Development & Technology

The Future Powertrain Portfolio

Fuel cells, eFuels, batteries – How to translate net zero ambitions into technology

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INSIGHTS

//01

4 key drivers accelerate the transformation to Net Zero technologies across industries: customers, investors, regulators and technological development.

//02

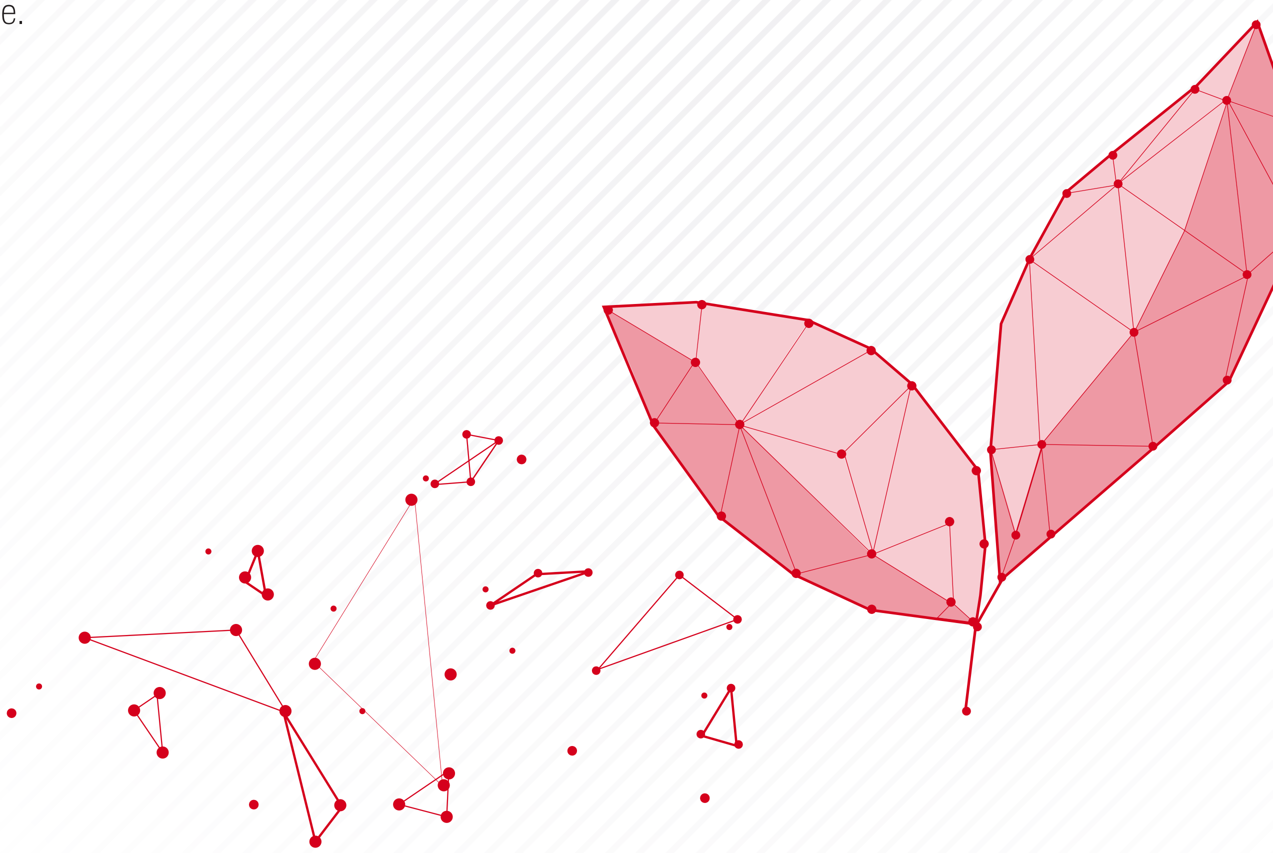
There will not be one single technological solution for all industries. Depending on product and application, key technologies will range from batteries, fuel cells to efuels.

//03

A company-specific technology strategy process is required that considers the technical and economic perspective in order to determine the most promising technology.

Introduction

In the global ambition to combat climate change, more than 180 countries committed to the Paris Climate Agreement to transform into a net zero society during the second half of this century. This commitment puts pressure on manufacturers of fossil fuel-powered products — and generates the need to transform their powertrain portfolio. For passenger vehicles, battery-electric powertrains are emerging as the mainstream option to achieve zero tailpipe emissions. Companies from other industries, from agriculture to aviation, also aim to replace fossil fuels, driven by customers, investors, regulation, and technological improvements. Compared to passenger vehicles, these applications have fundamentally different requirements, which in various cases cannot be met by batteries alone. Other technologies like fuel cells and eFuels are potential alternatives, but their technical and economic performance strongly depend on application and use case. Furthermore, these powertrains will improve their technological competitiveness compared to conventional drives. For companies to successfully transform, it is critical to set up the right technology strategy early on. This paper outlines an approach to build such a strategy in order to enable stakeholders to take the right steps to prepare their powertrain transformation, for a sustainable — and competitive — future.



Industries from agriculture to aviation: four key aspects drive net zero across industries

The strong push to replace fossil fuels and strive towards net zero emissions by 2050 will already affect industries from agriculture to aviation in the near future. This push is driven by four key factors:

- **Customer Awareness:** End customers are increasingly aware of their ecological footprint, which will affect transportation industries on road, rail, water and in the air. Customers are changing their behavior towards lower-carbon service options and a recent study shows that about 70 percent of customers are willing to pay more for a green delivery of the products they ordered, with about 60 percent also willing to wait longer.[1]

- **Capital Markets:** Private and institutional investors are focusing more on the aspect of sustainability in their investment decisions, impacting companies across industries. In addition to a rising awareness of ESG ratings on capital markets and a net zero commitment of multiple large investment funds, the Net Zero Banking Alliance, a global group of banks that represents more than 40 percent of global banking assets is committed to aligning their lending and investment portfolios with net zero emissions by 2050.[2]

- **Emission Regulation:** Regulators at the supranational, national, regional, and city level have already and will continue to implement policy measures to reduce emissions with an effect across industries. These regulations also affect industries such as construction, where, for instance, the city of Oslo has set a target only to use zero-emission equipment in public projects by 2025,[3] or shipping, where the International Maritime Organization has set a target to eliminate carbon emissions close to 2050.[4]

- **Technology Improvement:** Technological advances in higher-efficiency and lower-carbon powertrain technologies improve their performance and cost and increase their competitiveness to conventional drives across industries. In terms of battery technology, dynamic R&D activities and upscaling[5] have decreased the manufacturing cost of an automotive battery pack by about 90 percent since 2010, while simultaneously improving performance parameters such as energy density.[6,7]

All industries need to confront these factors and the transition towards net zero emissions. In order to make this transformation economically viable, suitable powertrain technologies are required that allow for low-carbon operation and continue to offer attractive business models for market players. The task for each company in these industries is to identify the right technologies for their products.

Passenger vehicles as pioneers: Battery-electric powertrains will become mainstream

Powertrain alternatives to conventional combustion engines have been a topic for passenger vehicles since the 19th century. For example, Ferdinand Porsche, engineer at Austrian coach manufacturer Lohner, unveiled a design of a front-wheeled battery-powered vehicle at the 1900 Paris Exposition.[8] At the time, lead-acid batteries could not provide enough range for the Lohner-Porsche to compete with cars powered by internal combustion engine with fossil fuels. However, more than 100 years later, the company Mr. Porsche founded has been among the pioneers to use advanced lithium-ion batteries in passenger cars, allowing for better range and performance. Major milestones of Porsche on its way to modern electrification are shown in Figure 1.

