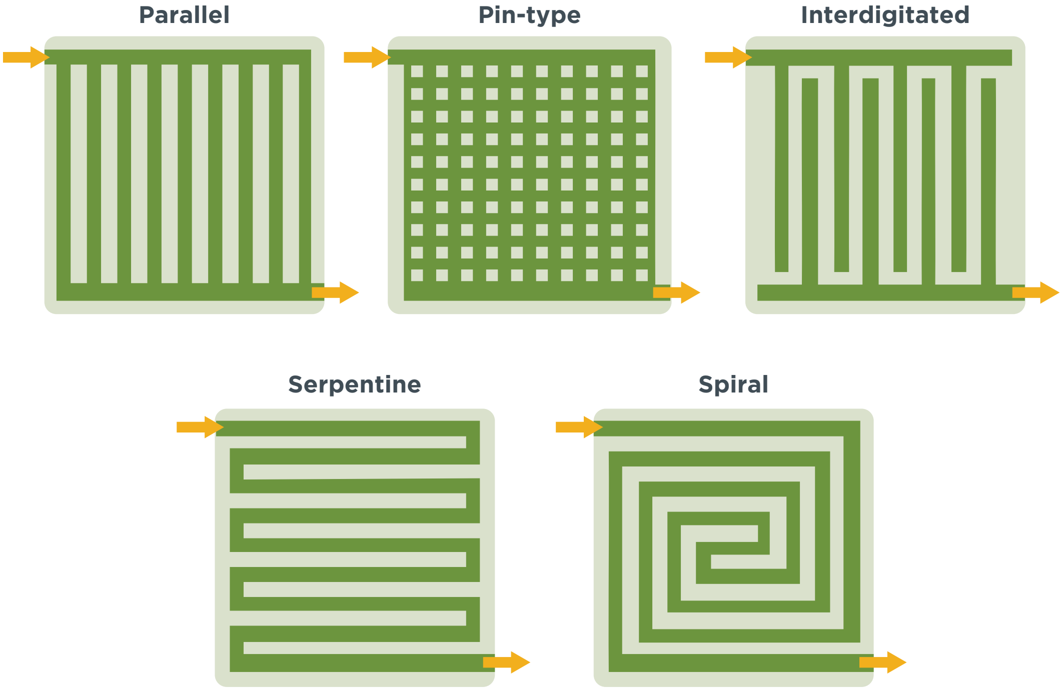

Figure 5. Main flow field designs for bipolar plates

Table 5. Summary of bipolar plate flow field designs (Sharma & Pandey, 2022)

Flow field design	Advantages	Drawbacks
Parallel	• Low pressure drops • Homogenous distribution of reactants	• Low water removal capacity • Voltage instability
Pin-type	• Low pressure drops	• Low water removal capacity • Uneven distribution of reactants
Interdigitated	• High water removal capacity • Homogenous distribution of reactants	• High pressure drops
Serpentine	• High water removal capacity	• Uneven distribution of reactants • High pressure drops
Spiral	• Low humidity requirements	• High pressure drops

The electricity generated by the fuel cell units is collected using current collectors, mainly gold-coated plates that connect the fuel cell units to the external load. Finally, end plates, also called clamp plates, provide the needed pressure to maintain the fuel cell stack structure and ensure gas impermeability.

Balance of plant

Operating a fuel cell stack requires additional auxiliary systems: the air loop, fuel loop, and cooling loop. These systems are referred to as balance of plant (BoP). Figure 6 shows a schematic of a fuel cell stack balance of plant.

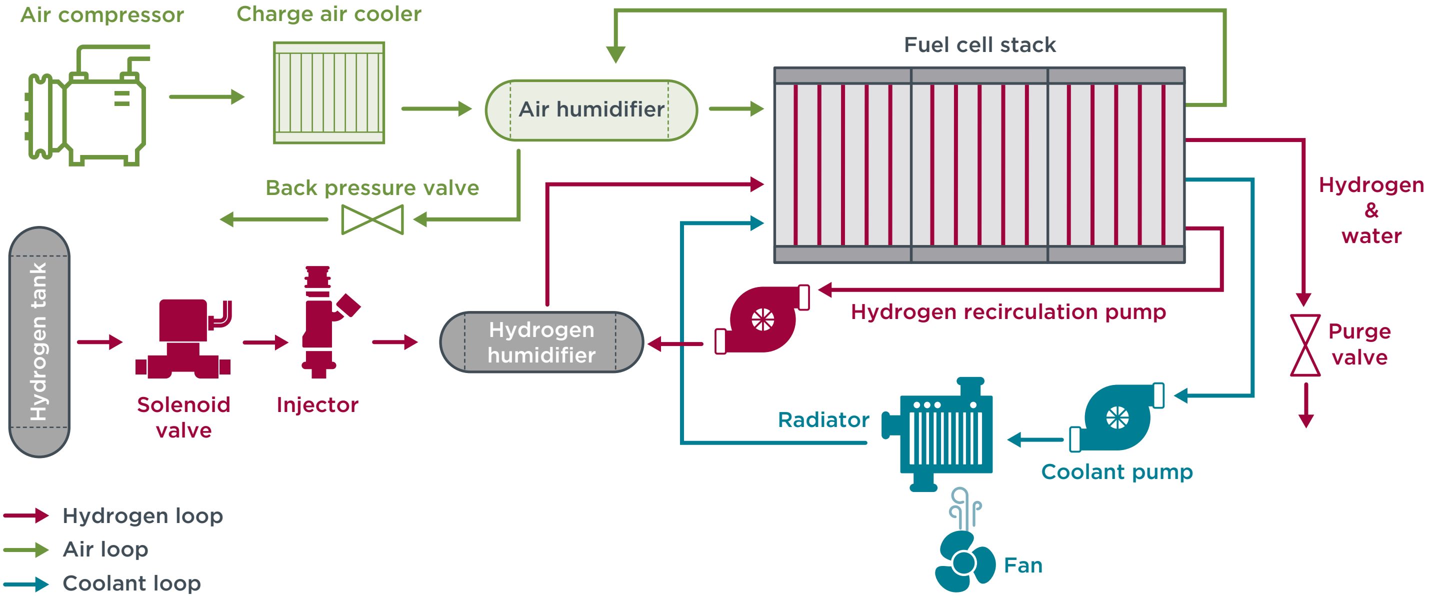

Figure 6. Schematic of a fuel cell stack balance of plant

The main task of the **air loop** is to supply sufficient oxygen to the cathode as a function of the required load. Fuel cell performance is highly affected by the oxygen pressure in the cathode, so a dedicated air compressor controls the intake air pressure. The air temperature downstream from the compressor could reach 150°C, which could dehumidify and degrade the fuel cell membrane. Thus, a charge air cooler manages the temperature of air flowing into the cathode. The air loop also contains a humidifier to keep the membrane from drying out and ensure proton conductivity. The air loop is the most energy-intensive auxiliary, and it could consume more than 15% of the fuel cell stack power.

The **fuel loop** supplies hydrogen to the anode. A pressure reducer valve might be needed because the required hydrogen feed pressure at the anode is very low, in the range of 1–4 bar. The system uses a humidifier to increase the moisture content and prevent drying out the electrolyte membrane, which might affect conductivity (Wang et al., 2020). The low-pressure hydrogen flow rate is then regulated using an injector. The agglomeration in the anode of water and nitrogen gas from the cathode reduces the hydrogen pressure, resulting in stratification and forming inert hydrogen zones affecting the fuel cell stack performance. For this reason, hydrogen and water are frequently removed using a purge valve. A hydrogen recirculation pump feeds hydrogen back in to the anode to minimize fuel loss.

The **cooling loop** aims to remove waste heat from the fuel cell unit to keep its operating temperature around 80°C—for PEM fuel cells—to avoid degradation and efficiency deterioration. In addition, an electric resistance heater might be needed during cold start conditions. The low operating temperatures of the fuel cell stack relative to diesel engines enforce a sophisticated radiator design. Achieving such a low operating temperature requires a careful choice of coolant and geometry to remove waste heat (Chen et al., 2021). Liquid cooling is the most-used method in fuel cell electric vehicles due to its large heat removal capability. However, this results in considerable additional weight and power consumption (Wang et al., 2021). Active air cooling is characterized by low additional weight and volume, but its heat extraction capability is significantly lower. Heat pipes can reject a large amount of heat, but they are not yet adapted to automotive applications (Wang et al., 2020). Table 6 provides a summary of the main thermal management technologies.

Table 6. Summary of thermal management technologies for fuel cell stacks

	Liquid cooling	Active air cooling	Heat pipes
Advantages	• High heat extraction capacity	• Low weight • Low volume	• High thermal conductivity
Drawbacks	• Additional weight • High power demand	• Limited heat extraction capacity	• Not mature for automotive applications

Hydrogen storage system

The onboard hydrogen storage system (HSS) is a central component of fuel cell vehicles, with several technologies under development. The most common hydrogen storage technique for vehicle applications is compressed gas at either 350 bar or 700 bar. Compressed H_2 gas at 350 bar is a standard storage technology for fuel cell buses. However, for trucks in long-haul operation, packaging restrictions limit the available volume of HSS tank size, which at 350 bar would result in a driving range of less than 400 km as reported by vehicle manufacturers (refer to Table 1) because of the low volumetric density of around 16 g H_2 per liter of tank, including the HSS's balance of plant. On the other hand, 700 bar compressed H_2 gas would provide a higher driving range thanks to its higher volumetric density at 27 g H_2 per liter of HSS. This results in a 10% increase in HSS cost per unit mass of usable $H_{2,}$ as reported by CNH Industrial (CNHI, 2020).

Liquid H_2, or cryogenic hydrogen storage, requires temperatures reaching -253°C (Rivard et al., 2019). This technology gained momentum recently as Daimler Trucks is collaborating with gas company Linde to develop liquid H_2 refueling technology for long-haul trucks, developing cryogenic hydrogen tanks for long-haul applications (Daimler, 2020). This HSS technology makes higher driving range possible because of higher volumetric density, exceeding 36 g H_2 per liter of HSS. In addition, CNH Industrial reports that cryogenic hydrogen storage tanks are much less expensive than compressed hydrogen gas storage, resulting in a 35% reduction in cost per unit mass of usable H_2 relative to 350 bar hydrogen gas storage technology (CNHI, 2020). On the other hand, this technology faces other technical and logistical challenges, such as H_2 tank boil-off losses and the need for hydrogen liquefaction. Currently only three such plants are operational in Europe (FCH JU & Roland Berger, 2020).

