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Performance metrics for refuelling protocols for heavy duty hydrogen vehicles

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R E P O R T

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Acronyms and Abbreviations

CHSS	Compressed hydrogen storage system
FC	Fuel Cell
FCV	Fuel cell vehicle
GHG	Greenhouse gas
GT	Gas turbine
H_2	Hydrogen
HDV	Heavy duty vehicle
LDV	Light duty vehicle
LH_2,	Liquid hydrogen
NH_3	Ammonia
SoC	State-of-Charge
TCO	Total Cost of Ownership

EXECUTIVE SUMMARY

This document aims at defining performance metrics for heavy duty vehicle refuelling protocols as a benchmark for this project, that would allow hydrogen fuel cell vehicle refuelling to compete with current diesel technology in terms of technical performance. Achieving good performances for liquid fuels refuelling is generally not as constraining as for gaseous fuels with respect to technical and cost challenges. Thus, diesel vehicles often have fuelling performances greater than real usage need, which is hardly affordable for hydrogen technologies nowadays. The real specific use cases may have a significant impact on the exact details for each performance requirements. The following table summarizes the identified relevant generic use cases and estimates associated refuelling performance metrics as a benchmark for hydrogen refuelling, which are necessary to compete with fossil fuel refuelling.

For the most relevant HDV segment, e.g. N3 tractor trailer vehicles in long haul use and M3 coaches, this report specifies a performance metric of 80 kg of hydrogen to be filled in 10 min to be competetive to diesel vehicle. For M2 and N2 vehicles and smaller N3 vehicles with less range requirements, it is estimated that 10-40 kg of hydrogen could be refilled in 5-8 min to be competitive.

Table 1: Generic use cases and estimations for associated refuelling performance metrics as a benchmark for hydrogen refuelling

Vehicle segment	Compressed hydrogen storage system (CHSS) capacity [kg]	Fuelling time [min]	Corresponding max. anticipated average H_2 flow [kg/min]
N1 commercial vehicle (included for comparative purposes)	2-10	3-5	2
N2 commercial vehicle	10-40	10	4
N3 commercial vehicle	40-80	10	8
M2 passenger carrier	10-40	8	5
M3 passenger carrier	30-100	12	8
Train, low case	150	10	15
Train, high case	500	15	33[1]
Inland ship, bulk carrier	4,500	60	75[2]
Inland ship, push barge	900	60	15
Inland ship, day cruise	300	30	10
Inland ship, river cruise	20,000	120	167[2]
Transport system, low	300	30	10
Transport system, high	1,500	60	25

Note: SOC should approach as much as possible 100%

[1] It is likely that such a system would have at least two independent tank systems. Accordingly, half the flowrate can be assumed.

[2] It is currently unsure whether these applications are feasible to refuel with gaseous hydrogen in their current operational scheme. It is well possible that options can be found to shorten the distances between fills or switch to alternative modes of supplying molecules, such as swappable containers, liquid hydrogen (LH_2), ammonia (NH_3) or other alternatives.

1 INTRODUCTION

The urgent need to reduce greenhouse gas (GHG) emissions to combat climate change applying more energy efficient technologies and reducing the dependency on non-sustainable energy sources is internationally recognized. During the United Nations Climate Changes Conference (COP21) in Paris, the European countries committed to reach a 27% increase in renewable energy, a 27% increase in energy efficiency, and a 40% decrease in GHG emissions until 2030. A drastic reduction in GHG emissions in the transport sector is a key element to fulfil these ambitious commitments. While zero emission technologies are reaching mass market in the passenger cars sector, a transition of heavy duty vehicles (HDVs) to zero emission is highly challenging.

Hydrogen fuel cell vehicles (FCVs) are an attractive technology for zero emission medium and heavy duty vehicles as it offers fast refuelling and high gravimetric storage density, and allows long distance transportation and intensive utilization.

Hydrogen for transport is currently undergoing an accelerated market expansion from primary use in light duty vehicles (LDVs) to the application in heavy duty vehicles (HDVs). This imposes two overall challenges regarding technical capability of fuelling equipment and the commercial fossil parity targets to be reached.