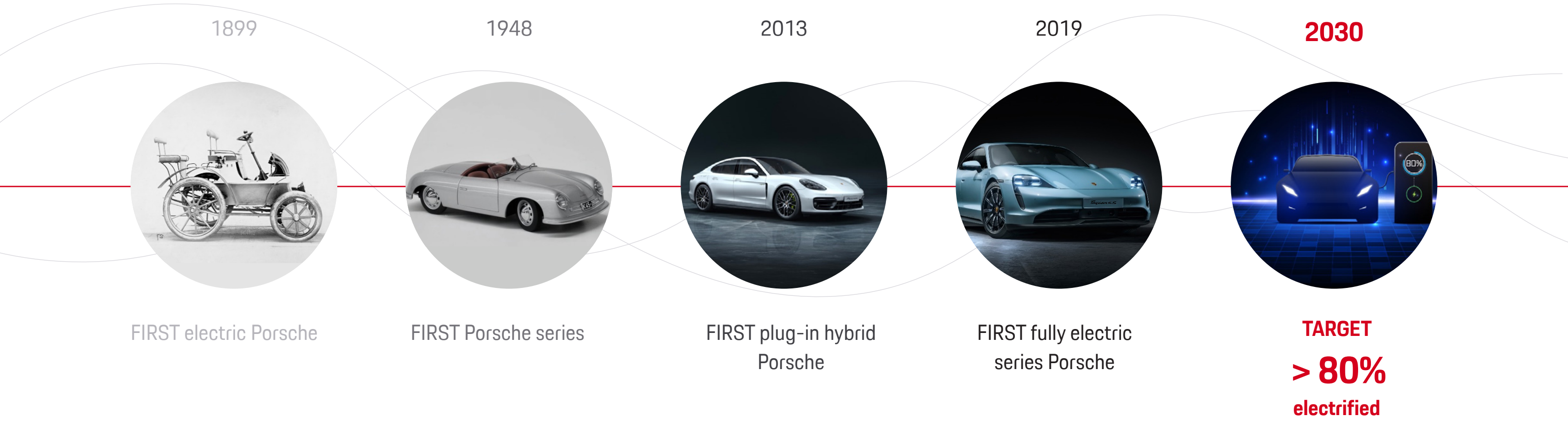


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Fig. 1. Example from Porsche | Passenger car powertrains have evolved from internal combustion engines to hybrid and fully battery electric drives.

Proof that battery-powered vehicles are attractive to premium customers has certainly been the market introduction of the Porsche Taycan. The first fully electric Porsche offers up to 560 kW of power and 450 kilometers of range,[9] with more than 30,000 sales just one year after its unveiling.[10] Encouraged by that, Porsche has stated its ambition to achieve more than 80 percent of sales from fully electric vehicles by 2030.[11] Besides Porsche AG, other relevant automotive OEMs such as Tesla, Stellantis, and Mercedes-Benz have announced ambitious sales targets for their electric portfolio,[12,13,14] making batteries the likely mainstream technology in the automotive market of the next decades.

Batteries are not the right solution for all industries

To analyze the market for powertrain technologies by product, it is split into five industries: Truck & Bus, Off-Highway, Railway, Shipping, and Aviation. In each of these industries, three exemplary products are selected for a detailed analysis.

Within the truck and bus industry, 7.5-ton trucks for applications in urban areas such as parcel transport, a typical city bus for local passenger transport and a 40-ton long-haul truck are analyzed. Battery electrification in this industry has already started. Within the segment of trucks between 5- and 7.5-ton gross vehicle weight, some manufacturers already offer electric trucks, including the FUSO eCanter[15] and the Mercedes-Benz eSprinter. City buses for public transportation are also available with electric powertrain and already in use, including the Solaris Urbino Electric and the Proterra Catalyst E2.[16] For 40-ton electric drive long-haul trucks, many well-known manufacturers, including, MAN Truck & Bus[17], DAF,[18] Tesla,[19] Scania,[20] Daimler,[21] and Volvo,[22] have already presented their first electric vehicles, but serial production has not started yet.

Products analyzed within the off-highway industry include medium-sized agricultural tractors with an engine power of 120 kW, excavators for urban construction work with a power of 180 kW, and a huge mining truck for the transport of extracted raw materials with a power of 2,000 kW. Battery electrification has already begun in the off-highway sector at companies such as Monarch, which will start producing fully electric small tractors in 2023.[23] The same applies to excavators — the Volvo EC product family is one example — which are already being developed as electric variants and will soon be commercially available.[24] For mining trucks, Caterpillar has recently successfully presented a technical concept. However, this product is still in the research and development stage.[25]

Within the railway industry, we look at regional trains to transport passengers between urban regions at an average speed of 80 km/h, inter-city trains for passenger transport between cities with an average speed of 120 km/h, and freight trains for transporting heavy loads for up to 2,000 km of range. The analyzed products assume operation on a railway where contact lines do not exist. Companies such as Alstom and Bombardier have already delivered the first products with a battery powertrain to railway operators.[26]

In the shipping industry, typical motor cruiser yachts for private usage are considered as well as medium-sized ferries for public transport and New Panamax container ships with a capacity of 14,000 twenty-foot containers for intercontinental routes. Within the shipping industry, only a few pilot projects within yachts and ferries exist, such as the electric ferry Siemens Ampere.[27] For large container ships, so far, no projects for battery electrification have been announced by ship manufacturers.

Within the aviation industry, vertical mobility with small helicopters travelling at 150 km/h on short trips are analyzed. Additionally, single-aisle aircraft for short-haul flights (up to four hours) and widebody aircraft for long hauls (up to 12 hours) have been considered. Vertical mobility is becoming increasingly important and is already being tested in the form of battery-powered air taxis by companies such as Volocopter or Lilium. In addition, within the short-haul aviation industry, the first projects of start-ups such as Zunum Aero and MagniX are experimenting with battery-electrification of small aircraft.[28, 29]

Even though pilot projects or first commercial deployments of battery electrification already exist in each of these industries, they are still predominantly powered by fossil fuels. Battery technology can represent a solution for a number of these products and is expected to further improve in the coming years.[30,31] However, as shown in Figure 2, batteries will not be competitive in all use cases, even in a time frame until 2050.

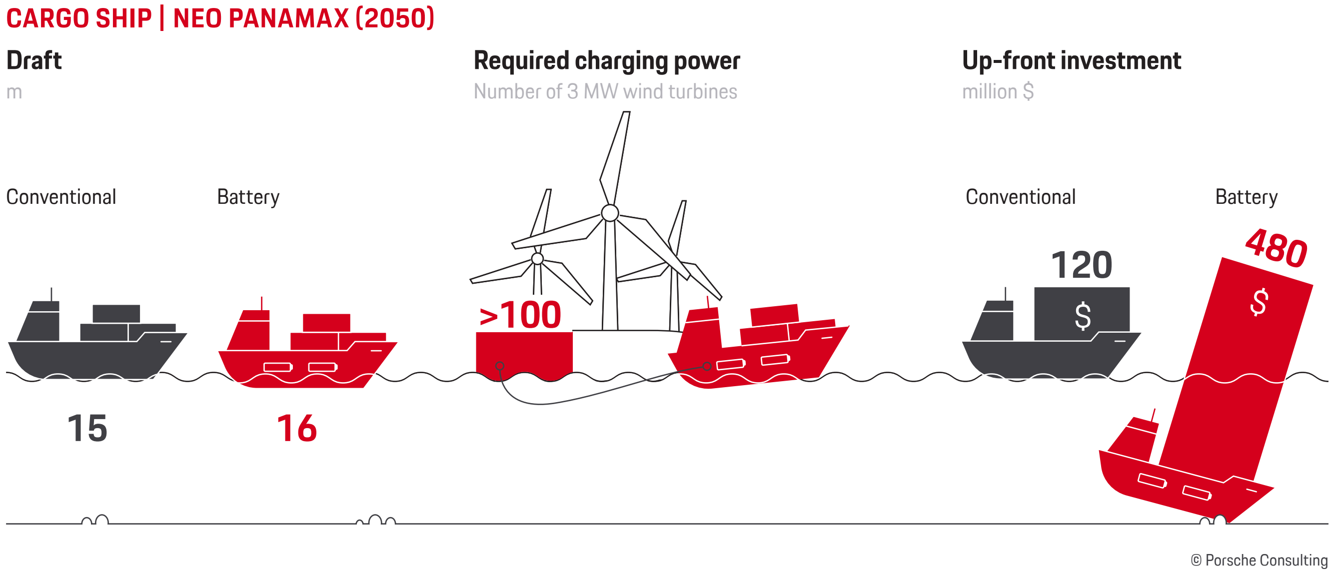


Fig. 2. Battery powertrains in large container ships are heavy, require high charging power and large investments.