Cryo-compressed hydrogen is a hybrid method combining compressed gas and liquid hydrogen where H_2 is compressed at 300 bar and stored at -150°C to -240°C. The use of compressed hydrogen at cold temperatures rather than ambient temperatures provides benefits including higher density, lower cost, reduced weight, and greater safety (Moreno-Blanco et al., 2019). Although this storage technology is still under development, it is expected to achieve volumetric density exceeding 40 g H_2 per liter of HSS (CNHI, 2020).

Another factor limiting the choice of onboard HSS is the hydrogen refueling supply. The 350 bar compressed refueling system is already used for buses and medium-duty vehicles, making it a mature technology that achieves high readiness levels. Similarly, 700 bar compressed refueling is also mature but with additional challenges related to the required high H_2 fuel flow rates, including the pre-cooling process and the compression technology, which have not yet been validated (H2 Mobility, 2021). Liquid H_2 and cryo-compressed H_2 refueling systems are still under development and experimentation (H2 Mobility, 2021). In addition, the energy required to compress and cool the different types of hydrogen fuel could range from 2 kWh/kg for the 350 bar compressed H_2 to 10 kWh/kg for liquid H_2, significantly raising fuel costs.

Although onboard HSS is not expected to result in any payload penalty for long-haul tractor-trailers in comparison with diesel counterparts, HSS volume might impose geometric challenges pushing truck manufacturers to adopt high volumetric density HSS —700 bar compressed H_2 or liquid H_2 instead of 350 bar compressed H_2 (Gangloff et al., 2016; Marcinkoski et al., 2016).

Table 7 summarizes the different hydrogen storage systems' technical specifications.

Table 7. Summary of hydrogen storage systems technical specifications as reported in the literature.

Parameter	350 bar H_2	700 bar H_2	Liquid H_2	Cryo-compressed H_2
Volumetric density [a]	16 g H_2/L	27 g H_2/L	36 g H_2/L	40 g H_2/L
Cost [a]	Reference	+10%	-35%	-
Hydrogen storage system technology readiness level [b]	8 - 9	8 - 9	4 - 6	-
Hydrogen refueling supply technology readiness level [b]	8 - 9	8 - 9	2 - 4	1 - 3
Energy required for compression and cooling [c]	2 kWh/kg H_2	3-5 kWh/kg H_2	10 kWh/kg H_2	3 kWh/kg H_2

[a] (CNHI, 2020)

[b] Technology readiness level adopted from (H2 Mobility, 2021): 1-observation, 2-formulation, 3-experimentation, 4-lab validation, 5-industrial validation, 6-technical demonstration, 7-prototyping, 8-qualification, 9-commercialization.

[c] (Aziz, 2021; Berylls Strategy Advisors, 2021; US Department of Energy, 2019)

Vehicle technical specifications and fuel economy modeling

Vehicle modeling is conducted to quantify the hydrogen consumption of FCETs under typical use profiles in the EU using a commercial simulation tool (Simcenter Amesim). The model simulates the vehicle's longitudinal dynamics and the behavior of the different sub-systems, namely the fuel cell unit, battery, and electric machine. The FCET model is similar to ICCT's battery-electric tractor-trailer model (Basma et al., 2021), with both truck models sharing the same chassis, cabin, electric machine, and transmission system. Figure 7 presents a schematic of the truck energy consumption model highlighting the main components affecting energy efficiency.

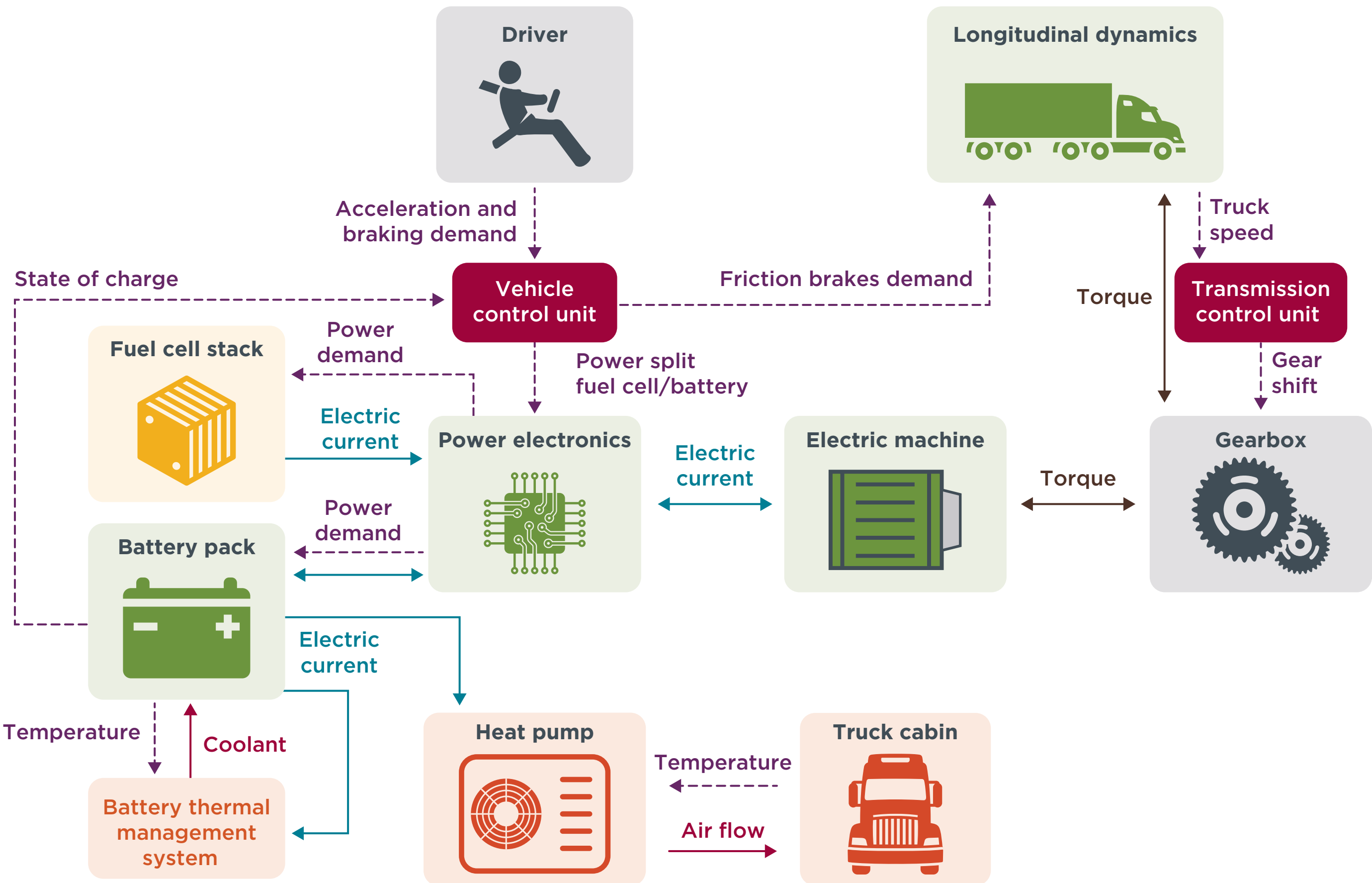

Figure 7. Schematic of the truck energy consumption model

The driver, modeled as a closed-loop controller, follows a pre-defined speed profile by providing acceleration and braking commands. The vehicle control unit (VCU) analyzes the driver's torque demand and transforms it into power demand from the fuel cell stack and the battery pack. The battery and the fuel cell stack supply the electric machine with the requested electric current to meet the driver's torque demand. The electric machine torque is then amplified by a two-speed gearbox and transmitted to the driving axle. A dedicated transmission control unit controls the gear shifting and determines the gear shifting strategy as a function of vehicle speed. Auxiliary power consumption is estimated by developing a battery thermal model and a dedicated battery thermal management system that consumes electric current directly from the battery. A truck cabin thermal model is also designed to estimate the truck cooling and heating needs, supplied by an air-to-air heat pump. The focus of this section is on the fuel cell stack model and the VCU, whereas more insights regarding the battery pack model, electric machine, gearbox, truck cabin, and heat pump can be found in a previous ICCT publication (Basma et al., 2021).

The fuel cell stack is modeled as a look-up table where the stack voltage and hydrogen fuel flow rate are expressed as a function of the electric current load. The fuel cell efficiency curve is shown in Figure 8 (Ferrara et al., 2021). The fuel cell stack peak efficiency is achieved at low load (~17% of maximum power). In other words, an oversized fuel cell stack can operate at more efficient operating points, enhancing the powertrain fuel economy. However, this results in a more expensive fuel cell stack and a higher truck selling price.

The powertrain model parameters are summarized in Table 8. The battery and the fuel cell size are considered similar to the currently available truck models presented in Table 1.