This document identifies performance metrics for heavy duty vehicle refuelling protocols that could be considered as a benchmark to allow Hydrogen FCVs to compete with current diesel technology. Achieving good performances for liquid fuels is generally not as constraining as for gaseous fuels in terms of technical and cost challenges. Thus, diesel vehicles often have fuelling performances greater than the actual application need which is hardly affordable for hydrogen technologies nowadays. Accordingly, it is assumed that some performance criteria can be adjusted to specific usage needs. Based on this statement, performance requirements for hydrogen vehicle could be determined for specific vehicle applications and usages.

2 FOSSIL PARITY REQUIREMENTS

Fossil parity is important for the market adaptation of hydrogen technologies. When an application offers the same or better cost performance characteristics than its fossil equivalent, market pull will be out of doubt and the adaptation of the technology is likely to not require additional support. In the early phase, subsidies can help achieve fossil parity, however, a well-designed system will work out for a case without subsidies. Therefore it is important to understand where these break-even points lie.

The four main performance criteria that determine the fossil parity are:

- costs;
- range;
- time to refuel;
- Final state of charge (SoC).

For each use case, these parameters determine whether the usage needs to be adapted when diesel technology is replaced with hydrogen technology or if it can be kept identical (which facilitate technology adoption).

3 SELECTED USE CASES AND ASSOCIATED TECHNICAL TARGETS

Performance requirements for heavy duty hydrogen vehicles can vary from one specific vehicle applications and usage to another. For example, current deployment projects and applications with commercial potential in a low to zero emission context could cover long haul tractor for freight, garbage trucks, city buses, coaches, regional passenger trains, mainline locomotives, inland shipping, and others. The following part presents different vehicle categories and an estimation of appropriate technical performance that should allow hydrogen to compete with fossil fuel.

3.1 Heavy duty road vehicles

3.1.1 Definition, categories and split in the European fleet

The definition of what is classified as heavy duty is highly divers in different parts of the world, however typically the definition is based on the weight of the vehicle and it's intended application or use case.

In Europe, for instance, when it comes to heavy duty road vehicles this question is answered succinctly by the following memo on the European Commission's strategy for reducing heavy duty vehicles' (HDVs) fuel consumption and CO_2 emissions, prepared in the lead up to the Regulation (EU) 2019/1242[3]:

> *What are Heavy-Duty Vehicles?*
>
> *HDVs comprise trucks, buses and coaches. HDVs are defined as freight vehicles of more than 3.5 tonnes (trucks) or passenger transport vehicles of more than 8 seats (buses and coaches). The HDV fleet is very heterogeneous, with vehicles that have different uses and drive cycles. Even trucks are segmented into several categories, including long-haul, regional delivery, urban delivery and construction.*[4]

Further details on the definitions of type-approved vehicles used in Europe can be found in the Directive 2007/46/EC[5] - for instance, the extract below from Annex II - Definition of vehicle categories and vehicle types:

> *Category M: Motor vehicles with at least four wheels designed and constructed for the carriage of passengers:*
>
> - *Category M_1: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat.*

[3] Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO_2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC.

[4] https://ec.europa.eu/commission/presscorner/detail/en/MEMO_14_366

[5] Directive 2007/46/EC of the European Parliament and of the Council of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles.

- *Category M_2: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes.*
- *Category M_3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes.*

Category N: Motor vehicles with at least four wheels designed and constructed for the carriage of goods.

- *Category N1: Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes.*
- *Category N2: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes.*
- *Category N3: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes.*

As a note, the term "medium duty" is also used to describe vehicles – whilst this doesn't appear to have a legal definition in EU terms, it is a term that seems to be relevant in the US, referring to truck Classes 3-6, which can have a gross vehicle weight rating range of 10,001- 26,000 lbs[6].

It can be seen above that commercial vehicles are classed in different European type classes (see also Figure 1).[7] From light to heavy, these are N1, N2 and N3 on the goods transportation sector and M2 and M3 on the passengers transportation sector. N1 are light commercial vehicles with a maximum gross weight of up to 3.5 t, whereas N2 covers a very wide range from 3.5 t to 12 t and N3 covers the range over 12 t for both fixed chassis and tractor trailer configurations. On the passenger vehicles' side, M2 covers multi-person carriers up to 5 t and M3 covers city buses and coaches with a gross wight above 5 t.

