Total Cost of Ownership (TCO) Analysis for Heavy Duty Hydrogen Fueled Powertrains

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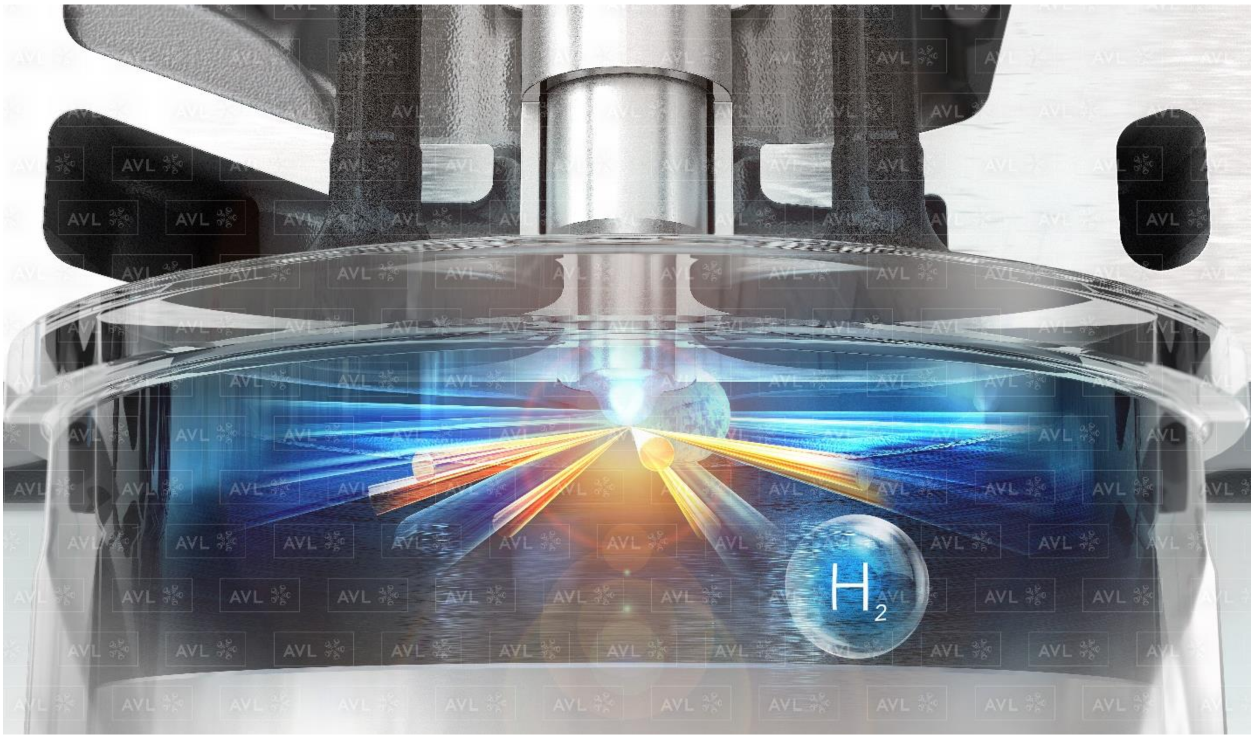

Executive Summary

- Modelling based analysis indicates H_2-HPDI has the potential to achieve fuel economy close to that of a FCEV for heavy duty applications, due to its high efficiency at both part and full loads.
- H_2-HPDI leverages a proven technology (Westport™ HPDI 2.0) and can be integrated into every heavy duty diesel engine platform, thus achieving scale quickly.
- The combined high efficiency and lower system costs relative to FCEVs, make H_2-HPDI the most capital efficient means to use hydrogen and lower CO_2 emissions near term and has the potential to remain competitive with fully industrialized FCEV in the future.
- With the short time to market and the competitive TCO, H_2-ICE will be an accelerant for H_2 infrastructure growth.

1. Motivation

In 2018 heavy duty vehicles exceeding 3,5 tons GVW were responsible for more than 240 million tons of CO_2 emissions in the European Union [i]. This mass of greenhouse gas emissions is representing roughly one quarter of all road transportation borne CO_2 emissions in the European Union [ii] and is mainly caused by four different vehicle classes; two long haul applications and two regional delivery applications. In order to significantly reduce the greenhouse gas emissions, the European Union has defined and released heavy duty CO_2 legislation with reduction targets of -15% in 2025 and -30% in 2030 compared to the baseline 2019/2020[iii].

