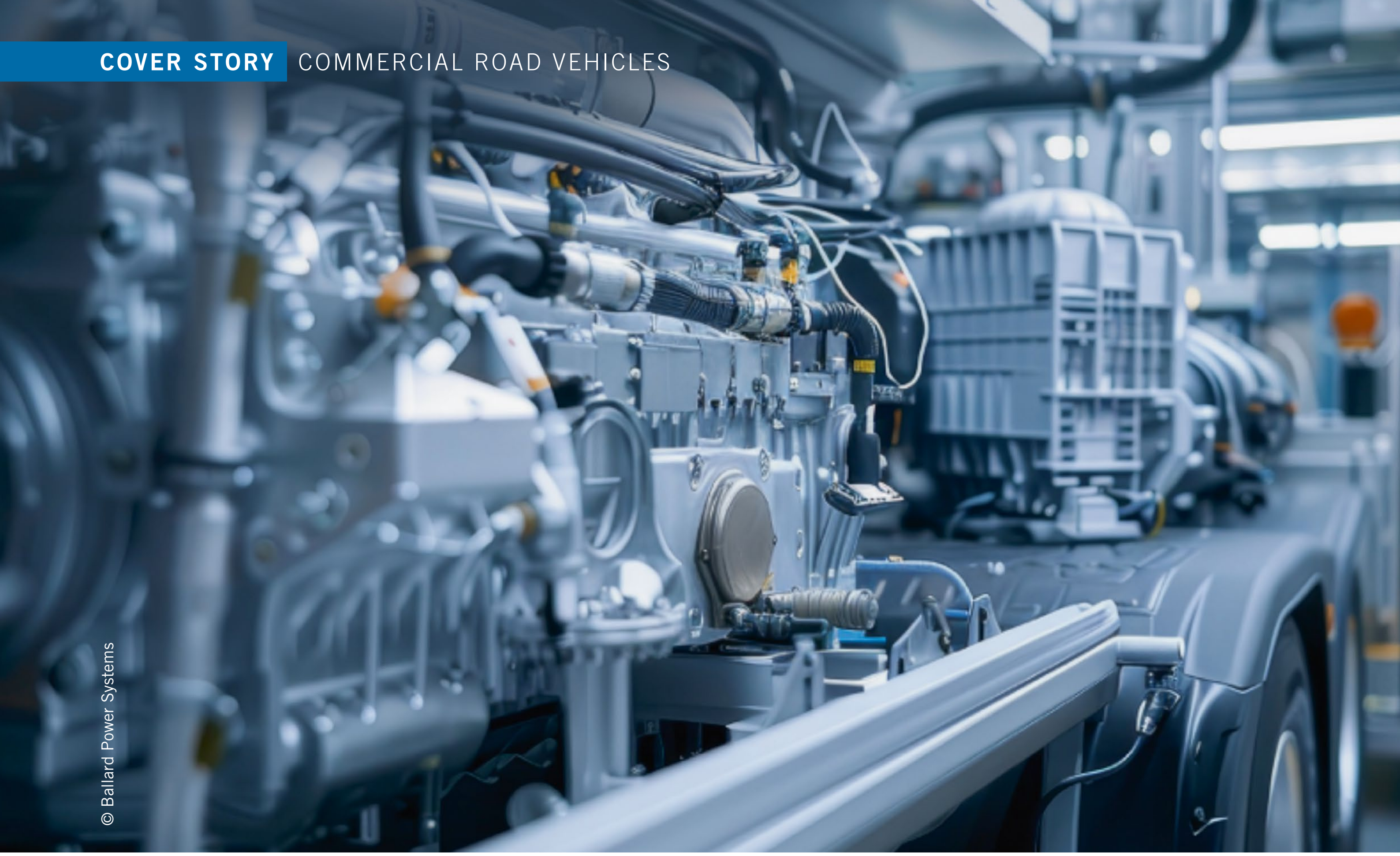
© Ballard Power Systems

WRITTEN BY

Julien Masson
is Business Development and Sales Manager at Ballard Power Systems in Lyon (France).

The transportation sector, particularly freight transport and logistics, remains one of the largest sources of global greenhouse gas emissions, and freight and logistics operators are under increasing pressure to transition to zero-emission technologies. Recent demonstrations and pilot fleets have already proven that Hydrogen (H_2) can successfully power a heavy-duty vehicle. The core question is whether hydrogen-based technologies can do so with acceptable efficiency, infrastructure demands, capital cost, and Total Cost of Ownership (TCO) in a sector that often operates on narrow margins. Hydrogen offers high gravimetric energy density and, when produced using renewable energy sources, provides a low-carbon alternative fuel that can be produced locally. Yet moving to deployment requires a full ecosystem: production, distribution, refueling infrastructure, and vehicle systems that can withstand demanding duty cycles.