Large container ships are an example of a product where batteries will likely not become competitive. This becomes clear when three factors are analyzed. First, the additional draft of such a ship, meaning the additional distance between the waterline and the keel of a ship due to the battery weight. Second, the required charging power; and third, the increase in up-front investment or purchase price of such a ship. For a New Panamax container ship in a typical use case, a 6 GWh battery would be required to safeguard travel times of at least five days without charging at port. From a technical perspective, the additional weight of such a battery compared to a conventional powertrain would be in the order of 15,000 tons (assuming a 2050 pack-level energy density of 310 Wh/kg, and reflecting the replacement of engine and heavy fuel oil tank). According to the Archimedes principle, this translates into an additional draft of one meter for a fully loaded ship. This would mean that such a ship, in contrast to its conventional counterpart, would not be allowed to cross the Panama Canal.[32] Furthermore, the required charging power for a ship with the assumed battery capacity would be approximately 400 MW during a stay in port of 15 hours. This is equivalent to the output of more than 100 wind turbines with a power of 3 MW operating at full capacity. Further, more than 1,000 typical fast-charging stations with 300 kW for electric vehicles each would be required. From an economic standpoint, the ship's purchase price would also increase by a factor of 4 from USD 120 to 480 million. The already existing challenge for ship builders to finance large ships would be significantly amplified and would require completely new approaches to obtain project funding.

The example of the container ship shows that technical and economic aspects can be decisive in the evaluation of powertrains. Hence, to identify the right technology for a product, a detailed analysis of these aspects is required.

Products and use cases need to be analyzed individually — technically and economically

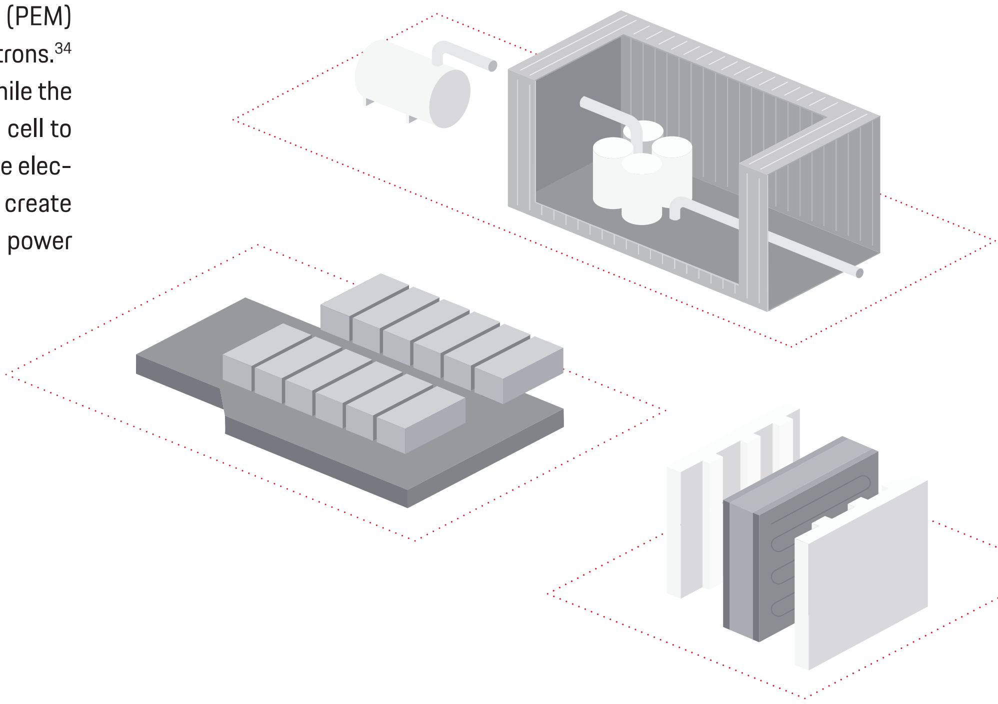
As demonstrated by the example of the container ship, battery technology is not suitable for all applications as an alternative to conventional powertrain technology. To fully replace fossil fuels, a solution with other alternative powertrain technologies such as fuel cells and eFuels will be necessary. In this paper, three categories of technologies are distinguished:

- **Battery** cells consist of two electrodes (cathode and anode), an electrolyte and a separator, which are surrounded by a cell housing. The separator acts as a physical barrier to prevent electric shorting but allows ions to dissolve through the electrolyte from the cathode to the anode and hereby force an electrical current through the electrodes of the battery.[33] Thus, chemical energy is converted into electrical energy, which can be used to power an external load.

- **Fuel cell** technology is characterized by two electrodes (cathode and anode) and an electrolyte, which are held together by a cell can. In the anode of a typical polymer electrolyte membrane (PEM) fuel cell, hydrogen is split into ions and electrons.[34] The ions dissolve through the electrolyte, while the electrons pass through the poles of the fuel cell to create an electric current. At the cathode, the electrons and the ions reunite with oxygen to create water. The electrical current can be used to power an external load.

- **Conventional combustion engines** or turbines can be powered by alternative fuels such as bioFuels or electro-fuels (eFuels).[35] eFuels are hydrocarbons that are synthesized out of captured carbon dioxide and green hydrogen. In the combustion chamber, the eFuel is mixed with oxygen. A controlled ignition and explosion of the gas mixture in the combustion engine creates a force, thus providing an energy source for the engine.

The selection of the most suitable alternative powertrain technology — battery, fuel cell, or eFuel — requires a comprehensive analysis of the technical feasibility and the total cost of ownership by product and use case. This analysis is conducted in two stages, as shown in Figure 3.



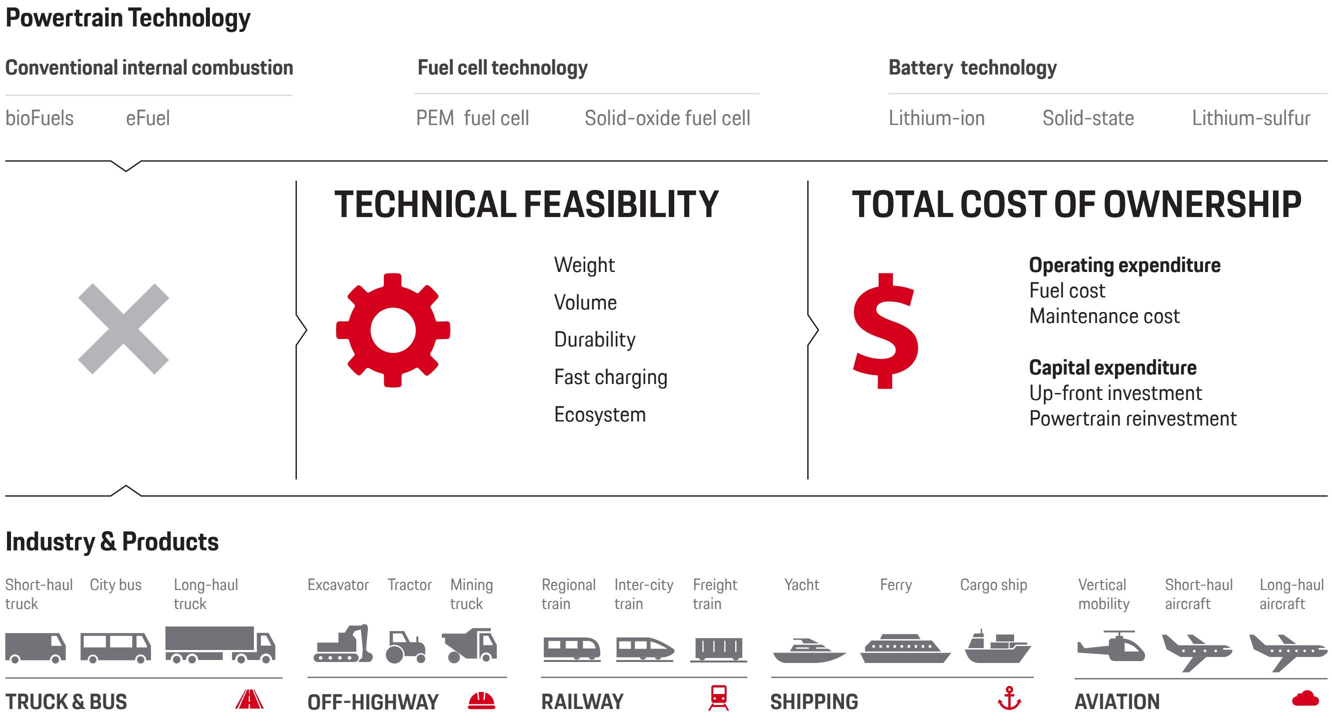


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Fig. 3. A two-step approach that considers technical and economic aspects is required for each product.