In order to set the general baseline, CO_2 emissions in grams per ton-kilometer were collected between July 2019 and June 2020 across the different specified heavy duty vehicle classes [ivv].

Conventional measures to achieve the needed reductions are the obvious next step, however the total potential on CO_2 reduction seems to be limited. Next to efficiency improvements of the combustion engine and reduction of the drivetrain losses, total vehicle weight reduction and improvement of the aerodynamic drag also work out beneficially in the Vehicle Energy Consumption Calculation Tool (VECTO), which is the simulation tool used. Until 2025 the possibility to achieve the required 15% reduction seems possible for certain manufacturers with early introduction of fuel saving technology on the conventional diesel powertrain combined with a moderate number of zero-CO_2 trucks.

At the latest by 2030 the potential of conventional measures based on existing engine design/architecture may reach a point of diminishing returns and alternative approaches must be chosen to avoid costly penalty payments. The alternatives basically are either a significant change in engine design/architecture or utilization of alternative energy carriers. One example of an alternative energy carrier can be natural gas [vi], which based on the fuel properties (HC ratio) has a significant CO_2 emissions reduction potential of up to 23% (fossil fuel based) [vii]. Note: Biomethane has very high Well-to-Wheel (WTW) CO_2 emission reduction potential. High penetration rates and full usage of the potential of natural gas engines are one further step towards the 2030 targets but fully CO_2 neutral energy carriers have a significantly higher impact on the fleet-CO_2-footprint, even with very low market penetration, when considering Tank-to-Wheel (TTW) emissions.

Via the definition of zero-emission heavy duty vehicle [viii], basically two energy carriers are defined as zero-CO_2 in the European Union TTW legislation: Electricity and hydrogen (H_2). Battery electric trucks may well be a viable solution when it comes to well defined driving profiles with low absolute driving ranges or opportunity charging. In order to ensure the versatile operation of current heavy duty vehicles, loss of payload and long charging duration make battery electric solutions less attractive. The quick refilling rates of H_2 compared to the required charging duration of a BEV makes H_2 a much more appropriate energy carrier for such use cases.

While most discussions about H_2 imply the use of fuel cells, there is also the potential to use H_2 in the internal combustion engine (ICE). H_2 ICE's allow OEM's to leverage investments in production infrastructure and existing powertrain, while almost entirely eliminating CO_2 emissions. While the price of H_2 is expected to lower in the coming years, fuel efficiencies similar to fuel cells will be critical for H_2 ICE solutions to be accepted by the market.

This paper explores the combustion strategies available for heavy duty H_2 ICE's and recommends the best combustion approach to compare both the total cost of ownership (TCO) and cost of CO_2 avoided to Fuel Cell (FCEV).

2. Hydrogen Commercial Vehicle Combustion Principles (PFI, ECDI, HPDI)

Heavy duty vehicles have relied on compression ignition diesel engine technology for decades and while diesel engines remain the dominant choice in heavy duty applications, there is an increasing move to gaseous fueled engine technologies. Two distinctly different combustion technologies exist in Euro VI markets – low pressure pre-mixed spark ignition and high pressure direct injection. Taking this into consideration, we investigated three potential combustion approaches for H_2:

1. H_2-PFI SI (**P**ort **F**uel **I**njection with **S**park **I**gnition)
2. H_2-ECDI SI (**E**arly **C**ycle **D**irect **I**njection with **S**park **I**gnition)
3. H_2-HPDI (**H**igh **P**ressure **D**irect **I**njection with pilot ignition)

In the case of PFI SI, the H_2 fuel is injected into the intake port at low pressure with ignition provided by a spark plug to initiate combustion of an essentially homogeneous charge of H_2 and air. In the case of ECDI, the H_2 injection takes place after intake valve closure just when the compression stroke begins, and the ignition is provided by a spark plug to initiate combustion of a mostly pre-mixed charge of H_2 and air. HPDI relies on late cycle direct injection of H_2 at high pressure. An injection of a small quantity of pilot fuel (e.g.: diesel) precedes the injection of H_2 and acts as a source of ignition. The overall combustion cycle is like a typical diesel engine combustion cycle and preserves diesel-like torque and efficiency over the engine map. The HPDI system works with high pressure supply of H_2 (either stored as compressed or liquid H_2 on-board the vehicle). In case of compressed H_2 storage (e.g. at 700 bar), on-board compression is only required when the supply pressure of H_2 from the tank falls below the fuel injection pressure (~300 bar) with modest amount of parasitic power consumption to drive the compressor.