There are essentially two technologies to consider – H_2 Internal Combustion Engines (H_2 ICEs) and H_2 Fuel Cell Engines (H_2 FCEs) – which differ in how the fuel is converted to power for the vehicle. While H_2 ICEs benefit from resembling the conventional combustion platform already used in diesel fleets, fuel cell engines are widely regarded as the more efficient and cleaner option. However, they may require greater changes to vehicle architecture and a higher upfront investment. Both solutions depend on a hydrogen supply chain, so the availability of low-carbon hydrogen and the pace of infrastructure build-out remain central to the debate. For operators of long-haul fleets, the TCO is ultimately the most important factor.

H_2 ICE CHARACTERISTICS

An H_2 ICE vehicle turns the chemical energy in hydrogen into kinetic energy. In practical terms, it resembles a conventional combustion engine, which has been refined for more than a century; its components are highly developed, and mass production has made them relatively inexpensive, with mature manufacturing value chains.

Hydrogen Drives for Long-haul Trucks – Internal Combustion Engine versus Fuel Cell

Long-haul freight transport is increasingly challenged to adopt zero-emission technologies. Hydrogen is considered a promising energy source for heavy-duty commercial vehicles. However, the question remains as to how it will be used: in an internal combustion engine or with fuel cells. Ballard Power Systems compares both propulsion systems from technical, economic, and operational perspectives.

But the H_2 ICE is not yet at the same maturity. Research and development continue to address fuel and air delivery, combustion, ignition, thermal management, lubricants, durability, emissions control, and materials that can tolerate both hydrogen and high temperature combustion [1]. An H_2 ICE also requires exhaust aftertreatment because it can produce NO_x and particulate matter, **FIGURE 1**. An H_2 ICE can be integrated into a conventional drivetrain with a transmission, drive shaft or shafts, rear differential, and axles.

FUEL CELL CHARACTERISTICS

Fuel cells convert the chemical energy in hydrogen directly into electricity, which then powers an electric drivetrain. A Fuel Cell Electric Vehicle (FCEV) resembles a Battery Electric Vehicle (BEV), but with a fuel cell engine, hydrogen storage, and enhanced cooling added, **FIGURE 2**. In that architecture, the fuel cell system reduces the number of battery packs required and therefore lowers associated weight. The applications considered here use Proton-exchange Membrane (PEM) fuel cell technology. A PEM fuel cell engine converts the chemical energy in hydrogen into electricity, which drives an electric motor.

The fuel cell and the battery both contribute to vehicle propulsion. Typically,

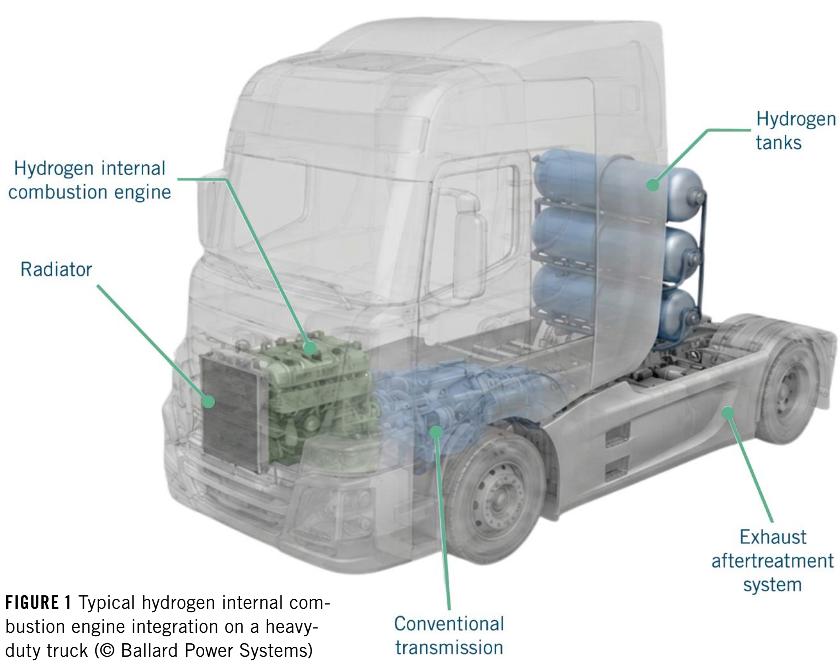

FIGURE 1 Typical hydrogen internal combustion engine integration on a heavy-duty truck (© Ballard Power Systems)