In the first stage of the analysis, a technical feasibility assessment is carried out to identify the feasible powertrain technologies for the product. Based on this, a total cost of ownership (TCO) for the specific technology alternative is calculated in the second stage of the analysis.

The technical feasibility assessment is conducted based on technical key performance indicators (KPIs) such as weight, volume, durability, and fast-charging capability of the powertrain system (e.g., batteries, fuel cells, engine, transmission, tank). To analyze the TCO, the most important purchase criterion in the analyzed industries, the capital (CAPEX) and the operating expenditures (OPEX) during the life cycle of a product are summed up. CAPEX is mainly determined by the purchase costs and includes not only the purchase price but also the investments for powertrain replacement over the lifetime. OPEX includes all costs that occur during the operation of the product. The latter are largely driven by fuel and maintenance costs.

With regard to technical feasibility, powertrain weight and volume are mainly determined by the power requirements of the product and the operating time between refueling of the use case. These two parameters drive the size of the battery, hydrogen storage, and fuel tanks of the respective powertrains. These vary significantly between industries and products, as shown in Figure 4. In this analysis, power requirements vary from 120 kW for small agricultural tractors to more than 50,000 kW for long-haul aircraft and cargo ships. Operating times can vary from 0.5 hours for vertical mobility applications to multiple days for large container ships.

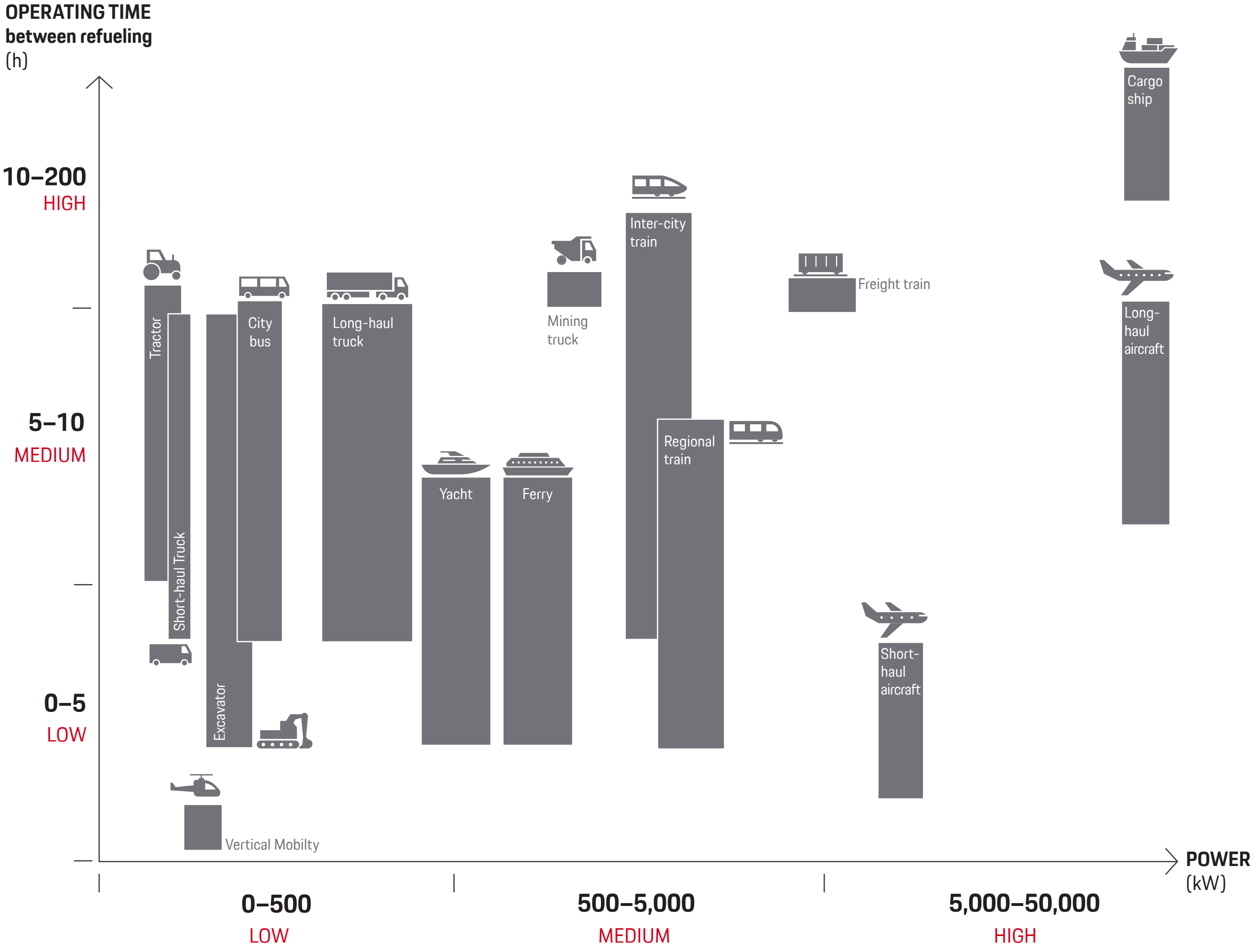

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Fig. 4. Use case requirements across industries vary significantly in terms of power and operating times between refueling.

Regarding total cost of ownership, the product-specific cost composition of OPEX and CAPEX is analyzed. For the 15 analyzed products using conventional powertrains, the cost share is shown in Figure 5. The TCO split varies significantly across all analyzed products. Particularly for land-based industries in truck & bus, off-highway equipment, and railway, OPEX dominates the TCO with a share of up to 90 percent. For ships and aircraft, in contrast, CAPEX has a significantly larger impact on TCO. It also becomes clear that for the previous example of cargo ships, a fourfold increase in the up-front investment may no longer allow for a viable business model.

Based on the outlined analysis, technical and economic requirements differ across industry, product, and use case. Hence, the requirements need to be analyzed in detail before their fulfillment by the different powertrain technologies can be assessed.