In the following table we have provided a pros/cons assessment of each of the three combustion strategies:

Combustion Mode	Pros	Cons	Comments
H_2-PFI SI	- Can utilize conventional low Pressure (<10 bar) gas injection fuel system - Robust and repeatable ignition of premixed H_2-air with a spark plug - Similar to existing SI natural gas engines	- Large displacement of intake air by low density H_2 and high propensity for knocking due to premixed H_2-air, limits maximum achievable torque - Substantial reduction in compression ratio (compared to diesel engines) has a large negative impact on thermal efficiency - Engine performance sensitive to environmental change (e.g. under very high ambient temperature conditions) -Risk of backfire	- Overall lower engine torque and efficiency compared to diesel - Can offer a near term solution by adapting existing fuel system and ignition system -Stoichiometric combustion with premixed H_2-air could be quite challenging due to combustion stability and backfire risk. Prefer lean burn combustion with EGR.
H_2-ECDI	- Does not displace intake air - Can modify/adapt conventional low-pressure gas injection fuel system for early cycle direct injection - Can achieve better overall torque compared to H_2-PFI combustion	- Premixed H_2-air limits maximum achievable torque due to potential for knocking and NO_x emissions - Reduction in compression ratio (compared to diesel engines) is required reducing thermal efficiency. - Higher wall heat transfer losses limit maximum thermal efficiency	- Can overcome some of the engine torque and efficiency limitations compared to H_2-PFI - Can offer a near term solution by adapting existing fuel system and ignition system -Stoichiometric combustion with premixed H_2-air could be quite challenging. Prefer lean burn combustion with EGR.

H_2-HPDI	- Can retain diesel engine compression ratio -Does not suffer from engine knocking as the H_2 and air are mixed towards the end of compression stroke just before ignition and combustion - Ability to achieve equal or higher torque compared to a diesel engine - Equal or improved engine efficiency compared to diesel or NG HPDI (See Figure 1). The achievable improvement is highest near full load. - Good combustion stability. Engine performance is less affected by environmental change compared to premixed engines.	- Requires high pressure H_2 injection (>200 bar) fuel system and increased parasitic loss - Requires very small quantity of pilot fuel for ignition	- Engine torque and efficiency equal or better than its gasoline or diesel counterpart - Relies on utilizing NG-HPDI technology that is commercially available and can offer near to long term solution. - Potential exists to utilize alternatives to fossil diesel fuel as pilot, e.g. synthetical diesel like fuels derived from renewable sources to mitigate well-to-wheel impact of pilot on CO_2 emissions.

Table 1: Comparison of Three H_2 Engine Combustion Technologies

There are other alternatives, such as RCCI (reactivity-controlled compression ignition) in addition to the above-mentioned combustion strategies that could be potentially investigated for use in a H_2 engine. Prior experience with other conventional fuels including natural gas, has shown that precise control of ignition and combustion over the entire engine map including high load conditions is quite challenging to achieve with RCCI combustion. Given the propensity of H_2 to ignite easily, the control of RCCI combustion becomes even more challenging. Hence for preliminary study at this stage, RCCI was not included in the present analysis.

3. H_2-HPDI Combustion Analysis and its Potential for Highest H_2-ICE Efficiency

For PFI SI and ECDI SI, a two-zone combustion model was used. It is a control volume based analytical engine model further developed from the original work of Catania et al [ix]. The original model was extended by adding predictive functions for flame propagation in premixed engines. HPDI combustion was simulated using a CFD model, the details for the combustion model can be found in a previous publication [x]. Figure 1 shows an example comparing indicated thermal efficiency between the three combustion approaches (PFI SI, ECDI SI and HPDI) as predicted from combustion modelling, for full load engine conditions. The indicated efficiency, as calculated from the combustion modelling, were relatively quite similar for part and full load operation.