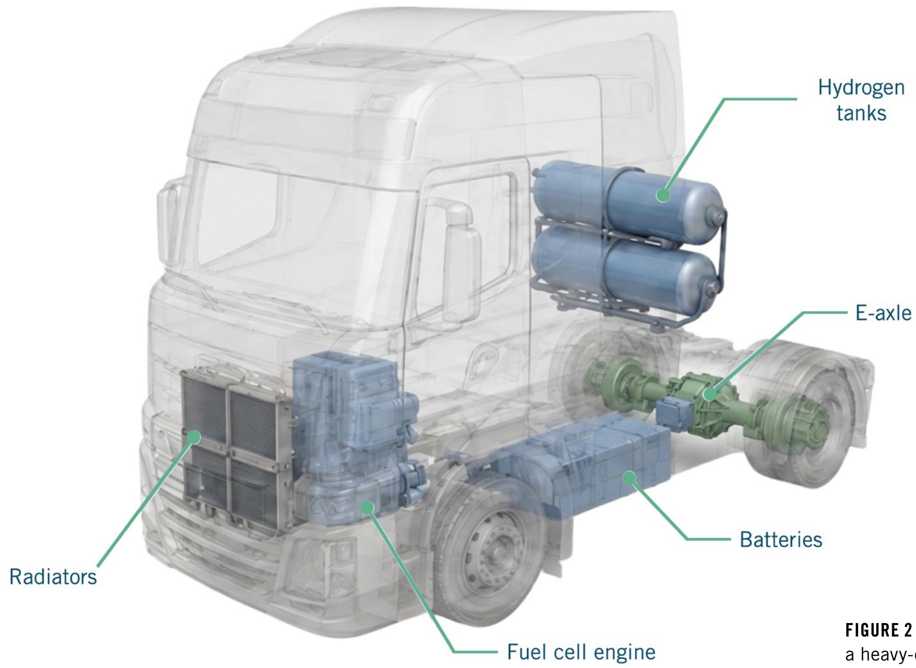

FIGURE 2 Typical hydrogen fuel cell integration on a heavy-duty truck (© Ballard Power Systems)

the fuel cell supplies the average power required for vehicle operation, while the batteries are used to provide the power needed for transients such as acceleration. The hybrid architecture with fuel cells is emission-free. Hydrogen-powered FCEVs are well suited to long-haul transportation, heavy payloads, and intensive duty cycles. They offer significant operational flexibility and can provide a near one-to-one replacement for diesel trucks.

TECHNOLOGY COMPARISON

Hydrogen combustion brings known technical issues. Hydrogen burns much faster and at higher temperatures than natural gas. In larger piston engines, this can create hot spots and force compromises in thermal management. Losses in power and torque may also require larger displacement. There are still open questions around durability and maintenance for H_2 ICE, including lubricant behavior, exhaust treatment under high water content, possible hydrogen embrittlement, and oxidation caused by water production. Several engineering challenges must still be faced before large-scale commercialization. The most immediate include pre-combustion control and injector lifetime, which remains limited today, **FIGURE 3**.

The two propulsion concepts differ significantly in terms of efficiency. In operation, fuel cell systems have typically demonstrated efficiency in the 48- to 58-% range. By contrast, H_2 ICE are constrained by the physics of converting chemical energy into mechanical motion, demonstrating efficiency in the 35- to 42-% range. Even with ongoing development, an FCEV will remain more efficient than an H_2 ICE vehicle, especially because an electric drivetrain can recover braking energy through regeneration.

Fuel efficiency directly determines fuel consumption. Actual efficiency and fuel use vary with vehicle type, duty cycle, and driver behavior, but the direction of travel is consistent: Fuel cell electric trucks are more efficient than H_2 ICE vehicles, and H_2 ICE trucks will always consume more hydrogen for the same duty cycle. Typical hydrogen consumption for a heavy-duty fuel cell truck (40 to 44 t) is about 8 to 10 kg per 100 km. As a reference point, a typical diesel heavy-duty truck consumes about 33 l per 100 km. If an H_2 ICE improved efficiency by 5 %, expected hydrogen demand would still fall in the range of roughly 10 to 12 kg per 100 km. To achieve the same range, H_2 ICE trucks require 10 to 20 % greater hydrogen storage capacity than fuel cell trucks due to the lower efficiency of the ICE technology. Looking ahead, this efficiency and consumption penalty will represent a major drawback relative to fuel cells, as TCO is the primary driver of decisions in the transportation segment. Current expectations are that H_2 ICE could be well-suited to retrofit programs and conditions where fuel efficiency and NO_x emissions are not the primary requirement such as agriculture and construction.