[6] https://afdc.energy.gov/data/10380)

[7] see e.g. Shell Commercial Vehicle Study, 2016. Available online: https://www.shell.de/promos/media/shell-commercial-vehicle-study/_jcr_content.stream/1467266241228/f5663d60116687f4a72bec0890878f9fc8caa4cf/shell-commercial-vehicle-study-english.pdf

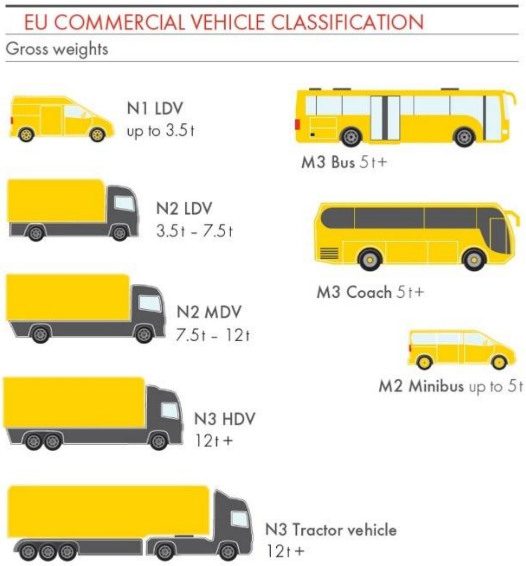

Figure 1: **EU commercial vehicle classification**

Source: Shell commercial vehicle study, 2016.

While N1 commercial vehicles make up the vast majority of the numbers of the vehicles in Germany, N3 vehicles only amounted to 13% of the vehicles registered in 2016 (see Figure 2).

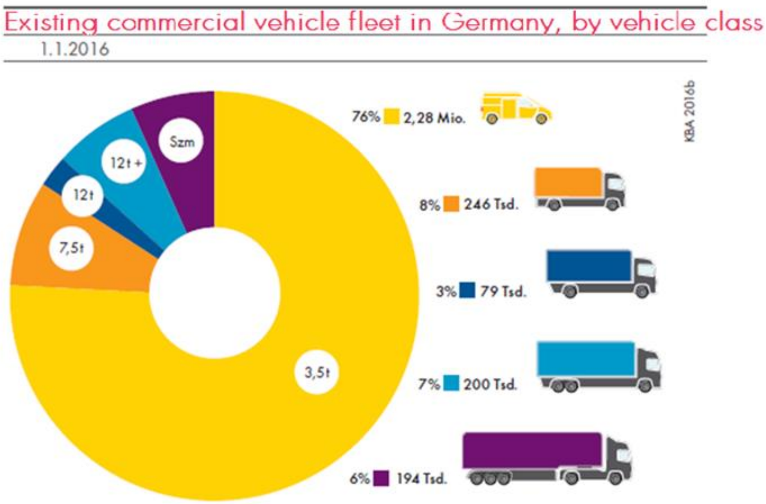

Figure 2: **Split of commercial vehicles according to weight class, as of 1.1.2016**

Source: Shell commercial vehicle study, 2016.

According to the Shell Commercial Vehicle Study from 2016, N3 vehicles were on average the youngest in the German fleet, as shown in Figure 3, indicating a relatively short turnover time.

The vast majority of HDVs are currently powered by diesel engines, especially in the N3 class (see Figure 4). For vehicle in the M3 category, the situation is similar: here only a small part of buses is powered by other fuels than diesel (see Figure 5).

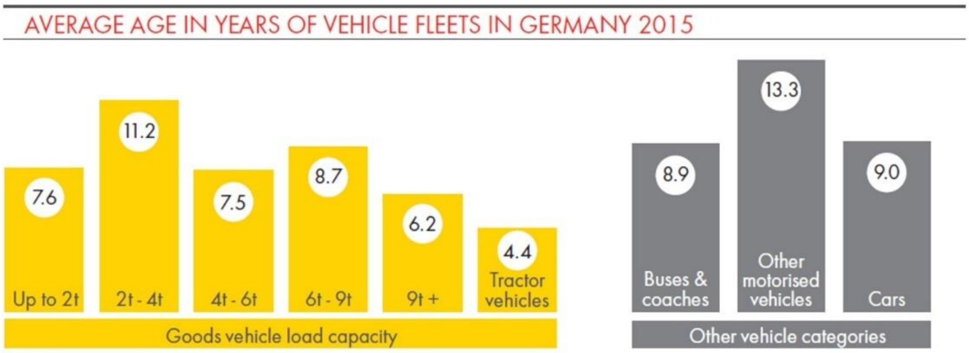

Figure 3: **Average age of commercial vehicles based on transportable weight, as of 1.1.2015.**

Source: Shell commercial vehicle study, 2016.