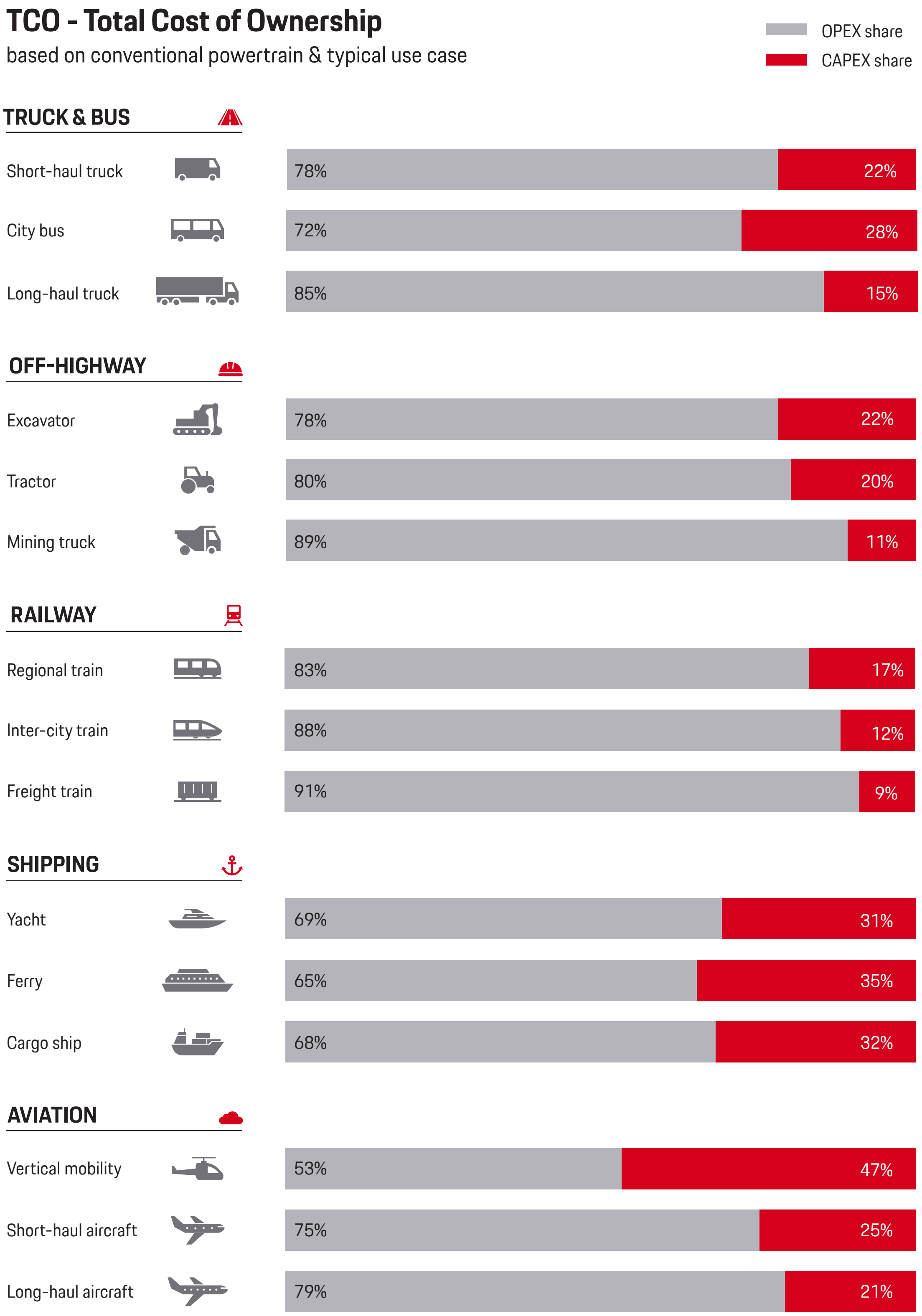

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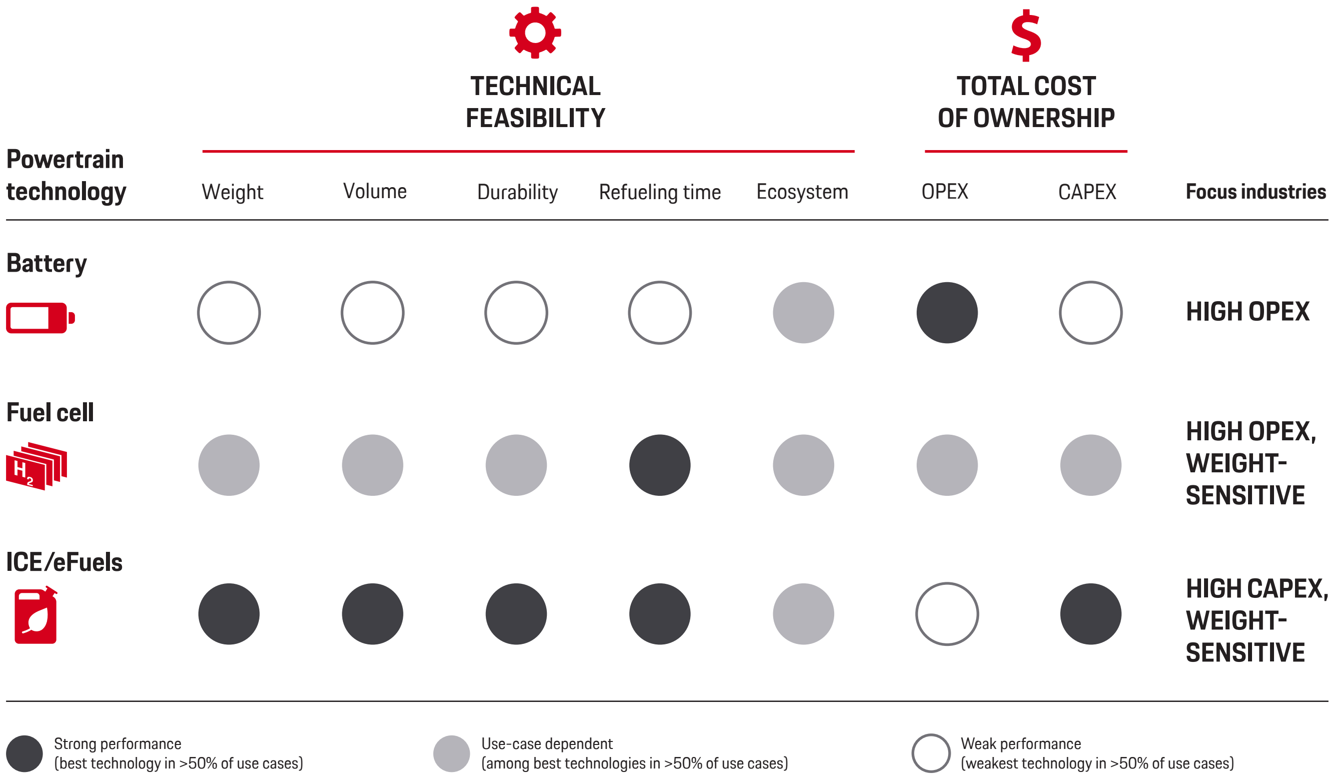
Fig. 5. Comparison of the total cost of ownership structure from truck & bus to aviation.

Each powertrain technology has its own up- and downsides

To provide an overall picture of strengths and weaknesses of the three analyzed technologies at the current state of technology, for each of the 15 products, two use cases have been defined based on upper and lower bounds of relevant parameters. The performance of the powertrain technologies has been compared in each of the resulting 30 use cases in the criteria weight, volume, durability, refueling time, ecosystem, OPEX, and CAPEX. The results are shown in Figure 6.



Powertrain technology	TECHNICAL FEASIBILITY					TOTAL COST OF OWNERSHIP		Focus industries
	Weight	Volume	Durability	Refueling time	Ecosystem	OPEX	CAPEX	
Battery	○	○	○	○	◍	●	○	**HIGH OPEX**
Fuel cell	◍	◍	◍	●	◍	◍	◍	**HIGH OPEX, WEIGHT-SENSITIVE**
ICE/eFuels	●	●	●	●	◍	○	●	**HIGH CAPEX, WEIGHT-SENSITIVE**

● Strong performance (best technology in >50% of use cases)
◍ Use-case dependent (among best technologies in >50% of use cases)
○ Weak performance (weakest technology in >50% of use cases)

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Fig. 6. Each powertrain technology has its specific advantages and matches different product requirements.

The evaluation shows that no technology is perfect, since none of the three technologies has a significant advantage in all criteria. Batteries have significant advantages when it comes to OPEX, due to their higher efficiency of 90 percent and lower maintenance cost (superior performance in all feasible use cases). Compared to batteries, fuel cells perform better in most use cases regarding weight, volume, durability, and CAPEX. For refueling time, they are superior (or equal in the case of ICE) across all use cases. The ICE powertrain with eFuels currently performs best in weight (superior performance in 20 use cases), volume, durability (superior performance in 17 use cases), and CAPEX (superior performance in all use cases). Even though the ICE performs better in weight, fuel cells have an OPEX advantage due to their higher energy efficiency (55 percent vs. 42 percent).