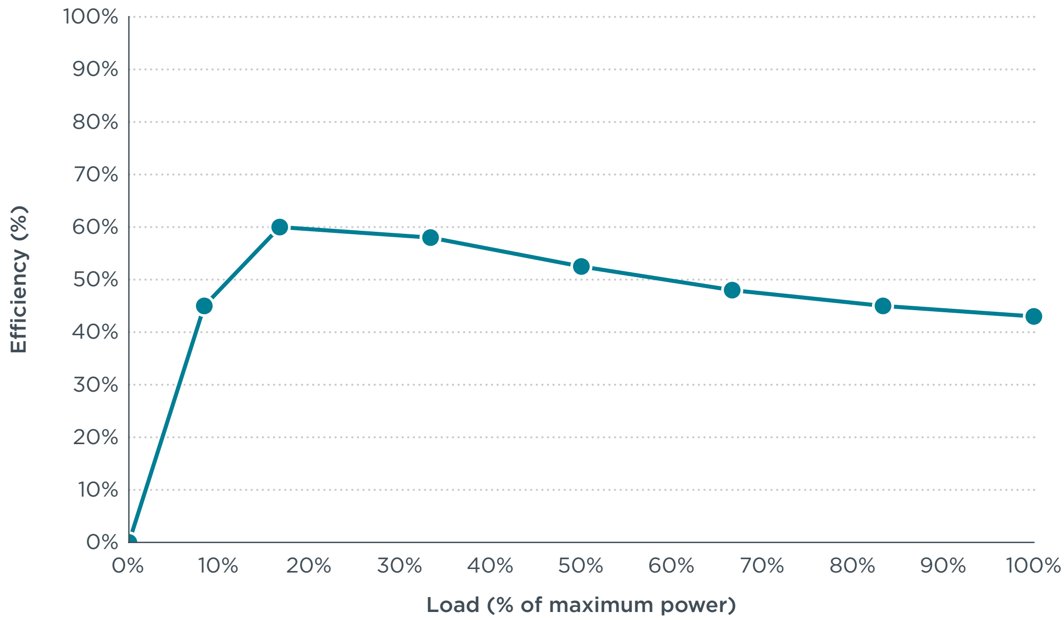

Figure 8. Fuel cell stack characteristic curve

Table 8. Summary of powertrain component parameters used in the simulation

Component	Specifications and model features
Battery	Chemistry: lithium nickel manganese cobalt oxide
	Nominal capacity: 72 kWh
	Nominal voltage: 660 V
	Maximum power: 170 kW
Fuel cell	Maximum power: 180 kW
	Nominal voltage: 200 V at full load
Electric machine	Type: permanent synchronous
	Maximum power: 350 kW
	Maximum torque: 4,000 Nm
	Maximum speed: 4,000 rpm
	Peak/continuous torque ratio = 1.4
	Efficiency: variable f (speed and torque) (Basma et al., 2021)
Transmission	Type: 2-speed gearbox [5,1] with 98.5% transmission efficiency
	Power axle: ratio = 2 with 97% transmission efficiency

The VCU transforms the driver acceleration and braking demand into power demand from the fuel cell stack and the battery. Since the power split between battery and fuel cell affects energy consumption, manufacturers implement various optimization techniques to control it. In this paper, we adopt a rule-based control strategy where the power split between the battery and the fuel cell is determined based on a predefined set of rules as shown in Figure 9. The control strategy is mainly defined based on the battery state of charge (SoC) and the electric motor power demand (P_{mot}). Three power thresholds are defined in the control strategy: low power (P_{low}), fuel cell power at maximum efficiency (P_{FC-eff}), and fuel cell maximum power (P_{FC-max}). In addition, two SoC thresholds are defined: SoC high, considered to be 95%, and SoC low, 80%. The VCU will split the motor power demand between the battery and the fuel cell depending on the electric motor power demand and the battery SoC.

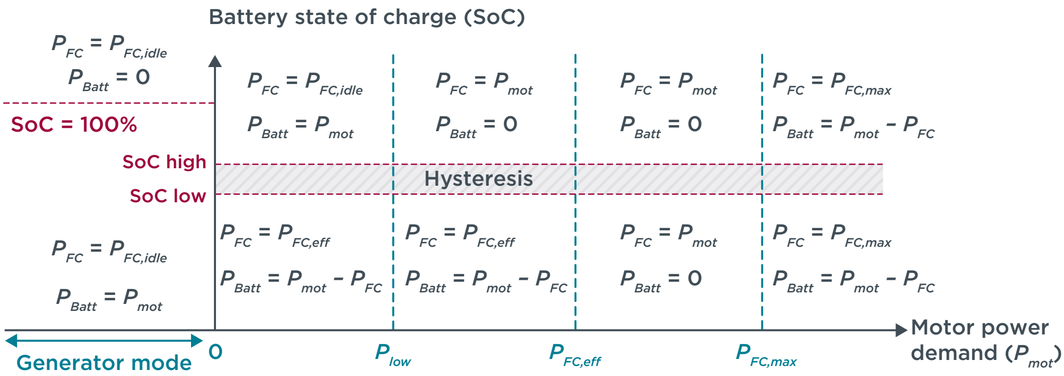

Figure 9. Schematic of the vehicle control unit

Hydrogen fuel consumption of fuel cell tractor-trailers

The proposed vehicle model is simulated over the parameters summarized in Table 9. Assumptions regarding improvement in road-load technologies, weight, and transmission system efficiency are documented in (Basma et al., 2021).

Table 9. Summary of vehicle simulation parameters

	Parameter	Current	Future
Road load	Drag coefficient	0.5	0.35
	Rolling resistance	0.005	0.004
Weight	Tractor	4,735 kg	4,135 kg
	Trailer	7,400 kg	6,200 kg
	Powertrain componentry	2,930 kg	2,470 kg
Transmission	Gearbox gears efficiency	98.5%	99.1%
	Differential efficiency	97%	98%
Fuel cell	Peak efficiency	60%	65%

We estimate the hydrogen fuel consumption in charge-sustaining mode, where the battery SoC at the end of the simulation is targeted to match the initial SoC. In practice, however, slight deviations in the final SoC are observed. Thus, hydrogen fuel consumption is corrected based on the additional electric energy consumption and the fuel cell unit average efficiency calculated over the entire drive cycle.

Hydrogen fuel consumption for current and future technologies

Figure 10 shows the fuel cell truck hydrogen consumption in the left panel and the required hydrogen tank size in the right panel for different driving ranges simulated over the VECTO long-haul cycle[1] at a reference payload of 19,300 kg and 15°C of ambient temperature for current and future vehicle technologies. Three driving ranges are considered: 500 km, 800 km, and 1,000 km.

The FCET hydrogen fuel consumption is in the range of 9 kg/100 km for a 500 km driving range under the simulation conditions for current vehicle technologies. The hydrogen consumption slightly increases to 9.2 kg/100 km for longer driving ranges, roughly a 2% increase, due to the need for a larger hydrogen tank which results in higher gross vehicle weight. With the expected improvement in vehicle road load technologies by 2030, chassis and trailer light-weighting, and improvement in the fuel cell unit conversion efficiency, hydrogen fuel consumption will be in the range of 6.64–6.72 kg/100 km, representing a 27% reduction. The fuel cell stack cycle-average efficiency is around 45% for current technologies and increases to 50% for future technologies.

The right panel of Figure 10 shows the needed hydrogen tank size measured in kg of usable hydrogen fuel. Under current vehicle technologies, the required hydrogen tank size is 45 kg to cover 500 km without refueling, a number slightly higher than most fuel cell truck models summarized in Table 1. For a 1,000 km driving range, the required hydrogen tank capacity is 92 kg. Such high storage capacity is not achievable by any of the currently available and announced FCET models in Europe, where most vehicles are equipped with 350 bar hydrogen storage tanks. Future vehicle technologies will result in lower hydrogen fuel consumption and thus reduced hydrogen storage tank size, as shown in the right panel.

1 Refer to Figure A1 in the appendix for more details regarding the drive cycle velocity and grade profiles.

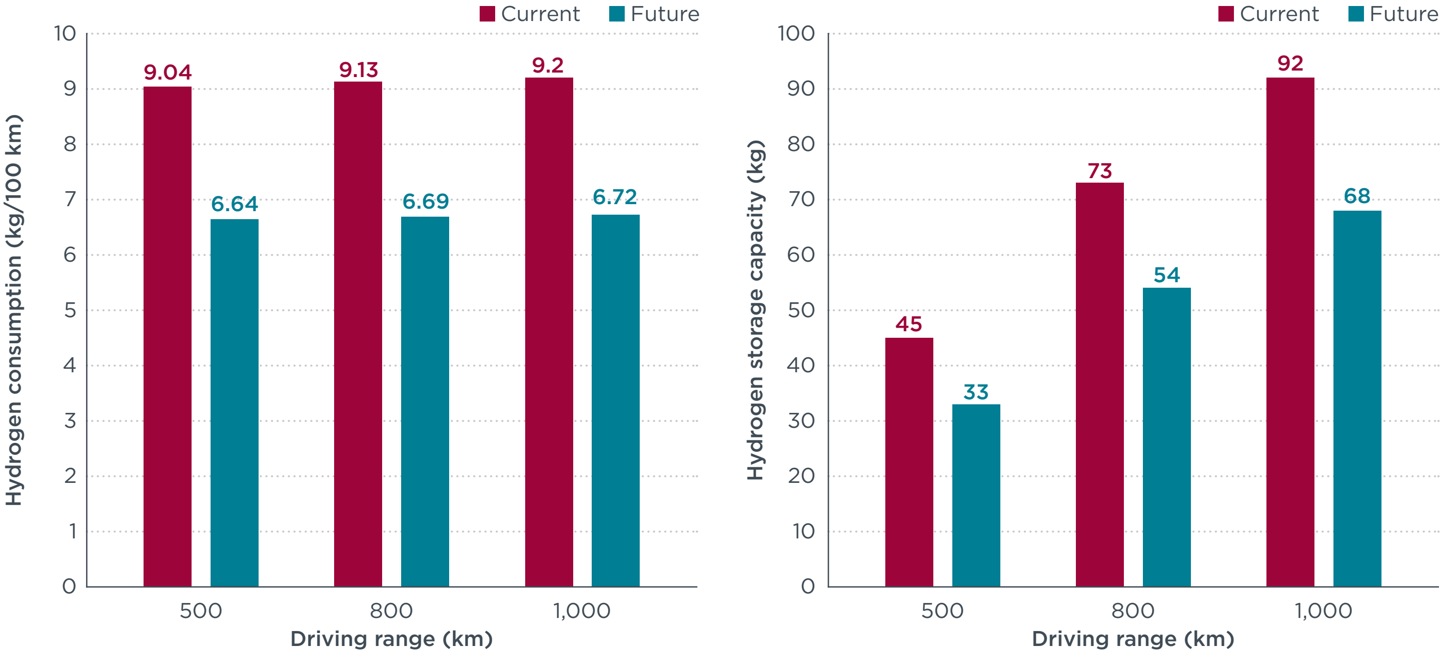

Figure 10. Fuel cell electric truck hydrogen fuel consumption (left) and required hydrogen tank size (right) for different driving ranges simulated over the VECTO long-haul drive cycle at a reference payload of 19,300 kg and 15°C ambient temperature for current and future vehicle technologies.