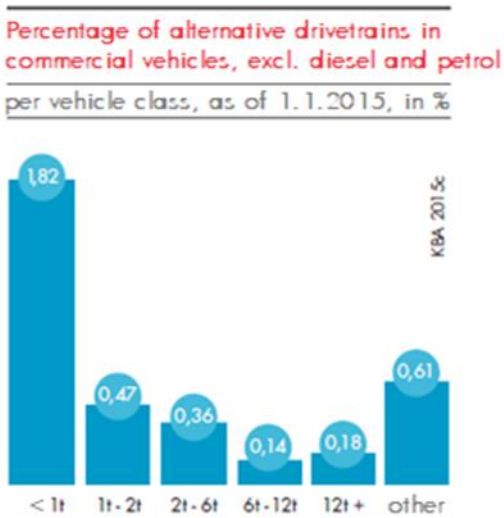

Figure 4: **Percentage of non-diesel and non-petrol drivetrains in commercial vehicles in Germany, as of 1.1.2015.**

Source: Shell commercial vehicle study, 2016.

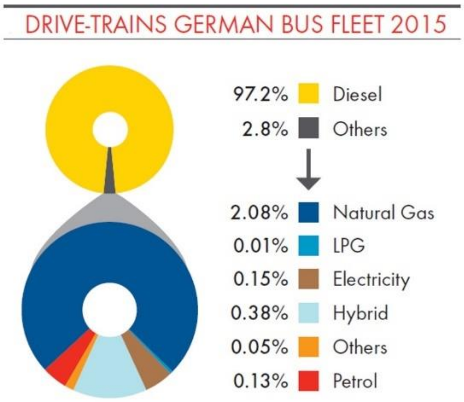

Figure 5: Split of drivetrains in the bus fleet in Germany, as of 1.1.2015.

Source: Shell commercial vehicle study, 2016

3.1.2 Performance target

A large part of the total cost of ownership (TCO) of a HDV is fuel, as shown in Figure 6, with a share of about 32% of the TCO operating a diesel truck in the EU:

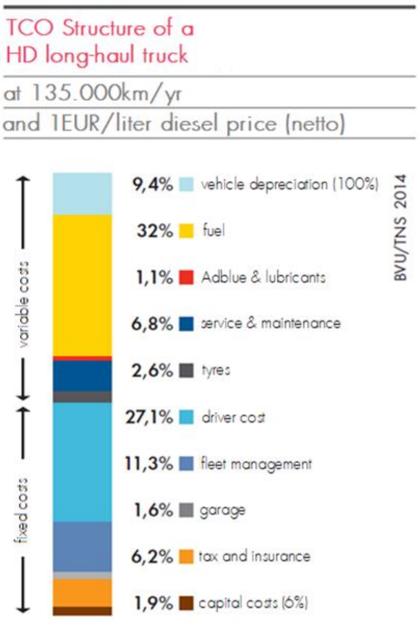

Figure 6: Typical total cost of ownership (TCO) for a long haul truck with 135,000 km/a and 1 €/L of diesel.

Source: Shell commercial vehicle study, 2016

Therefore, this project considers diesel fuel as a reasonable benchmark. Diesel cost is a good metric to judge both fuel cost competitiveness and the overall use-case.