Overall, the fuel cell electric hybrid architecture offers true zero tailpipe emissions, a more efficient drivetrain, and lower fuel consumption, which reduces the amount of hydrogen storage required and extends range between refueling stops. In the push toward electrification, fuel cells are emerging as a key complementary solution to batteries in the heavy-duty trucking segment.

For traditional truck OEMs, H_2 ICE may offer a practical pathway to retain much of the existing combustion engine supply chain, building on years of investment while enabling continued use of their well-established ICE expertise without requiring a complete shift to a new technological ecosystem. Although this is seen as an interesting pathway, it remains uncertain how large the window of opportunity will be – and whether the technology will achieve widespread adoption or remain confined to niche applications.

In the long term, fuel cells are expected to offer a stronger value proposition than H_2 ICE technology when considering TCO, emissions, efficiency, and range. However, H_2 ICE could serve as an effective first step for OEMs to enter the hydrogen economy while infrastructure is being developed. In this regard, the H_2 ICE technology could be presented as an interim solution.

COMPARISON OF TOTAL COST OF OWNERSHIP

Fuel cell engines are currently more expensive than diesel engines, but costs continue to fall as designs mature, production volumes increase, and manufacturing scales up. The cost of H_2 ICE is not yet widely published, but it is likely to remain above diesel for the same reasons that natural gas engines have taken decades to approach cost competitiveness [2]. Hydrogen price remains the single most important factor affecting the viability of both technologies. As demand grows across industries and governments continue to support hydrogen deployment, prices are expected to fall in many markets.

TCO MODELING

Ballard's TCO model examines how the cost of using heavy-duty vehicles may decline over time and when parity with other drivetrain options can be reached.

FIGURE 3 Characteristics comparison between fuel cell engines and hydrogen internal combustion engines (TRL: Technology Readiness Level) (© Ballard Power Systems)

Comparison with Diesel ICE	Fuel Cell Engine (FCE)	Score	H_2 ICE	Score
Cooling	More radiators due to lower coolant temperature	Not as good	More heat to reject (lower efficiency) but same radiator	Equal to
Drivetrain	Few mechanical losses, higher performance (torque), less fluids, few moving parts, regenerative brake energy	Better than	No difference	Equal to
H_2 tank	Higher volume for same range	Not as good	Even higher volume for same range	Much worse
Engine	Few moving parts, no lubricants, similar power density, higher specific power	Better than	Combustion (Otto cycle), lubricants, moving parts, lower power density	Not as good
Efficiency	Higher efficiency	Better than	Equal efficiency	Equal to
Lubricants	Zero	Better than	No difference	Equal to
NO_x	Zero	Better than	Lower than diesel but aftertreatment required	Equal to
CO_2	Zero	Better than	Much lower	Better than
Particulate matter	Zero	Better than	Possible (from lubricants)	Equal to
Noise	Quieter for FCE	Better than	Noisier for H_2 ICE	Not as good
Maturity	TRL 8–9 – large fleet deployments	Not as good	TRL 6–7 – demonstration vehicles	Much worse
Cost	– Refer to cost comparison (below) –			