The result of the analysis shows that, at the current state of technology, batteries are most suitable for high OPEX application in use cases where weight plays a subordinate role. If weight is decisive, fuel cells or ICE powertrains with eFuels can be the right choice depending on the structure of the TCO. Therefore, a case-by-case evaluation of the product is required to determine the most suitable technology. Since the previous analysis was based on the current state of technology and technologies are expected to improve over time, this case-by-case evaluation needs to be future-oriented and consider a forecast of dynamic technological developments.

To take the dynamic development into account, relevant powertrain KPIs are forecasted on a chronological scale. Weight- and volume-based KPIs such as the pack-level energy density of batteries or the system-level power density of fuel cells determine weight and volume of the different powertrains, and hence, as in the case of long-haul trucks, the remaining weight and volume available for cargo. The durability such as the cycle life of batteries determines if a powertrain can last for the required product lifetime or if replacements are necessary. Powertrain and hence product CAPEX are affected by the pack- or system-level costs of batteries, the fuel cell and hydrogen storage, and ICE engine costs. Powertrain efficiencies determine the required amount of energy or fuel and thus largely affect product OPEX. The forecasting results of relevant KPIs of the different powertrains are provided in Figure 7.

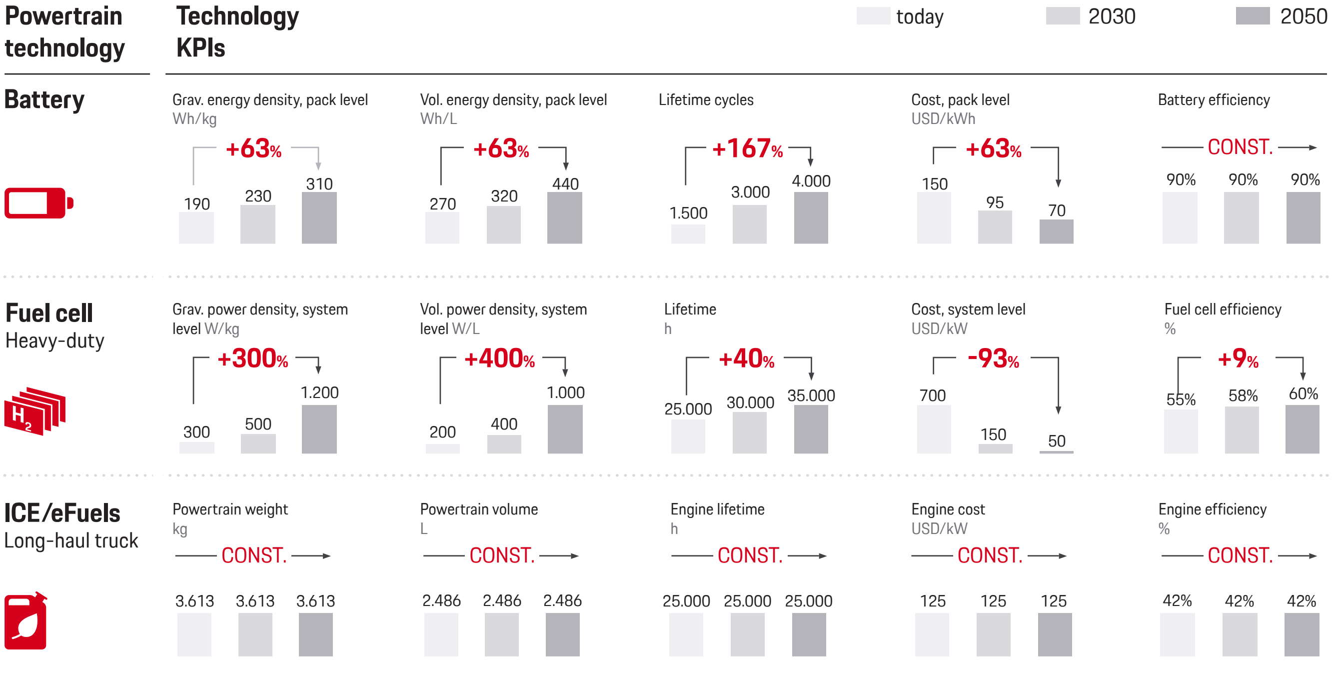

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Fig. 7. Dynamic R&D and upscaling will improve technology KPIs, influencing their technical and economic performance over time.

For batteries, significant technological potential exists on the process, system, and material level. For battery materials, development paths include an increase in the nickel content of cathode active materials to above 80 percent as well as an implementation of silicon-rich anodes. Both aspects contribute to a higher volumetric and gravimetric energy density as well as additional cost potential. Beside improvements on the material level, process innovations or concepts such as cell-to-pack can further improve performance and reduce cost.[36, 37]

For fuel cells, further improvements can be expected. Weight reductions and hence an optimization of the power density can be achieved by more compact components such as thinner membranes, an increased use of lightweight materials such as carbon fiber for bipolar plates, and a stronger integration of components. Cost reductions can be anticipated by leveraging economies of scale and pushing global production to above 100,000 systems per year; a further reduction of the platinum loading to below 0.1 g/kW; and by seizing cost advantages from global component production.

In contrast to the battery and fuel cell, combustion engine performance has been continuously improved over decades and therefore already reached a high maturity level. Here, no major technological optimizations are expected. With regard to eFuels, significant economic potential is connected to a reduction in production cost. These reductions are driven by upscaling, lower cost of renewables due to an optimized location, reductions in carbon capture cost, decreased capital cost of electrolyzers, and synergies with existing assets for oil refining.

Long-haul trucks as an example: Forecasting technology and tipping point

In this section, the case study of a long-haul truck is used to outline the dynamic analysis of both steps, the assessment of the technical feasibility, and the economic competitiveness of future powertrain technologies. The truck-trailer combination has a gross vehicle weight of 40 tons and has been specified to operate missions with an average trip distance of 1,000 kilometers. The analysis has been based on the model structure published in a recent study on long-haul transportation.[38]

The assessment of the technical feasibility considers relevant powertrain parameters (“powertrain KPIs”) that are affected by the powertrain technology used, such as weight, volume, durability, and fast charging or refueling. The benchmark of a conventional diesel powertrain is used to estimate the fulfillment of product and/or customer requirements. Figure 8 shows the assessment of the technical feasibility for a proton-exchange membrane (PEM) heavy-duty optimized fuel cell in a long-haul truck.