The FCET hydrogen fuel consumption simulation is also conducted over the VECTO regional delivery cycle at a reference payload of 12,900 kg for three driving ranges, 300 km, 400 km, and 500 km. As shown in Figure 11, current FCET technologies result in hydrogen consumption ranges between 8.8 and 9.15 kg/100 km, with the required hydrogen fuel tank ranging between 27 and 46 kg. Improvement in vehicle road load technologies by 2030 will reduce hydrogen consumption by 22% to between 7 and 7.13 kg/100 km. Figure 10 and Figure 11 data are summarized in the appendix in Table A1 and Table A2, and Figure A2 in the appendix shows the battery SoC and the powertrain components' power profiles as dictated by the vehicle control unit.

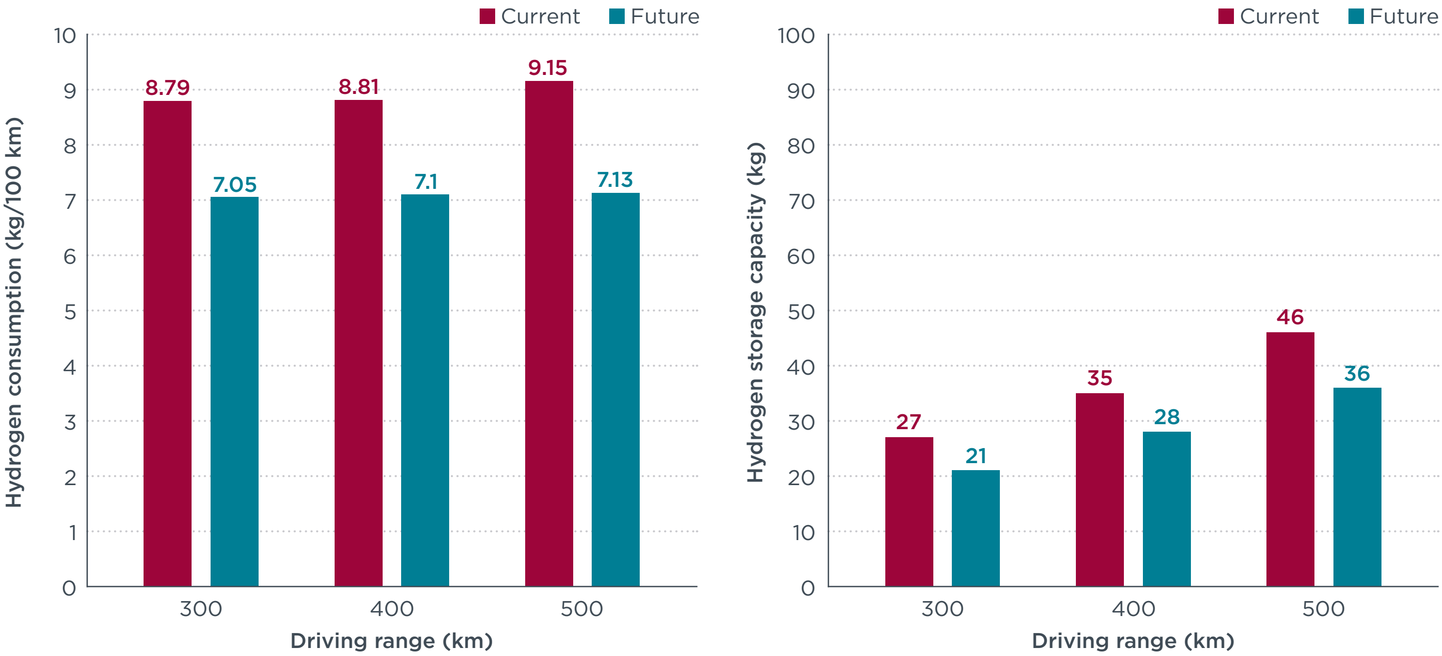

Figure 11. Fuel cell electric truck hydrogen fuel consumption (left) and required hydrogen tank size (right) for different driving ranges simulated over the regional delivery drive cycle at a reference payload of 12,900 kg and 15°C ambient temperature for current and future vehicle technologies.

Analysis of payload and temperature impact on hydrogen fuel consumption

The energy consumption of zero-emission trucks is sensitive to their operating conditions, such as speed, grade, payload, and ambient temperature (Basma et al., 2021). The FCET model is simulated over a range of payloads between 2,900 kg and the maximum payload capacity of the truck and at three temperatures—15°C, -7°C, and 35°C—for current and future vehicle technologies over the long-haul cycle, as shown in Figure 12 and tabulated in the appendix in Table A3.

For the case of current vehicle technologies at a fixed ambient temperature of 15°C, the hydrogen consumption increases by 55% from 6.87 kg/100 km at 2,900 kg payload to 10.62 kg/100 km for the maximum truck payload of 26,935 kg. Similarly, for future vehicle technologies, the hydrogen consumption rises by 66% from 4.82 kg/100 km to 8 kg/100 km as the payload increases from 2,900 kg to the maximum truck payload capacity of 29,195 kg.

Ambient temperature has a minimal impact on the truck's hydrogen consumption, reaching a maximum 4% increase in cold/hot weather conditions (-7°C and 35°C) relative to moderate weather conditions (15°C). Most of this increase is driven by the cabin thermal needs in the cold weather case and the battery thermal management system needs in the hot weather case. Table A4 in the appendix summarizes the average power demand for the cabin and the battery thermal management system needs. It is worth mentioning that fuel cells generate a significant amount of heat that could be recuperated to supply the entire truck cabin heating needs during cold conditions.

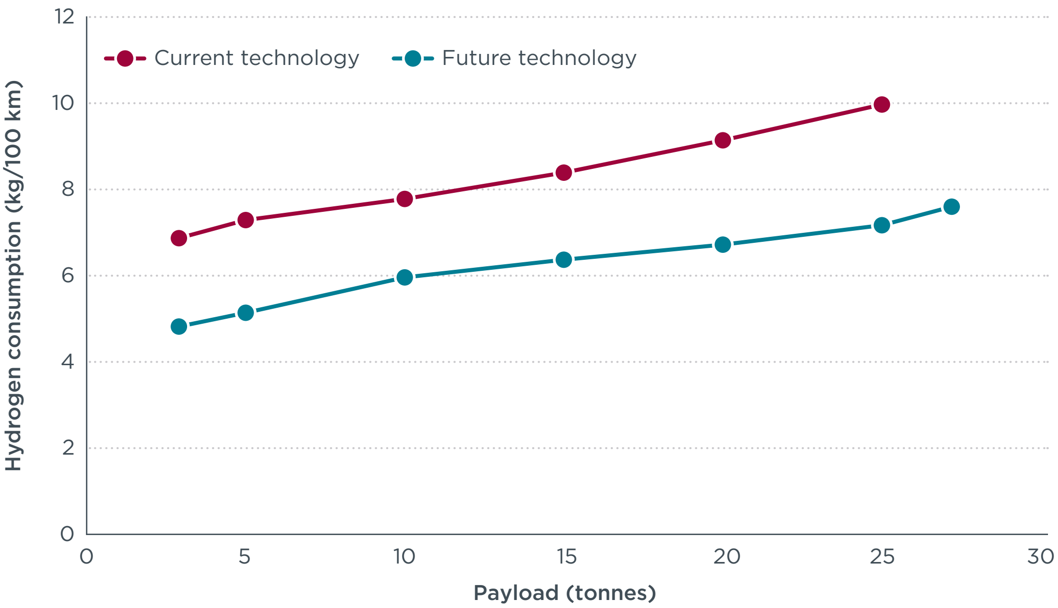

Figure 12. Fuel cell electric truck hydrogen fuel consumption at different payloads simulated over the long-haul cycle for current and future vehicle technologies based on a 15°C ambient temperature (hydrogen tank design of 500 km).

Volume and geometry challenges for hydrogen storage in fuel cell long-haul tractor-trailers

The available volume for onboard hydrogen storage is a critical factor in determining the driving range of FCETs. Truck geometry and packaging considerations impose constraints on the maximum volume of hydrogen storage and thus the maximum truck driving range (CNHI, 2020). This section examines the impact of such constraints on range considering several hydrogen storage technologies, including 350 and 700 bar compressed hydrogen, liquid hydrogen, and cryo-compressed hydrogen. This section does not aim to provide design recommendations but is intended to assess the impact of packaging constraints on the driving range for different types of hydrogen storage.

A global geometric approach is adopted to examine the volume constraints onboard FCETs by considering the truck geometry as shown in Figure 13 (Kast et al., 2018). It is assumed that the hydrogen tanks will be installed at the back of the driver's cabin in a similar approach to the Hyundai Xcient fuel cell truck for gaseous hydrogen storage technologies (Hyundai, 2021). The tractor's dimensions constrain the total packaging volume of the hydrogen tanks. These dimensions are estimated based on the Volvo FH sleeper cab tractor-truck (Volvo Trucks, 2021), as summarized in Table 10. More details about this approach can be found in the appendix, "Volume capacity methodology and data" in Table A5 and Table A6.