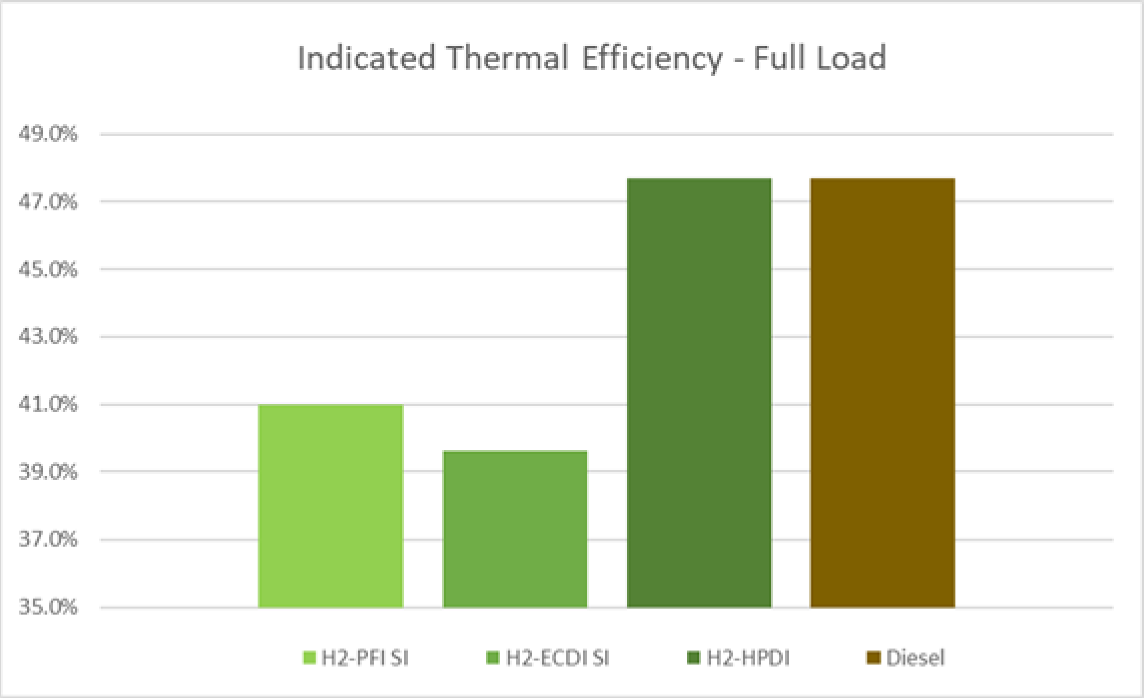

Figure 1: Comparison of Engine Indicated Efficiency with Three Different Combustion Approaches (PFI SI, ECDI SI and HPDI) for H_2 with a Diesel Reference under Full Load Operation

While ECDI SI shows higher IMEP potential than PFI SI, the combustion models predict no advantage in thermal efficiency. The higher mean charge velocity in ECDI increases the thermal loss due to higher wall heat transfer rate. The propensity of a premixed charge of H_2 and air to pre-ignite (engine knock) at high initial temperatures requires significantly lower compression ratio for operation over a wide range of operating conditions and thereby reduces overall engine efficiency. To minimize the difference in the indicated efficiencies between PFI SI and ECDI SI, dedicated combustion system layout for the ECDI SI would be required.

H_2-HPDI significantly outperforms the other combustion approaches in thermal efficiency. H_2 operation with the current HPDI fuel system outperforms natural gas in terms of thermal efficiency. This is mainly due to lower equivalence ratio for H_2 at given fueling energy level, higher kinetic energy for H_2 jets as well as higher tolerance of H_2 combustion to fuel rich operation. Overall, H_2-HPDI combustion offers the best performance in terms of efficiency, retained power density, and combustion robustness.

H_2 ICEs drastically reduce CO_2, HC and PM emissions, leaving NO_x as the most prominent tail pipe emission. For H_2-HPDI under identical operating conditions compared to a diesel engine it is expected that the NO_x emissions would be higher due to higher temperature combustion of H_2. The models indicate NO_x emissions can be managed with EGR and commercially available Urea-SCR NO_x exhaust aftertreatment technology. H_2 is a strong reducing agent and its potential use for exhaust aftertreatment will certainly be explored.

The H_2-HPDI engine, as modelled, eliminates over 98% of CO_2 emissions. There is a small quantity of CO_2 contributed by the combustion of the pilot fuel and the trace amounts contributed by the engine lubricating oil and by the SCR NO_x reagent (AdBlue).

As H_2-HPDI stands out in terms of thermal efficiency and managing the NO_x appears to be achievable, it will be the H_2 combustion strategy carried forward in the following financial modeling.