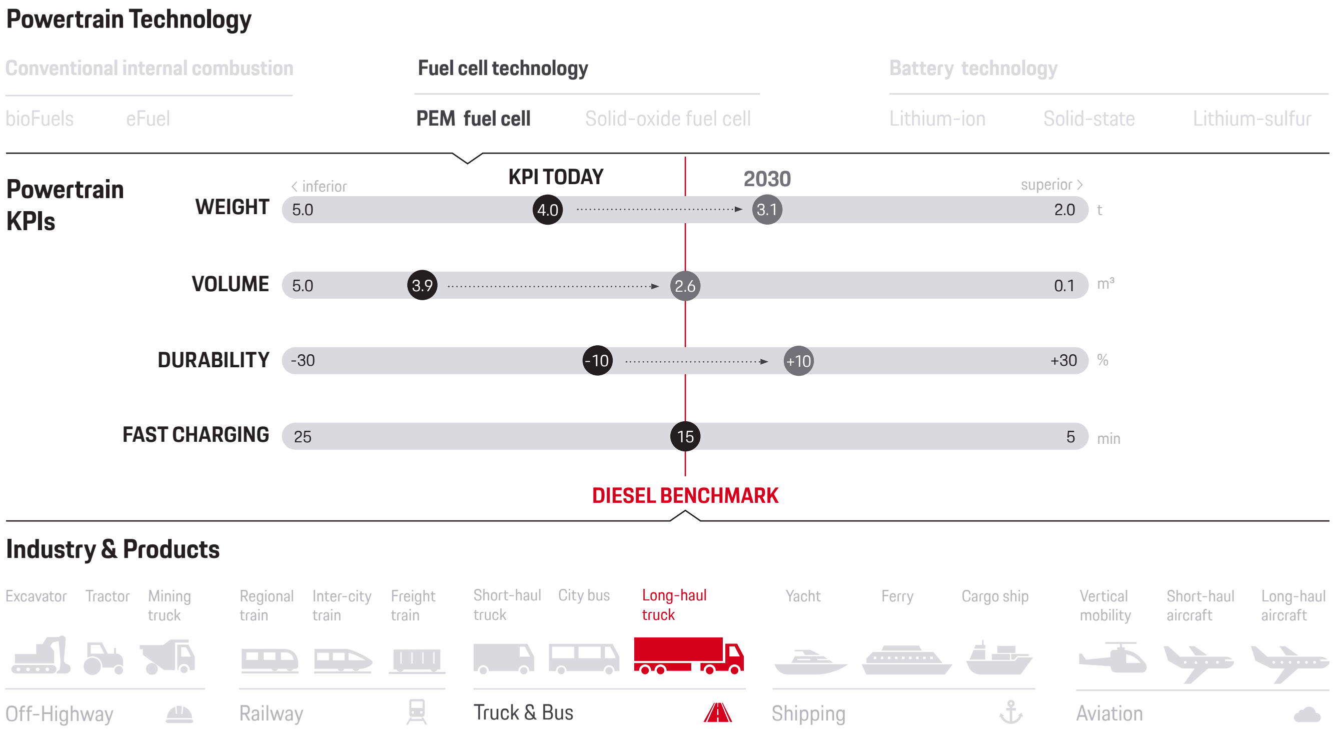

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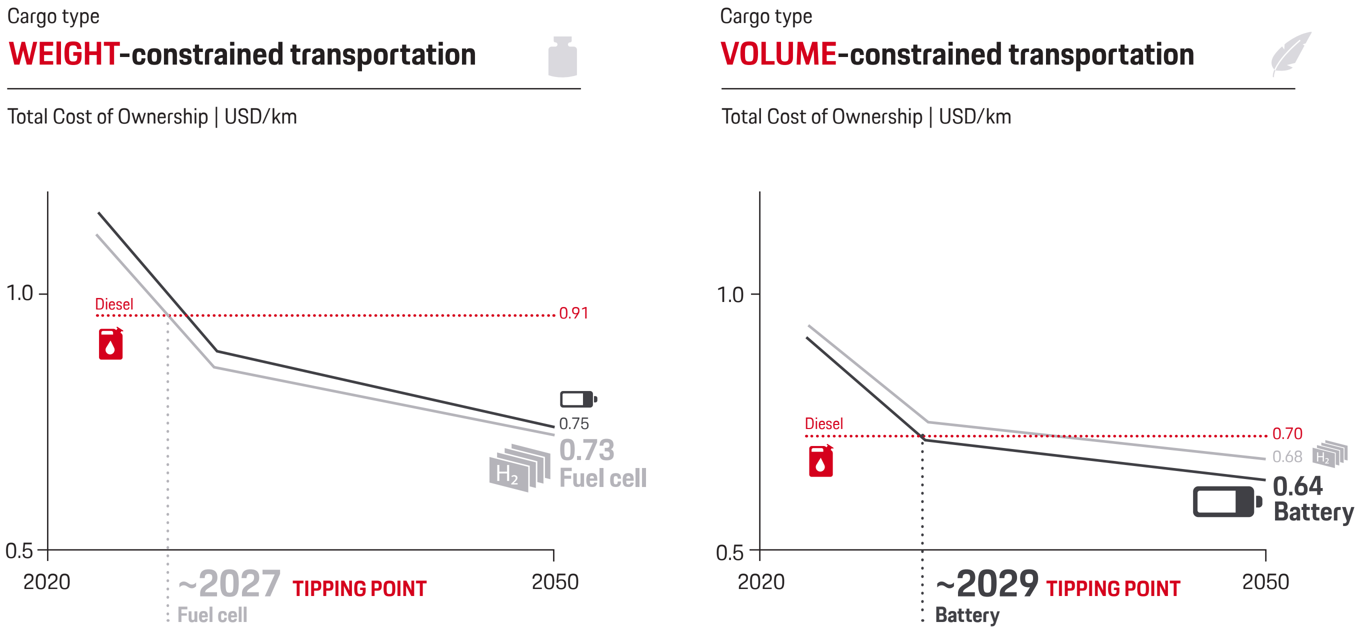
Fig. 8. Relevant technical parameters of a fuel cell powertrain in long-haul trucks will match those of a conventional diesel truck by 2030.

At the current technological level of the fuel cell powertrain, it has disadvantages compared to the incumbent diesel powertrain in most of the above-mentioned powertrain KPIs. It is about 0.5 tons heavier and 1.3 m^3 larger, mainly due to the large, heavy hydrogen storage (1.7 tons, 1.2 m^3) and the fuel cell system itself (1.2 tons, 1.8 m^3). Further, current heavy-duty optimized fuel cells do not fully achieve the durability of mature diesel engines. When considering the expected improvements by 2030 of the gravimetric and volumetric capacities of the hydrogen storage (resulting in a decreased weight of 1.3 tons and a volume of 0.8 m^3) and the power density of the fuel cell system (0.7 tons, 0.9 m^3), as well as improvements in the durability, the fuel cell powertrain can reach similar or better levels in each powertrain KPI. Thus, the technical parity of fuel cell to conventional powertrains in long-haul trucks can be assumed to be reached by 2030 based on the outlined criteria.

The assessment of the economic competitiveness of powertrain technologies considers all costs that are relevant to the decision-maker of the truck powertrain choice. All of them are aggregated to distance-based total cost of ownership (TCO in USD per kilometer) and include all types of OPEX such as fueling and maintenance costs, CAPEX for the upfront truck investment, and opportunity cost for cargo capacity deficits and forgone profits due to idle times during truck charging. Similar to the assessment of technical feasibility, the TCO of fuel cell and battery powertrains is compared to the benchmark of a diesel truck to determine economic tipping points. Figure 9 shows the expected development of TCO for the long-haul truck depending on the type of cargo transported. On the left-hand side, the use case of weight-constrained transportation is shown for cargo such as liquids or construction materials, as an example for a weight-sensitive industry where more powertrain weight means less profits. On the right side, the use case of volume-constrained transportation is shown for cargo such as parcels, where powertrain weight is less important. For this analysis, constant fuel prices have been assumed.



Constant prices for diesel (1.6 USD/l), hydrogen (10.0 USD/kg), and electricity (0.4 USD/kWh) assumed.
Source: Porsche Consulting TCO model, Mauler et. al (2022) "Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector."

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Fig. 9. Tipping points and competitive technologies vary by use case. Long-haul trucks with battery and fuel cell powertrains will be economical by 2030.

In both cases, the expected technological developments in fuel cells and batteries will allow truck TCO to fall over time and undercut the diesel benchmark of 0.91 USD/km and 0.70 USD/km by 2030. In weight-constrained transportation, where fuel cell trucks can outplay their weight advantage, the main drivers are the improvements of fuel cell system cost (-0.12 USD/km 2030 vs. today), weight improvement of hydrogen storage and fuel cell system (-0.10 USD/km), and less hydrogen consumption (-0.04 USD/km). For volume-constrained transportation, where battery trucks can show their OPEX advantage, the main drivers are reductions in battery cost (-0.10 USD/km) and less idle time through improved higher power charging (-0.09 USD/km).

Hence, technical and economic tipping points of new powertrain technologies in long-haul truck transportation will be reached by 2030 and a powertrain transformation in the sector is to be expected. In this low-margin industry, haulers that are anticipating this transformation in time can safeguard competitive advantages and improve their market position. Truck manufacturers need to define the right technology strategy to develop attractive products for their customers. To achieve this, understanding customer requirements and their use cases is key, since the right technology is a matter of application.

Each industry has its individual powertrain portfolio and transition speed

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Fig. 10. A scenario of the future powertrain portfolio in the European industries for truck & bus, off-highway, railway, shipping, and aviation.

Since each product and use case has its own technical and economical tipping point, forecasts can also be made on an industry and regional level. Using this methodology, the powertrain portfolio and the transition speed can be predicted for each industry. Figure 10 shows a scenario of the evolving future powertrain portfolio across industries in Europe.