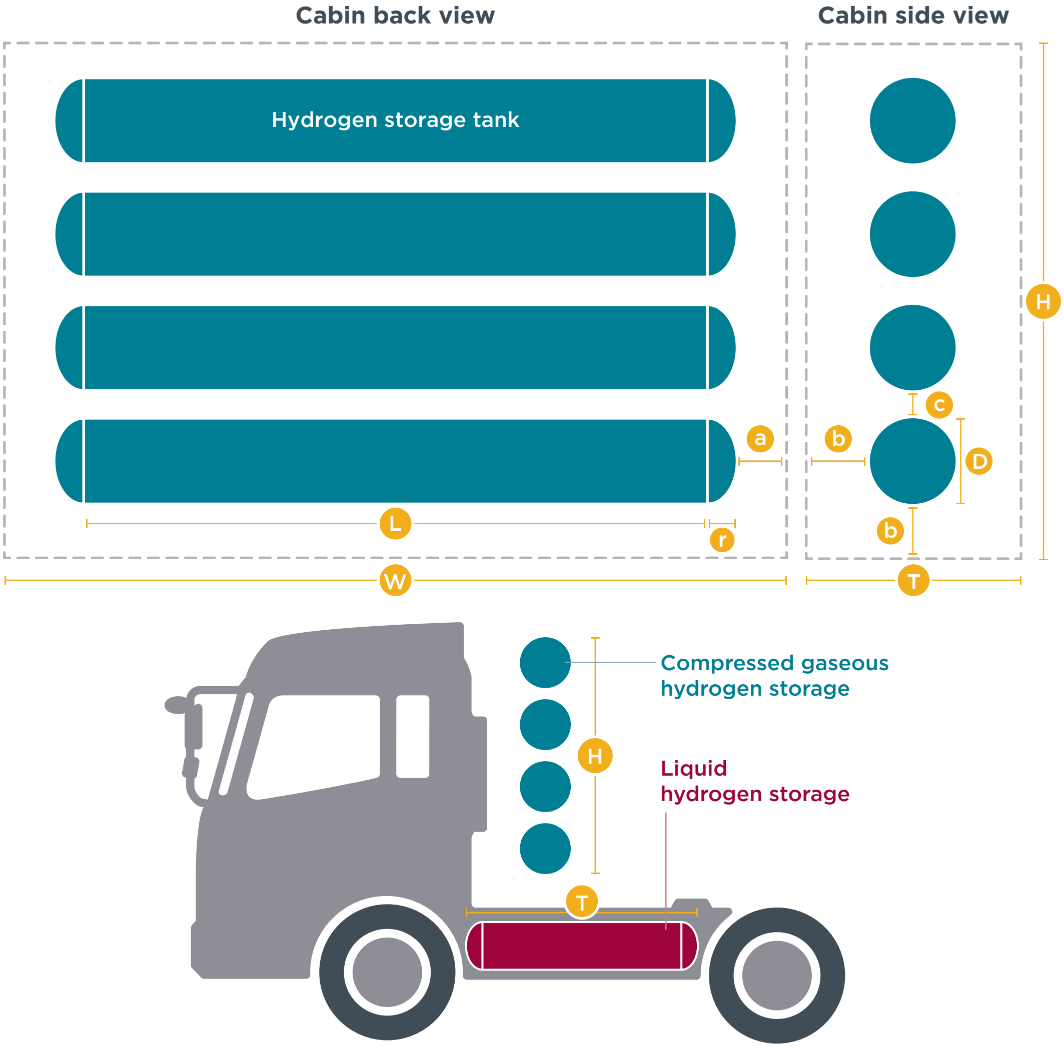

Figure 13. Schematic of hydrogen storage system design onboard a fuel cell tractor truck (for illustration purposes only).

Table 10. Truck dimensions and packaging clearances used to estimate the hydrogen storage volume based on (Volvo Trucks, 2021). Clearances are adapted from (Kast et al., 2018).

Dimension	W	H	T	a	b	c	r[2]
Value (m)	2.2	2.25	0.9	0.09	0.05	0.05	0.1

2 r is the tank valve buffer.

To maximize the volume capacity of the truck, the length of the tank is considered to be the maximum possible length of 1.82 m considering the geometry constraints, while the tank diameter and the number of tanks along each dimension are designed to maximize the volume capacity. The maximum total effective hydrogen storage volume onboard is around 2,000 liters. Refer to Table A5 and Table A6 in the appendix for more insights regarding the layout choice for the hydrogen storage system.

Another design choice would be placing the hydrogen tanks on the sides of the tractor between the axles. This approach is adopted by Daimler Trucks for the Mercedes GenH2 fuel cell truck. Hydrogen tank supplier SAG is developing liquid hydrogen tanks with a diameter of ~ 0.7 m and a length of 2.5 m (Winklhofer, 2021). Liquid hydrogen is stored at low pressure, allowing such designs with large tank diameters. The main advantage of this design compared with hydrogen tanks stored at the back of the cabin is that it doesn't compromise the driver's cabin space or the trailer space, as the dimensions of the tractor-trailer are regulated in Europe (European Commission, 2019a). The maximum storage volume under this design choice is almost equal to that of the back-of-cabin hydrogen storage design. The following analysis is valid for both design choices.

With a maximum onboard hydrogen storage capacity of just over 2,000 L, different storage technologies will yield different amounts of hydrogen in kg, dictated by the fuel volumetric density. Table 11 and Figure 14 show the maximum achievable FCET driving range for different hydrogen storage technologies considering the truck volume constraints. The 350 bar compressed hydrogen tanks allow a maximum of 32 kg of hydrogen onboard, which translates to a 370 km driving range for current vehicle technologies and a 500 km range for future technologies. With higher volumetric density, more hydrogen mass can be stored, making greater driving range achievable. A 700 bar compressed hydrogen storage system enables up to 600 km of driving range today, which is expected to increase to 800 km by 2030. Liquid and cryo-compressed storage solutions provide the highest ranges, reaching 800–900 km for current technologies and most likely exceeding 1,000 km by 2030.

Table 11. Maximum FCET driving range considering truck volume constraints for different hydrogen storage technologies for current and future vehicle technologies.

Storage technology	Maximum hydrogen storage mass onboard (kg)	Maximum driving range (km)	
		Current technology	Future technology
350 bar compressed	32	370	500
700 bar compressed	54	600	800
Liquid	72	800	> 1,000
Cryo-compressed	80	900	> 1,000

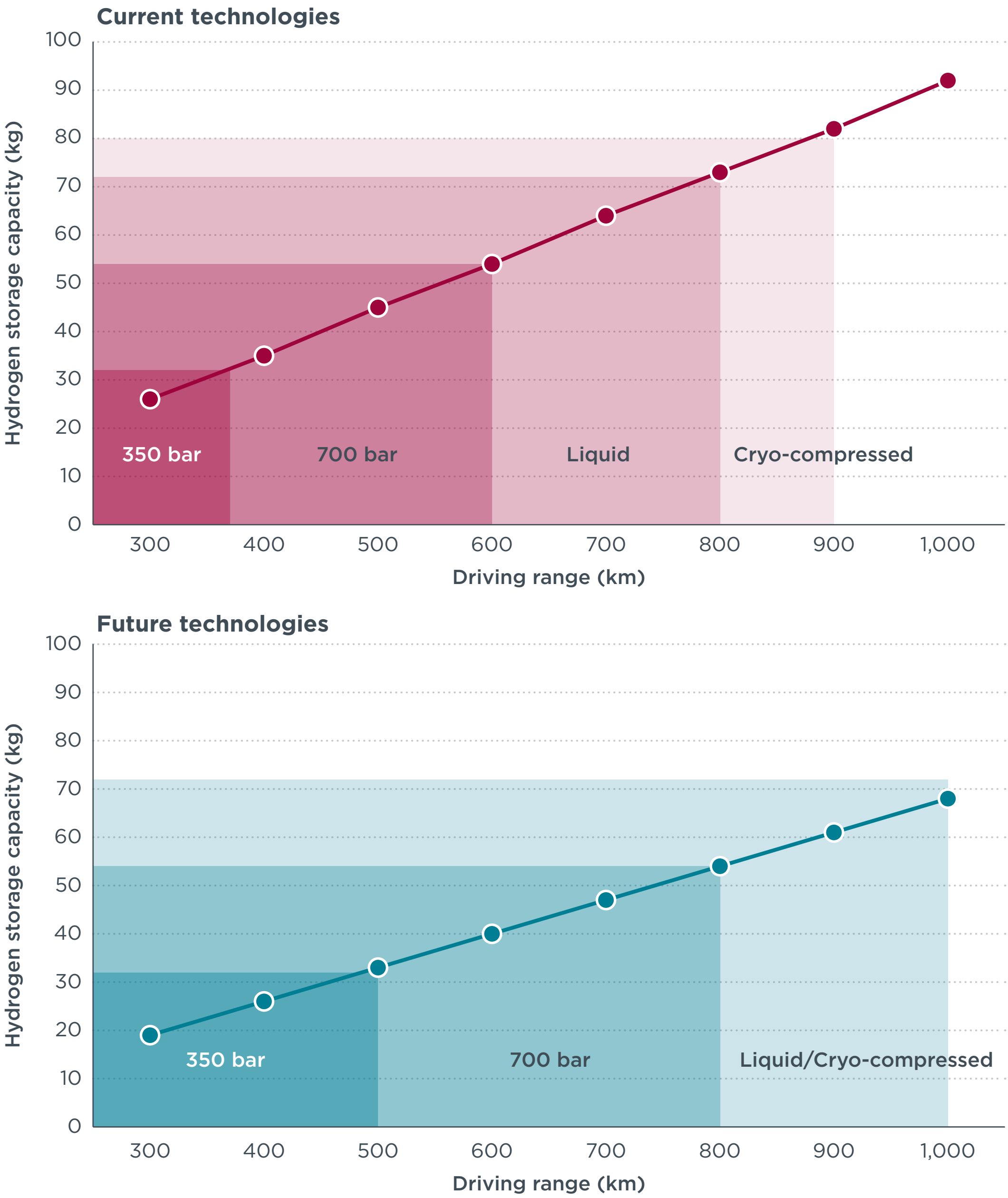

Figure 14. Maximum achievable FCET driving range for different hydrogen storage technologies for current and future vehicle technologies considering onboard volume constraints for hydrogen storage.

The choice of hydrogen storage technology is critical for FCETs in long-haul operation. Given that these trucks travel distances exceeding 500 km per day, liquid hydrogen storage seems to be the fittest technology capable of providing the needed driving range for long-haul tractor-trailers to operate without the need for refueling during the day. Other storage technologies with a lower volumetric density, such as the 350 and 700 bar compressed hydrogen tanks, may require refueling during the day.