4. Total Cost of Ownership Comparison

The comparison of total-costs-of-ownership (TCO) was done for trucks with the following powertrains: (1) Conventional diesel powertrain with 12-speed automated manual transmissions and EURO VI compliant exhaust aftertreatment system, (2) H_2 fuel cell (PEM) trucks with 700bar H_2 storage and (3) H_2-HPDI trucks with same transmission and aftertreatment system as conventional diesel powertrain, 700 bar H_2 storage and a booster compressor.

The major boundaries for the investigations are:

1. Vehicle prices: Vehicle prices were calculated taking into account changes of major components and expected industrialization over time. Starting with 110.000 EUR for a conventional diesel truck, fuel cell trucks were varied from 2.6 to 3.4 times more expensive than diesel trucks (with e.g. fuel cell system prices including balance of performance of 500 to 750 EUR/kW) and 1.3 to 1.4 times for H_2-HPDI trucks (mainly due to H_2 storage tank)
2. For the energy consumption a typical highway operation in Germany was taken as reference. The energy consumption was simulated by AVL for different powertrain configurations, e.g. EURO VIb and EURO VId diesel powertrains, pressurized fuel cell systems w/ peak efficiencies of 60% and H_2-HPDI engine w/ the same efficiency as the diesel engines. In addition to the diesel and H_2 consumption, AdBlue consumption as well as pilot fuel were also considered
3. Prices for energy carriers were set to 1.5 EUR/l diesel, 6 EUR/kg $H_{2.}$ AdBlue price was set to 0,33 EUR/l.
4. The service and maintenance costs were varied as a function of the powertrain: Fuel cell trucks ~1/3 lower costs than conventional diesel trucks and H_2-HPDI trucks with slightly higher costs than the conventional diesel truck due to the additional efforts to service the compressor between the tank and the H_2-HPDI injectors
5. It is assumed that trucks are operated over a 5-year period with an annual mileage of 116.000 km, according to (EU) 2019/1242, Annex 1, Table 4 for 5LH category.
6. Driver costs were assumed w/ 60.000 EUR/year and kept the same for all truck variants
7. Residual value was set to zero for all trucks
8. No subsidies and/or road tolls and exemptions considered
9. Tire costs were considered w/ approx. 3,600 EUR each ~150,000 km

The various assumptions in view of initial truck prices and efficiencies can be used to reflect different (future) points in time. Figure 2 shows the results for the near-term view for the different powertrains, around year 2025. The following graphs are showing high and low cases for the H_2 powertrains caused by still existing uncertainty of prices and volumes. The lighter parts of the bars are representing the range in TCO from the range in assumptions stated above.