In this scenario, for truck and bus, a growing fleet share of new powertrain technologies can be expected by 2025, starting with urban mobility. Until 2045, technical and economical tipping points in the medium- and longer-haul segments will drive the transition towards net zero. Key technologies include batteries based on high-nickel and lithium iron phosphate (LFP) chemistries, proton-exchange membrane (PEM) fuel cells powered by hydrogen, and to decarbonize the legacy fleet, eFuels or bioFuels.

For off-highway machinery, first movers whose customers particularly value sustainability are kicking off the use of bioFuels in the existing legacy fleet in 2030. Subsequently, small and mid-sized construction and agricultural machinery as well as large-size off-road machinery will reach their tipping points. In 2050, net zero ambitions can be achieved by high-nickel and LFP-based batteries, PEM fuel cells, and the use of eDiesel, bioDiesel, and bioEthanol in the legacy fleet and in particularly challenging use cases.

For trains on railways where an electrification by overhead power lines is not economical, in 2025, first movers are using bioDiesel in the first parts of the fleet. By 2050, the way to net zero will be paved by the subsequent decarbonization of rail-based plant and port equipment and of commuter and regional trains. Key technologies include LFP batteries, sodium-ion batteries, PEM fuel cells, and the use of bioDiesel and eDiesel in the existing legacy fleet.

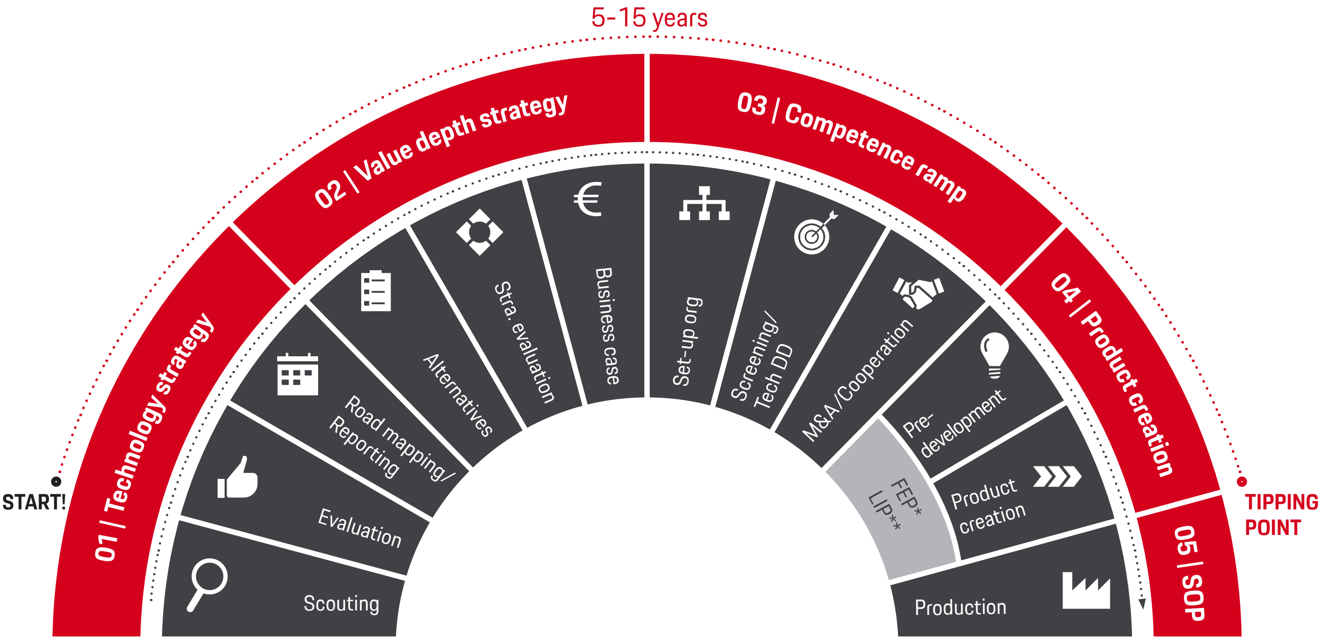
The first parts of the shipping industry will be decarbonized in 2025, starting with first movers and followed by cruise lines, ferries, and cargo ships. The latter will be supported by the establishment of green corridors: international shipping routes where the use of low-carbon fuels is supported by policy and infrastructure to allow for an early economical adoption. Even though more battery and PEM fuel cell use cases will become viable and a higher availability of green fuels at international ports can be expected, net zero cannot be achieved in that scenario in the considered time horizon.

In aviation, binding European targets for the use of SAF (sustainable aviation fuels, including eKerosene and bioKerosene) will already be in place starting from 2030. The ReFuelEU regulation requires an increasing use of SAF shares as aviation fuels, which are exceeded by the targets of multiple first movers. Despite evolving new segments such as vertical mobility, a growing availability of low-cost eFuels in Europe and the use of fuel cells and advanced battery concepts like lithium-sulfur or lithium-air, net zero will not be achieved in the considered scenario until 2050.

In the shown scenario, industries are moving at different speeds towards net zero. For truck & bus and railway (without power lines), the transition of first noteworthy parts of the European fleet will start by 2025 and will be transformed by 2045. Starting from 2030, the off-highway machinery, the shipping, and the aviation industry will set in but move at different speeds. While the off-highway equipment industry can reach net zero by 2050, the hard-to-abate sectors of shipping and aviation will remain below the net zero target.

Technology strategy: An integrated approach for the powertrain transformation

For companies to successfully prepare for these transformative changes, a five-phase process from technology strategy to product SOP, shown in Figure 11, is required. Depending on the technological complexity and product lead times, this process needs to be initiated up to 15 years before market entry in order to launch a competitive product with the right technology.



* Factory creation process | ** Supplier qualification

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Fig. 11. For companies to successfully transform, the right technologies have to be identified early in order to industrialize and commercialize attractive products on time.

During the technology strategy phase, technology scouting is conducted to monitor relevant technologies based on patent activities, market intelligence, and competitor moves. These technologies are then evaluated with regard to their technology readiness, technical performance and cost in the target products and use cases. Further, technologies are road mapped to allow for a future perspective on their development. This is achieved by developing data-driven forecasting models for critical technological parameters and validating the results by experts from industry and academia. Once a target technology has been identified, a value chain strategy is set up from material and component level to product integration. Strategic options to cover the value chain are developed, evaluated regarding risks and opportunities, and financially assessed by a business case. After a top management decision for the most attractive option is made, the competence ramp-up starts where required complements to the in-house organization are initiated and new competencies are acquired from outside the company. The latter is achieved by selecting a strategic partner or M&A target after an in-depth screening of relevant market players and a due diligence process to minimize technological and financial risks. In the product creation phase, the technology is integrated into the company's predevelopment activities and synchronized with the development process for specific target products. After successful validation of prototypes or samples, the technology is transferred to series production, where the focus shifts to managing the factory ramp-up and the stabilization of the defined supply chain. This five-phase process allows for a data-driven approach to identify and industrialize the technologies most suitable for a company's products. In each step, it is fully transparent regarding technological data, market data, and decision criteria.

In their ambitions towards net zero, companies face high technological and regulatory complexities that need the courage for transformative change that affects their entire organizations. Companies that are willing to take on that challenge can be guided in the development of their technology strategy, as outlined in this paper. This guidance is essential to satisfy and inspire customers and investors, to safeguard future competitiveness, and to successfully bring progressive and climate-friendly technology on the market — and these companies are needed for a successful combat against climate change.

IN BRIEF

01 All industries need to transform to net zero powertrain technologies due to stakeholder interests and improved technology performance.

02 For passenger vehicles, the battery is set to become the dominant net zero powertrain technology.

03 Battery powertrains are not suitable for all industries and use cases, due to technical and economic reasons.

04 Fuel cells and eFuels can be a more attractive powertrain, particularly for weight-sensitive and/or CAPEX-driven use cases.

05 To identify attractive powertrains, technical feasibility and total cost of ownership need to be forecast.

06 To secure market readiness, the technology strategy needs to be followed by a value chain, competence, development, and production strategy.

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Appendix

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