The refueling time is also of great importance for long-haulers. The reported refueling time for the Hyundai Xcient fuel cell truck—the only commercial fuel cell truck in Europe to date—ranges from 8 minutes to 20 minutes to fill the 32 kg 350 bar hydrogen tank, resulting in a refueling rate in the range of 1.6 kg H_2/min to 4 kg H_2/min (FuelCellsWorks, 2020). For the 700 bar hydrogen tanks, there are no reported refueling rates for FCETs. Nonetheless, a Linde 700 bar hydrogen refueling station in Malaysia refuels fuel cell buses at almost 1 kg/min. Hydrogen refueling solutions for passenger vehicles at 700 bar record a higher rate, reaching ~1.67 kg/min (Hyfindr, 2022). At these rates, it would take 30 to 50 minutes to fill a 700 bar tank with 54 kg of hydrogen to cover 600 km of driving. It is still unclear the rate of liquid hydrogen refueling for heavy-duty vehicles, but the U.S. Department of Energy targets 8 kgH_2/min for all hydrogen fuel types by 2030 (Marcinkoski, 2019). Such high refueling rates can reduce truck refueling times significantly. However, high refueling rates require more expensive equipment, and hydrogen tank precooling will also be necessary (Elgowainy et al., 2018). That would be in addition to pressure drop challenges for low capacity reservoirs, especially for 700 bar refueling stations (Caponi et al., 2021). This will increase the already expensive hydrogen fuel price at the pump.

Tank-to-wheel energy efficiency comparison between fuel cell, battery-electric, and diesel tractor-trailers

While fuel cell and battery-electric powertrains have zero tailpipe emissions, their well-to-wheel CO_2 performance depends on the emissions caused by hydrogen and electricity production. Thus, the energy efficiency of zero-emission truck technologies is an important metric for assessing their environmental performance. In addition, the operating expenses of trucks, mainly the fuel/electricity costs, are directly affected by the energy efficiency of the trucks.

Figure 15 shows the electricity equivalent energy consumption at the level of the onboard storage system of the fuel cell, battery-electric, and diesel tractor-trailers simulated over the long-haul and regional delivery cycles for current and future vehicle technologies. The vehicle specifications for each powertrain typology are the same, differing only in the propulsion unit and transmission system using the same modeling methodology presented earlier. The energy content of 1 kg of hydrogen is 33.3 kWh. The energy content of 1 liter of diesel is almost 10 kWh. Figure 15 data are tabulated in the appendix in Table A7.

All powertrain typologies record a significant reduction in energy consumption for the future technology scenario (2030). This is mainly driven by improvements in road-load technologies, such as aerodynamics, rolling resistance, and chassis light-weighting which affect both diesel[3] and zero-emission trucks. More details about these improvements can be found in a previous ICCT publication (Delgado et al., 2017).

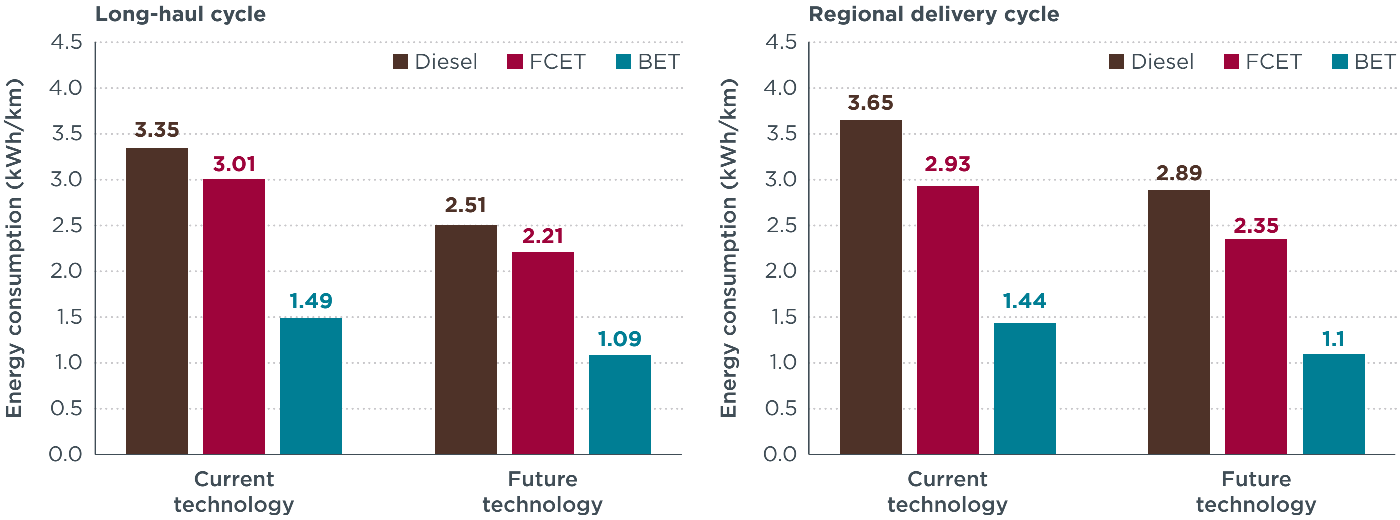

Figure 15. Tank-to-wheel electricity equivalent energy consumption of diesel, battery-electric, and fuel cell electric trucks over the long-haul cycle (payload of 19,300 kg and 500 km driving range) and regional delivery cycle (payload of 12,900 kg and 300 km driving range) for current and future vehicle technologies.

3 This improvement is in line with what would be required to meet the 2030 targets set by the HDV CO_2 standards while making use of the regulatory flexibilities and incentives (Basma, Saboori, et al., 2021).

The battery-electric truck (BET) powertrain records the lowest energy consumption over both drive cycles, 55% to 57% less than the diesel powertrain and almost 50% less than the FCET over the long-haul cycle. This is directly driven by the low efficiency of internal combustion engines and of fuel cell stacks which achieve 60% peak efficiency and around 45% cycle-average efficiency. The FCET shows a 10% reduction in energy consumption relative to a diesel truck of the same specifications. This increases to 12% by 2030, mainly because of the increase in fuel cell efficiency to 65% at peak and 50% for cycle average.

Similarly, over the regional delivery cycle, the BET records the lowest energy consumption at 50% less than the FCET. Relative to diesel trucks, the BET registers a 60% reduction in energy consumption, greater than the 50% reduction obtained over the long-haul cycle. This mainly reflects the benefits of brake energy recovery for the electrified powertrains, which improve their energy efficiency.[4] The FCET also records a greater reduction in energy consumption relative to the diesel truck over the regional delivery cycle (20% over the regional delivery cycle relative to 10% over the long-haul cycle), also resulting from the benefits of regenerative braking. In addition, the more transient nature of the regional delivery cycle allows the fuel cell stack to operate at partial loads with higher energy conversion efficiency.

Payload capacity of zero-emission tractor-trailers

The payload capacity of zero-emission heavy-duty tractor-trailers is a critical issue for fleet operators. This section quantifies and compares the payload capacity of fuel cell, battery-electric, and diesel tractor-trailers through a detailed truck weight virtual teardown analysis conducted by Ricardo Strategic Consulting US on behalf of the ICCT (Anculle et al., 2022; Sharpe & Basma, 2022). Table 12 presents a teardown analysis of tractor-trailers' weight without the powertrain and auxiliary components. Table 13 summarizes the weights of the different components in zero-emission tractor-trailers considering technologies current in 2021.

Table 12. Tractor-trailer weight teardown without zero-emission powertrain and auxiliary components (Basma et al., 2021).

Component	Weight	
	Current technology (2021)	**Future technology (2030)**
Truck body and structure	1,551 kg	
Drivetrain and suspension	1,388 kg	
Chassis	980 kg	
Wheels and tires	816 kg	
Total without trailer	4,735 kg	4,135 kg
Trailer	7,400 kg	6,200 kg

4 This behavior was also observed over other cycles and different tractor-trailers specifications in a recent ICCT study in China. Check Figure 6 of (Mao et al., 2021).

Table 13. Zero-emission tractor-trailer component weights (Anculle et al., 2022; Sharpe & Basma, 2022).

Component	Specification		Weight multiplier	
	Battery electric	Fuel cell	Current	Future
Battery pack	Varies by range	72 kWh	0.14 kWh/kg	0.23 kWh/kg
Fuel cell system	-	180 kW	0.6 kW/kg	
Hydrogen tank	-	Varies by range	0.046 kg H_2/kg (700 bar)	
Electric drive	350 kW		0.4375 kW/kg	
Power electronics	350 kW		3.6 kW/kg for BET 5 kW/kg for FCET	
On-board charger	44 kW	6.6 kW	0.95 kW/kg for high power 1.12 kW/kg for low power	
Air compressor	6 kW		0.087 kW/kg	
Steering pump	9 kW		0.072 kW/kg	
Air conditioning unit	10 kW		0.91 kW/kg	
Heater	10 kW		1 kW/kg	
Battery thermal management	350 kW		3.5 kW/kg for BET 7.14 kW/kg for FCET	

Another constraint that may limit the payload capacity of zero-emission trucks is the drive axle load which is strictly regulated in the EU. This is evident in the case of FCETs, as highlighted in figure 16. Installing hydrogen storage tanks at the back of the driver's cabin may shift the fifth wheel backward which increases the share of the drive axle load supporting the loaded trailer weight and reduces that of the steering axle (non-drive axle in the figure). This implies that less cargo weight is allowed to respect the maximum drive axle load which means lower payload capacity. The payload capacity loss can be estimated by applying static torque equilibrium equation at the non-drive axle. This would result in an increase in the drive axle load by a factor of '$d_{shift}/(d_1+d_2)$', where d_{shift} is the shifted position of the fifth wheel while d_1+d_2 is the tractor wheelbase. Considering typical values of 0.4 m for d_{shift} and 4.2 m for the wheelbase, this would result in up to 10% increase in the share of the drive axle load supporting the loaded trailer weight. In other words, this means that the payload capacity of the FCETs could be reduced by up to 10%.

The previous analysis considers that the trailer length would remain the same, resulting in a longer tractor-trailer. While the total length of tractor-trailers in the EU is regulated, article 9a of the 2019 amendment to the Council Directive 96/53/EC (European Council, 1996) states that the maximum length can be exceeded provided that the new cab design improves the aerodynamic performance and energy efficiency of the truck. Increasing the drivers' cab length to accommodate hydrogen tanks—and consequently the total length of the tractor-trailer—might be interpreted as a means of energy efficiency enhancement. A shorter trailer design could be implemented which would result in a lighter trailer. However, this would reduce the total cargo volume and thus reduce payload capacity.