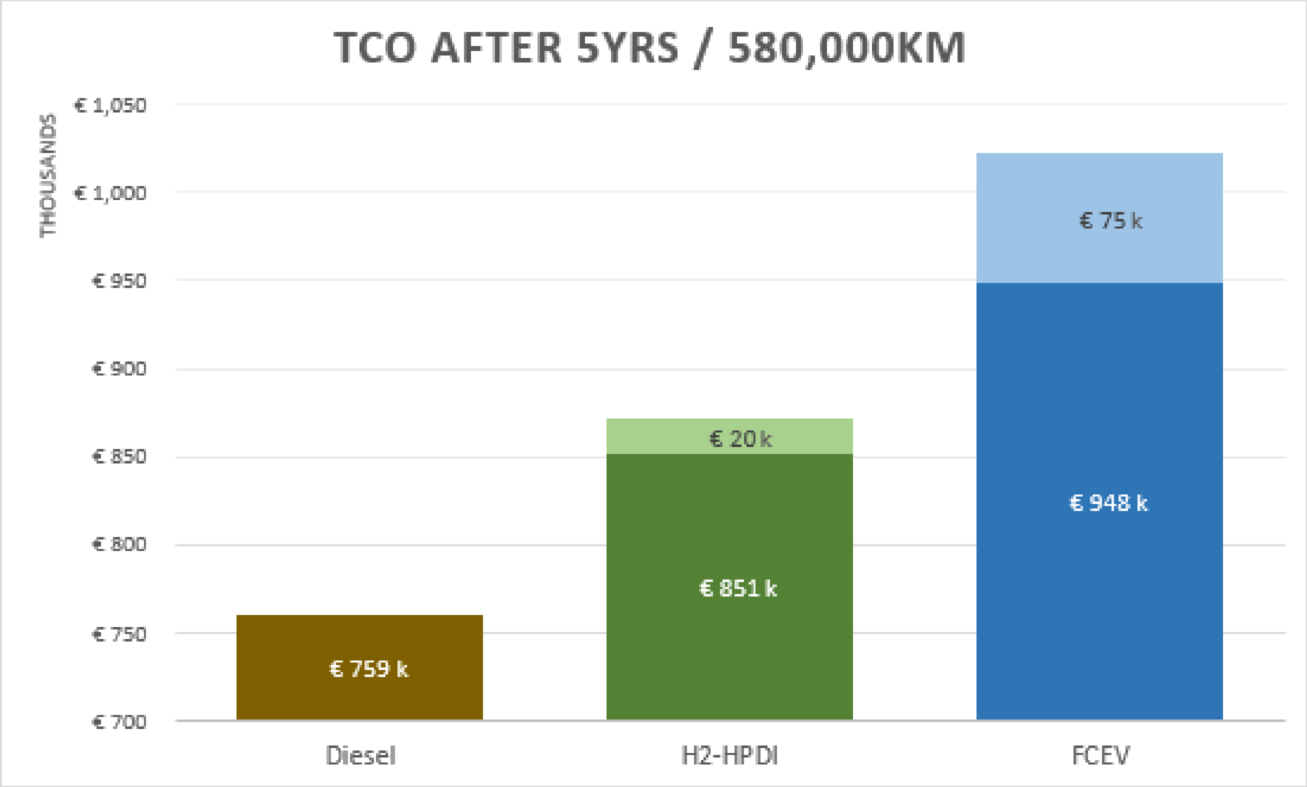

Figure 2: Total Cost of Ownership after 5 Years of Operation

Without considering road tolls, the diesel powertrain as reference is still the one with the lowest TCO, and the H_2-HPDI powertrain has the potential for lower TCO than FCEVs. The main reason for the H_2 HPDI advantage vs. FCEVs is that H_2 HPDI provides a sound balance between acquisition costs and operating expenses. As noted in the assumptions above, the acquisition cost for H_2 HPDI-powered trucks will be much closer to the price of current diesel trucks, since H_2 HPDI powertrains will leverage the existing, mature, and highly optimized supply chains for internal combustion engines, while also providing operating costs that are forecasted to be within approximately 8% of FCEVs in commercial vehicle applications with high load-factors.

In the near term, H_2-ICE and especially H_2-HPDI engines are a suitable solution for building up H_2 fueling infrastructure. In the mid-term, fully industrialized fuel cell powertrains (expected to be relevant beyond year 2030) are aiming for substantial reduction of the initial cost. H_2-HPDI solutions also show future potential to improve efficiency by raised injection pressure and with hybrid systems. With these measures, H_2-HPDI has the potential to have similar efficiency as future fuel cell powertrains. So, even in the long-term H_2-HPDI will remain very competitive in terms of TCO, with lower product development risk.

5. CO_2 Reduction Potential

The CO_2 reduction potential, from a tank-to-wheel perspective relative to diesel-powered trucks, is 100% for fuel-cell trucks. For H_2-HPDI solutions considering hydrocarbon pilot fuel consumption, lube oil and AdBlue, the CO_2 reduction potential is greater than 98%. For fleet operators with the objective to reduce transport-related CO_2 emissions, trucks with H_2-HPDI powertrains would certainly be an attractive option in terms of their CO_2 reduction potential, offering substantially higher CO_2 reduction than other measures like hybridization of diesel powertrains.

Another measure of CO_2 reduction is the cost per ton of CO_2 avoided. The values in Figure 3 reflect the TCO for the different powertrains (reference year 2025) divided by the amount of CO_2 "avoided" (tank-to-wheel, relative to diesel-powered trucks) over a 5-year period. Due to the high absolute CO_2 reduction of H_2-HPDI and the moderate increase of TCO compared to diesel powertrains, H_2-HPDI trucks show the lowest costs per ton of CO_2 avoided.