Legend, compared to diesel	Better than	Equal to	Not as good	Much worse

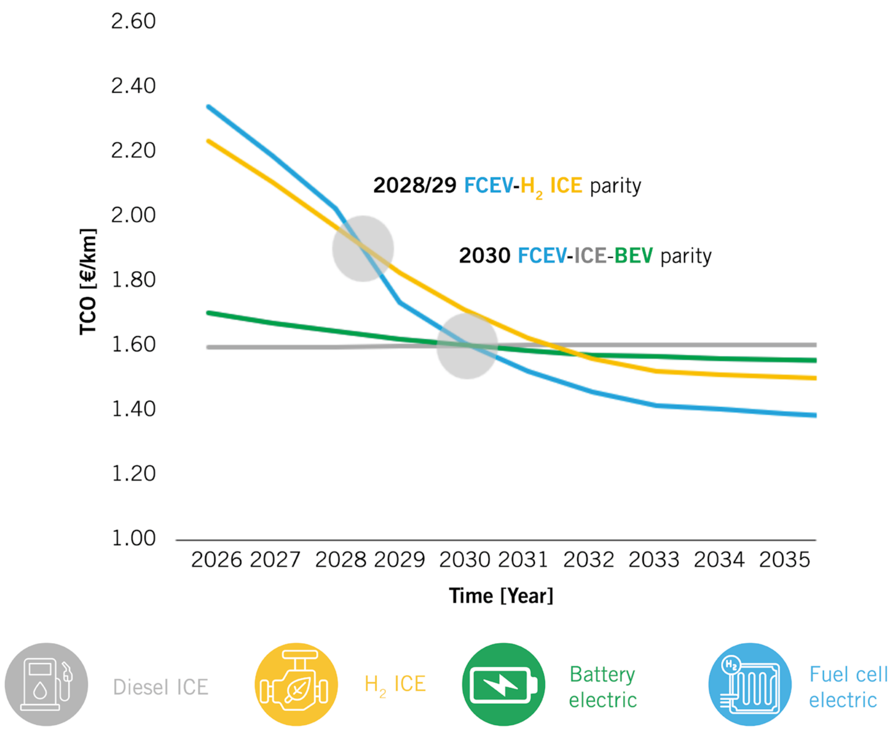

FIGURE 4 Outlook for Total Cost of Ownership (TCO) for long-haul trucks in Germany (© Ballard Power Systems)

An illustrative case study considers a fleet of 100 long-distance heavy-duty trucks operating 120,000 km per year in Germany. In this example, the fleet is assumed to use low-carbon hydrogen supplied through a third-party infrastructure.

The analysis reveals that energy cost is the largest contributor across all technologies, which highlights the importance of both lowering fuel cost and improving efficiency. For FCEVs, the next most significant factor is capital expenditure, particularly the fuel cell system and hydrogen tanks. Those costs are expected to drop significantly over time, with Ballard projecting a 70-% reduction in fuel cell engine cost, **FIGURE 4**.

For the example fleet, the model indicates that FCEVs can reach price parity with H_2 ICE vehicles by 2028/29, assuming an average H_2 ICE efficiency of 40 %. In this framework, the main drivers are fuel cell capital cost, fuel efficiency, and hydrogen pricing.

Based on the assumptions, FCEVs are expected to achieve cost parity with BEVs and diesel ICE vehicles by 2030. This will be primarily driven by lower hydrogen prices, contributing roughly two-thirds of the required TCO reduction, and by reductions in FCEV capital expenditures, accounting for the remaining one-third.

The conclusion from this scenario is that H_2 ICE has only a limited window of competitiveness in the long-haul heavy-duty market because it consumes more hydrogen and performs less efficiently than fuel cell technology. The model also does not add any penalty for current or future emissions charges on ICE-based technologies, which would matter even more for long-haul and urban operators.

CONCLUSION

Both technologies enable the use of hydrogen in heavy-duty road freight transport. H_2 ICE offers the advantage of technological familiarity and can make it easier for manufacturers to enter the hydrogen economy. But it still faces major questions about efficiency, environmental performance, maturity, and long-term economics. As emissions regulations become stricter, the cost and complexity of H_2 ICE are likely to rise. In contrast, FCEVs are simpler and contain fewer parts than any ICE. They are more expensive today, but scaling volumes, standardization, and manufacturing improvements should move them toward price parity and eventually below the cost of ICE platforms. Taken together, lower cost at scale, lower hydrogen consumption, lower weight, and zero tailpipe emissions make fuel cell engines the more credible path to true zero-emission heavy-duty fleets, especially in trucking where operating efficiency is critical. While H_2 ICE may serve as a transitional technology and retain advantages in certain niche, off-road, agricultural, or specialty applications, FCEVs appear better positioned to meet the performance, economic, and environmental requirements of large-scale zero-emission trucking.

REFERENCES

[1] U.S. Department of Energy (ed.): Hydrogen Production Technologies – 2023. Online: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/2023-amr-05-hydrogen-production-technologies.pdf, access: August 5, 2026

[2] Cummins (ed.): How natural gas engines lower total cost of ownership for commercial fleets. Online: https://www.cummins.com/news/2023/09/19/total-cost-using-natural-gas-engines, access: August 5, 2026