On the other hand, liquid hydrogen storage tanks installed on both sides of the tractor unit between the axles are not supposed to shift the position of the fifth wheel. However, recent demonstrations by the Mercedes GenH2 FCET have revealed a so-called 'technology tower" mounted at the back of the drivers' cabin which assembles the fuel cell units, their power electronics, and the heaters used to vaporize liquid hydrogen. This technology tower may shift the location of the fifth wheel backward.

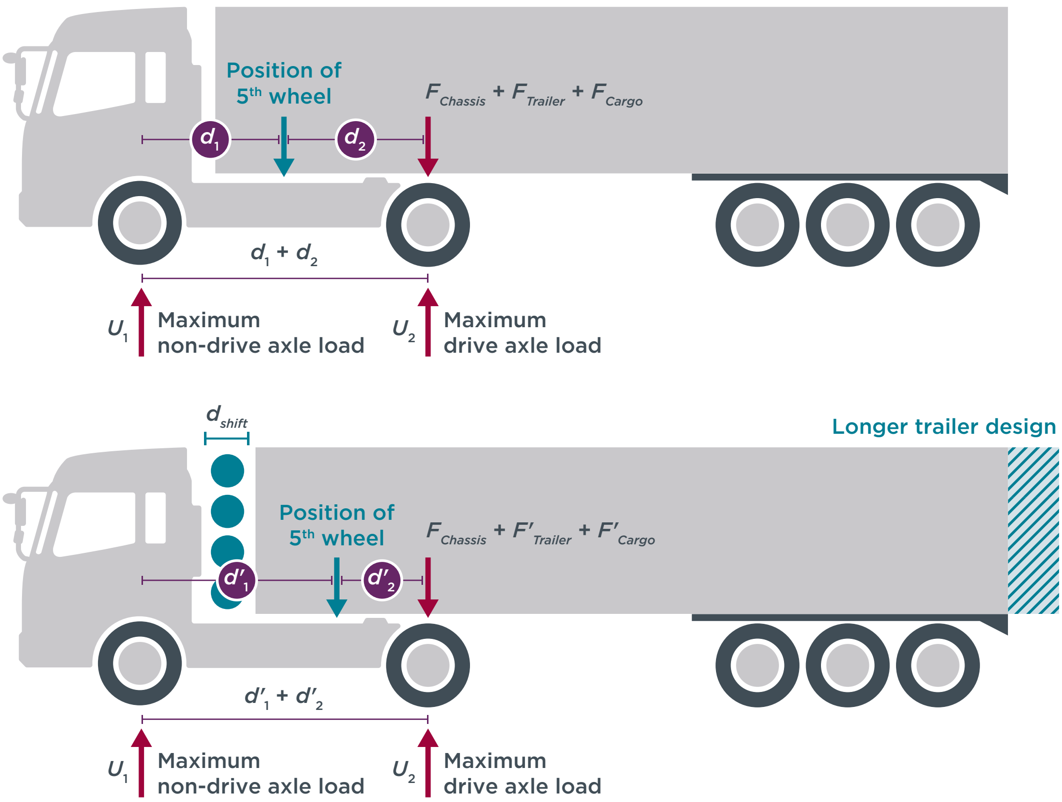

Figure 16. Demonstration of the impact of hydrogen storage system design onboard a fuel cell tractor truck on the drive axle load (for illustration purposes only).

Figure 17 shows the payload capacity of fuel cell and battery-electric trucks at different driving ranges under current and future vehicle technologies considering the additional gross vehicle weight allowance introduced for zero-emission powertrains by regulation EU 2019/1242 (European Commission, 2019b), which states that the maximum authorized weight shall be increased by the additional weight of the zero-emission technology capped at 2 tonnes. The figure also shows the FCET minimum payload capacity considering the axle load constraint.[5] The FCET records no payload penalty relative to its diesel counterpart at all driving ranges from a GVW perspective. However, constraints related to maximum drive axle load may result in a 2 to 3 tonnes payload penalty relative to diesel trucks. On the other hand, BETs have the lowest payload capacity with current technologies, and the maximum payload decreases as the driving range increases. While future vehicle technologies improve the payload capacity of all powertrain typologies—primarily driven by light-weighting and better powertrain energy efficiency—BETs will benefit the most from future technologies thanks to improvements in battery energy density, which will reduce or eliminate their payload disadvantage.

5 In the case of axle load limitation, the additional 2 tonnes allowance in GVW for zero-emission HDVs are not considered.

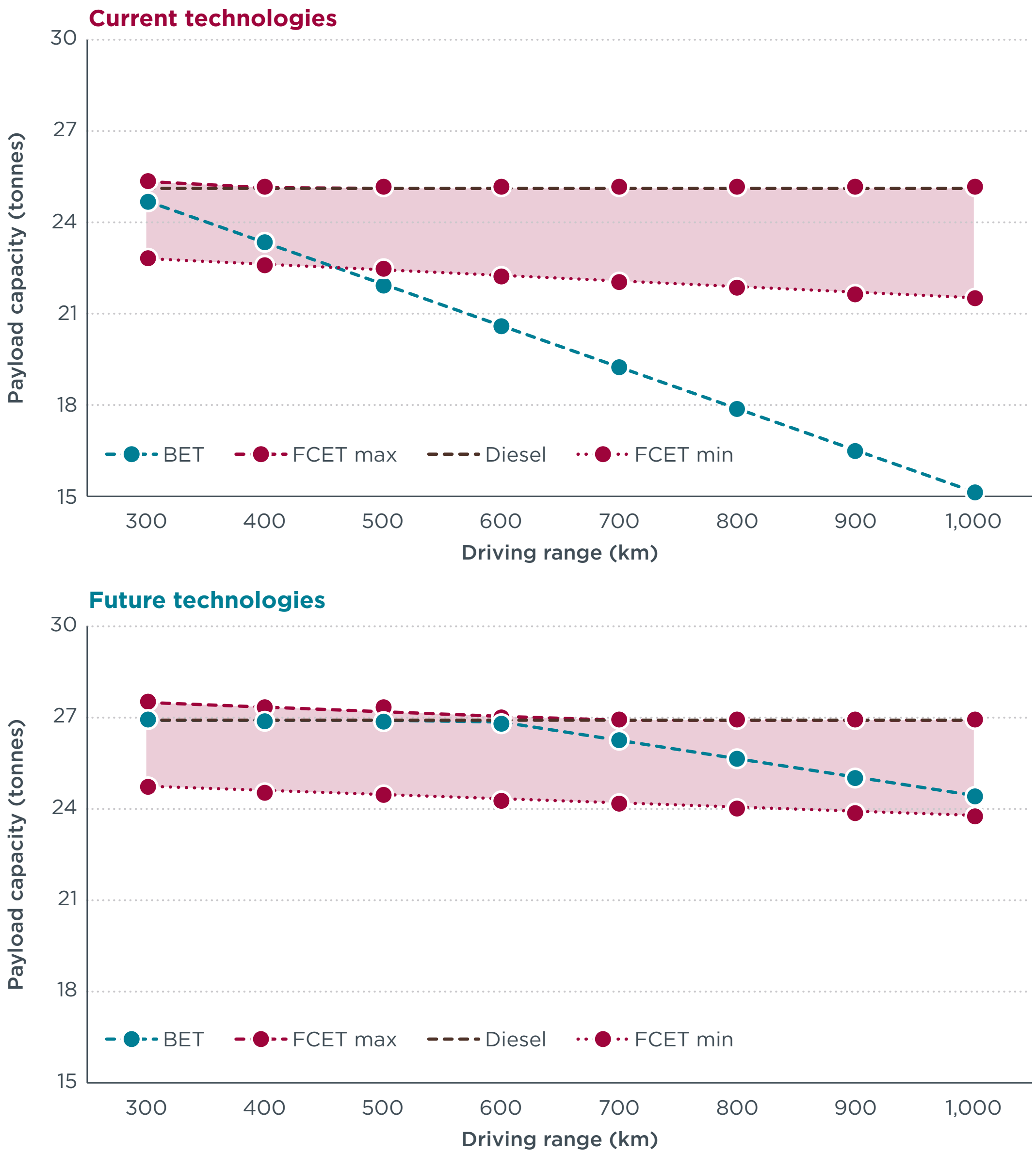

Figure 17. Payload capacity of battery-electric, fuel cell electric and diesel trucks at different driving ranges under current and future vehicle technologies. Simulated over the long-haul cycle at a reference payload of 19,300 kg and 15ÅãC ambient temperature.

For a 500 km driving range, FCETs today may suffer from up to 10% payload penalty relative to the diesel truck, while BETs have a 13% payload penalty. Future BETs are not expected to have any payload penalty at this driving range. For very high driving ranges at 1,000 km, FCETs may suffer up to 10% payload capacity losses relative to the diesel truck driven by the maximum drive axle load. At the same time, the BET suffers a 40% payload penalty due to the large battery required (1,884 kWh). Future technologies reduce the payload penalty of BETs to 9%. The data shown in Figure 17 are available in Table A8 in the appendix.

Conclusions and key findings

This study analyzed the application of fuel cells in long-haul tractor-trailers, beginning with a summary of the technology trends for powertrain architecture, fuel cell units, and hydrogen storage. We quantified the hydrogen consumption of fuel cell tractor-trailers under typical mission profiles and operating conditions in Europe using detailed vehicle simulation and compared the payload and energy efficiency of the fuel cell, battery-electric, and diesel technologies.