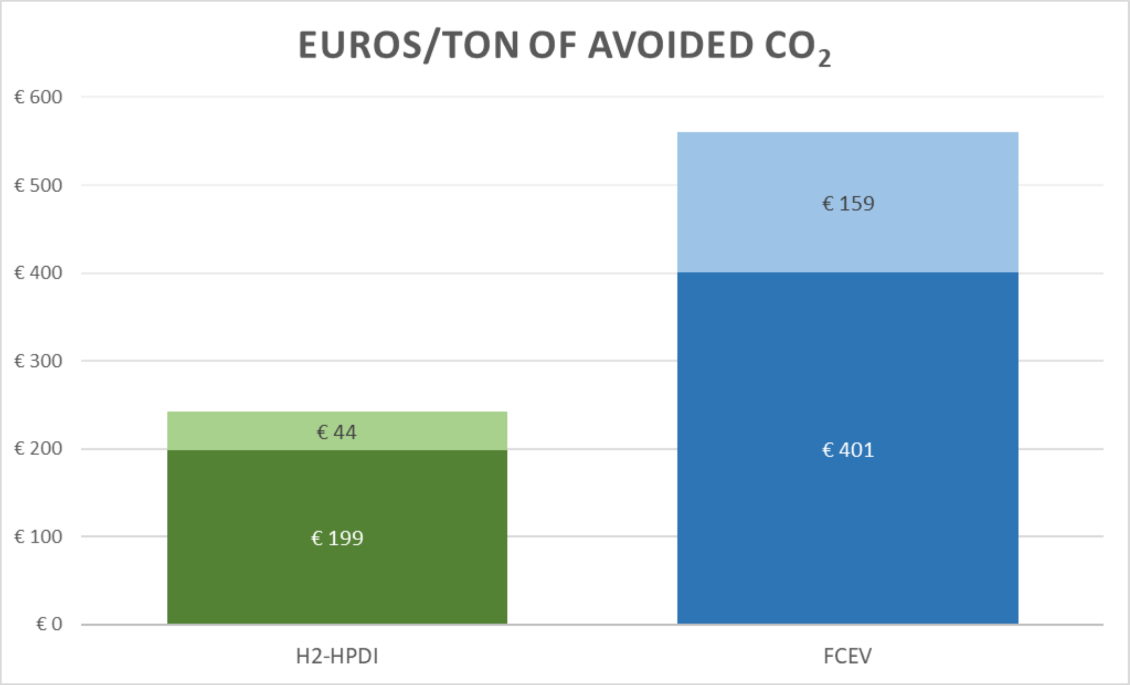

Figure 3: Costs per Ton CO_2 Avoided (Reference: Conventional Diesel Truck)

6. Summary and Outlook

Our analysis shows a high efficiency H_2 ICE powertrain (namely H_2-HPDI) can outperform FCEV's in terms of TCO, especially in the near term (2025). While we expect that FCEVs will become significantly more cost effective over time, we also expect further improvements in the TCO of H_2 HPDI-powered trucks through complementary technologies such as hybridization. In terms of acquisition cost, H_2-HPDI leverages a proven technology, currently in production, which can be integrated into every OEM's diesel engine platform. In terms of operating costs, H_2-HPDI's high efficiency at part and full loads reduces FCEV's fuel economy advantage to only 8%, for the route modelled. In the near term, the low TCO positions H_2-HPDI to be the most capital efficient means to use H_2 and lower CO_2 emissions from heavy duty applications. In the midterm, the FCEV costs and thus TCO penalty will decrease as FCEVs achieve scale. H_2-HPDI technology can help pave the way for H_2 infrastructure expansion, which is beneficial for the growth of FCEV's as well, since they will share the same fuel storage solutions.

For governments promoting the use of H_2 as a zero-CO_2 solution for heavy duty transportation, H_2-HPDI should be a very attractive solution. H_2-HPDI reduces the subsidies needed to encourage the build out of H_2 infrastructure, while accelerating the reduction of CO_2 and pollutant emissions in the transport sector. H_2 fuel providers will need a stable consumer to match fuel supply against and will benefit from significantly higher volumes with H_2-HPDI vehicles on the road.

Currently, for H_2-ICE's to qualify as zero-CO_2 emissions solutions in Europe, they must not produce more than 1g CO_2/kWh. H_2-HPDI, using a hydrocarbon pilot fuel, will be slightly above this criterion but can deliver large CO_2 reductions economically in the near term. In the future it is possible to transition H_2-HPDI to a carbon free ignition approach through technology development and meet the 1 g CO_2/kWh threshold.

In order for any H_2 ICE to be successful, it will need to meet future pollutant emission levels. H_2-HPDI has suitable technical characteristics to meet these challenging goals and has the potential to accelerate adoption of H_2 in the heavy duty sector.

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