We arrive at the following key findings:

- **Fuel cell tractor-trailers' hydrogen fuel consumption is in the range of 9 kg/100 km today, potentially decreasing to 6.6 kg/100km by 2030.** Depending on the size of the hydrogen storage tank, the hydrogen fuel consumption of fuel cell tractor-trailers ranges between 9 kg/100 km and 9.2 kg/100 km under moderate, 15°C weather conditions and reference payload of 19,300 kg over the VECTO long-haul cycle. With the expected improvement in truck road load technologies, material light-weighting, drivetrain, and fuel cell efficiency, truck fuel economy has the potential to improve by almost 30%, reaching 6.6 kg/100 km to 6.7 kg/100 km.
- **Fuel cell tractor-trailers need at least a 45 kg hydrogen tank today to cover 500 km without refueling and a 92 kg tank to cover 1,000 km**. Most of the announced and already commercialized fuel cell truck models in Europe are not equipped with such a tank size, limited by the widely deployed 350 bar hydrogen storage technology with its low volumetric energy density.
- **Truck payload significantly affects hydrogen consumption**. Truck hydrogen consumption is highly sensitive to payload, and consumption could increase by 20% at maximum payloads relative to average payloads defined in VECTO.
- **Ambient temperature has a minimal impact on fuel cell tractor-trailer energy efficiency.** The energy simulation results under several weather conditions showed that the truck cabin and battery thermal needs have a minimal effect on energy efficiency, quantified at a 2% to 4% increase under representative cold and hot conditions in Europe (-7°C and 35°C).
- **Liquid hydrogen is a more suitable onboard storage technology for applications with very high driving ranges reaching 1,000 km and limited access to refueling stations**. Liquid hydrogen storage technology can provide trucks with the high driving range needed in long-haul operation without refueling. The lower volumetric density of other hydrogen storage technologies accompanied by truck volume and geometry constraints would require drivers to stop more frequently for refueling, reducing the range advantage of fuel cell electric trucks over battery-electric trucks. However, the technology readiness level of liquid hydrogen storage and refueling stations is still low today.
- **Fuel cell electric tractor-trailers are 10% to 12% more energy efficient when compared with equivalent diesel trucks at the tank-to-wheel level, while battery-electric trucks remain the most efficient powertrain technology**. Simulation results have shown that fuel cell tractor-trailers record a 10% to 12% improvement in energy efficiency relative to diesel trucks. On the other hand, battery-electric powertrains are at least 50% more efficient than their fuel cell counterparts in long-haul operation and 55% to 60% more efficient than diesel trucks. Truck energy efficiency can play a pivotal role in driving the total cost of operation and the total life-cycle greenhouse gas and pollutant emissions of tractor trucks, especially when considering the very high daily and annual driving mileages of long-haulers.
- **Fuel cell tractor trucks show a similar payload in comparison to their diesel counterparts from a GVW perspective.** However, axle load constraints may reduce their payload capacity. For any driving range application, fuel cell tractor-trailers are not expected to record payload losses relative to diesel trucks. However, constraints related to the design and location of the hydrogen storage system may increase the share of the drive axle load supporting the loaded trailer weight resulting in a lower payload capacity. On the other hand, battery-electric tractor-trailers suffer from payload loss for applications with daily mileages higher than 500 km. By 2030, the improvement in energy efficiency for all powertrain technologies accompanied by material light-weighting will make the battery-electric tractor-trailers' payload penalty less severe even for very high driving ranges at 1,000 km.

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Appendix

Hydrogen fuel consumption data

Table A1. Fuel cell electric truck hydrogen fuel consumption and required hydrogen tank size for different driving ranges simulated over the **long-haul** drive cycle at a reference payload of **19,300 kg** and 15°C ambient temperature for current and future vehicle technologies.

Driving range (km)	Hydrogen fuel consumption (kg/100 km)		Hydrogen tank size (kg)	
	Current Technology	Future Technology	Current Technology	Future Technology
500	9.04	6.64	45	33
800	9.13	6.69	73	54
1,000	9.20	6.72	92	68

Table A2. Fuel cell electric truck hydrogen fuel consumption and required hydrogen tank size for different driving ranges simulated over the **regional delivery** drive cycle at a reference payload of **12,900 kg** and 15°C ambient temperature for current and future vehicle technologies.

Driving range (km)	Hydrogen fuel consumption (kg/100 km)		Hydrogen tank size (kg)	
	Current Technology	Future Technology	Current Technology	Future Technology
300	8.79	7.05	27	21
400	8.81	7.10	35	28
500	9.15	7.13	46	36
800	9.27	7.24	74	59
1,000	9.37	7.30	94	74

Table A3. Fuel cell electric truck hydrogen fuel consumption simulated over the **long-haul** drive cycle at several payloads and ambient temperatures for current and future vehicle technologies.

Kg/100 km	Current technology			Future technology		
Payload (kg)	15°C	-7°C	35°C	15°C	-7°C	35°C
2,900	6.87	7.06	6.97	4.82	5.02	4.92
5,000	7.29	7.48	7.39	5.14	5.31	5.21
10,000	7.78	7.92	7.85	5.96	6.12	6.06
15,000	8.39	8.55	8.49	6.37	6.50	6.44
20,000	9.14	9.30	9.30	6.72	6.86	6.83
25,000	9.97	10.12	10.15	7.17	7.30	7.30
Maximum	10.05	10.13	10.17	7.6	7.73	7.77

Table A4. Average power demand for the cabin and the battery thermal management system simulated over the **long-haul** drive cycle at several payloads and ambient temperatures for current vehicle technologies.

Power demand (kW)	Cabin			Battery		
Payload (kg)	15°C	-7°C	35°C	15°C	-7°C	35°C
2,900	0.08	1.94	0.79	0.697	0.81	1
5,000				0.699	0.8	1.03
10,000				0.75	0.75	1.1
15,000				0.74	0.64	1.12
20,000				0.75	0.52	1.63
25,000				0.8	0.48	1.91
Maximum				0.83	0.46	2.1

Drive cycles and power profiles

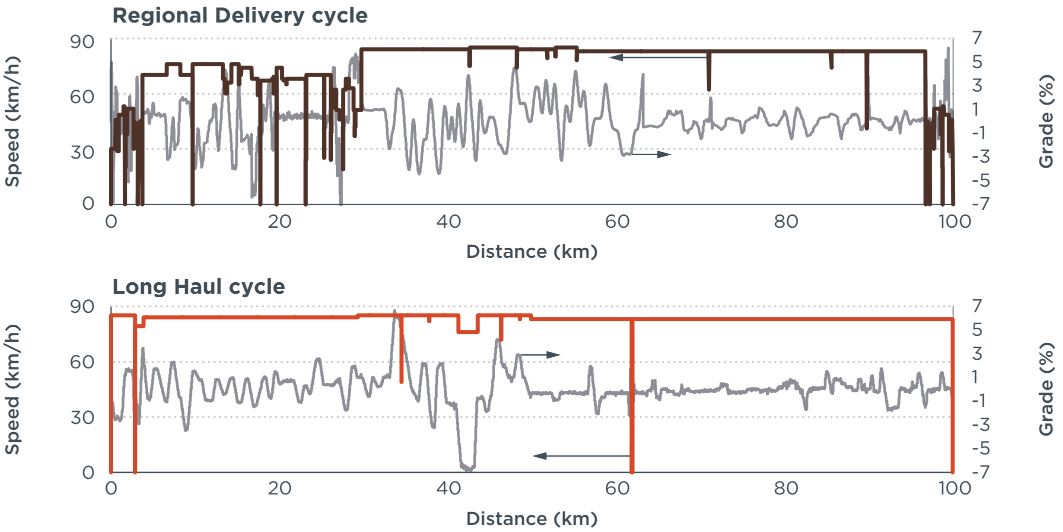

Figure A1. Long Haul and Regional Delivery VECTO cycles

Figure A2. Electric motor, fuel cell system, and battery power profiles and state of charge as a function of time simulated over the VECTO long-haul drive cycle at a reference payload of 19,300 kg and 15°C ambient temperature for current vehicle technologies.

Volume capacity methodology and data

The truck's geometry imposes constraints on the hydrogen tanks' diameter, length, and the number of tanks along the H and T dimensions. It is assumed that there is one tank along the W dimension. In general, if there exist N_H tanks along the H direction and N_T tanks along the T dimension, then the length L and diameter D of the hydrogen tanks are dimensionally restricted as follows:

$$L \leq W - 2 \times (a + r) \quad (1)$$

$$D \leq \frac{T - b \times (1 + N_T)}{N_T} \quad (2)$$

$$D \leq \frac{H - c \times (1 + N_H)}{N_H} \quad (3)$$

Table A5. Hydrogen tank maximum allowable diameter for different design setups

Tank Diameter (m)		N_T				
		1	2	3	4	5
N_H	1	0.80	0.38	0.23	0.16	0.12
	2	0.80	0.38	0.23	0.16	0.12
	3	0.68	0.38	0.23	0.16	0.12
	4	0.50	0.38	0.23	0.16	0.12
	5	0.39	0.38	0.23	0.16	0.12

Table A6. Effective hydrogen storage volume capacity for different design setups

Total Volume (m^3)		N_T				
		1	2	3	4	5
N_H	1	0.91	0.40	0.23	0.15	0.10
	2	1.83	0.80	0.47	0.30	0.21
	3	2.00	1.21	0.70	0.45	0.31
	4	1.43	1.61	0.93	0.60	0.41
	5	1.09	2.01	1.17	0.75	0.51

Electricity equivalent energy consumption data

Table A7. Electric equivalent energy consumption of diesel, battery-electric, and fuel cell electric trucks over the long-haul cycle (payload of 19,300 kg and 500 km driving range) and regional delivery cycle (payload of 12,900 kg and 300 km driving range) for current and future vehicle technologies.

Energy consumption (kWh/km)	Current Technology			Future Technology		
	Diesel	BET	FCET	Diesel	BET	FCET
Long-haul cycle	3.35	1.49	3.01	2.51	1.09	2.21
Regional delivery cycle	3.65	1.44	2.93	2.89	1.10	2.35

Payload capacity data

Table A8. Payload capacity of battery-electric and fuel cell electric trucks at different driving ranges under current and future vehicle technologies. Simulated over the **long-haul** cycle at a reference payload of **19,300 kg** and 15°C ambient temperature.

Driving range (km)	Current technology payload capacity (kg)			Future technology payload capacity (kg)		
	Diesel	BET	FCET	Diesel	BET	Fuel cell
300	25,116	24,704	25,343	26,916	28,666	27,499
400		23,339	25,139		28,063	27,346
500		21,974	25,116		27,460	27,194
600		20,609	25,116		26,857	27,042
700		19,243	25,116		26,253	26,916
800		17,878	25,116		25,650	26,916
900		16,513	25,116		25,047	26,916
1,000		15,148	25,116		24,444	26,916