For a N3 tractor trailer configuration the fuel costs can be approximated as follows:

Table 2: Estimation of fuel costs parity between diesel and hydrogen for a N3 tractor trailer configuration

	Unit	Value
Fuel consumption	l/100 km	31
Indicative diesel price	€/l	1.20
Diesel cost/100 km	€/100 km	37.20
Hydrogen consumption	kg/100 km	8
Break even H_2 price	€/kg	4.65

Today, diesel trucks often are equipped with tank sizes ranging from 400 L to 2,500 L – enough to give a day`s worth of autonomy on the low end and a full route across Europe and back on the high end. It is understood that the high volume of diesel is usually chosen by hauliers that operate long haul routes from locations where cheap diesel is available (e.g. Romania, Bulgaria, Turkey, etc.) to locations where fuel is more expensive (e.g. ports of Antwerp, Rotterdam, Hamburg, etc.) and it is a commercial factor to the haulier to be able to utilize cheaper fuel for the entire tour. For hydrogen, these large cost deltas across Europe are not necessarily expected. Therefore, whithin this project a target range of 1,000 km for a tractor trailer is assumend as a reasonable range factor for the calculations (which corresponds to 11.5 h of driving at an average speed of 80 km/h plus a 10% margin). Diesel vehlices can be refueled in typically 8-15min, depending on the tank size, whereas larger tank systems with a tank at either side of the chassis often work with two dispensers and a refueling nozzle for each side of the truck, bringing the average duration of a refuelling process to about 10 minutes.

In order to achieve comparative refueling for **N3 tractor trailer vehicles in long haul use and M3 coaches, a good metric would be to be able to fill 80 kg of hydrogen in 10 min**. This is also consistent with the recently published US Department of Energy Technical Targets for Hydrogen Fueled Long Haul Tractor-Trailer Trucks[8]

For **M2 and N2 vehicles and smaller N3 vehicles with less range requirements, the performance can be lower, it is estimated that 10-40 kg of hydrogen could be refilled in 5-8 min** to be competitive.

For N1 vehicles, up to 10 kg of hydrogen can be filled in 3-5 min, which is corresponding to current light duty refueling protocols in use, such as SAE J2601-1 DEC2016[9].

Within these relatively broad generalisations, the type of application may have a significant impact on the exact details for the requirements.

[8] https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

[9] SAE J2601-1 DEC2016: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles, Revised 2016-12.

3.2 Non Road vehicles

Some other relevant applications include non-road vehicles such as trains and inland ships. The requirements are suggested to be as follows:

Typical CHSS volumes:

- Trains: 150-500 kg[10]
- Inland ships: 300-20,000 kg[11]

Table 3: Estimated hydrogen capacity needed for inland ships

Ship categorie	Power [kW_{mech}]	Storage size (Compressed gasous hydrogen) [kg H_2]
Bulk carrier	706	4,569
Push barge	400	874
Day cruise	132	282
Cabin Cruise (River)	2,100	20,576

Source: Strombasierte Kraftstoffe für Brennstoffzellen in der Binnenschifffahrt, NOW/BMVI, 2019.

It is assumed that trains will have a target fill time of 15-30 min[12] .

For inland ships, a distinction between the different types has to be made. Since a bulk carrier for cargo and a cabin-cruise ship require very large amounts of hydrogen – if the current operating mode is maintained – gaseous hydrogen applications may not be a straight forward option. For day-cruise ships and push barges, i.e. a push/tow unit for cargo floats, fill times of 20-40 min should be acceptable.

It is worth noticing that some of the knowledge that will be generated within the PRHYDE project could also benefit to the use case of refueling a hydrogen “transport system”, for instance tube trailers. Their capacity range from 300 kg to 1,500 kg and can be filled in a time between 30 min and 1 h.

3.3 Performance metrics considered for different applications

Following from that, for the purpose of this project, the anticipated average fill rates for various hydrogen vehicle applications are determined as listed in Table 4.

Achieving a high final State-of-Charge (SoC) close to 100% is one of primary issues of the protocol development. The effect of the initial temperature and pressure of the vehicle hydrogen tank and refueling time (or flow rate) on the final temperature and the final SoC is very important. Hence, approaching 100% SoC is challenging from a

10 https://shift2rail.org/wp-content/uploads/2019/04/Report-1.pdf

11 Source: Strombasierte Kraftstoffe für Brennstoffzellen in der Binnenschifffahrt, NOW/BMVI, 2019.

12 https://shift2rail.org/wp-content/uploads/2019/04/Report-2.pdf

safety point of view due to potential overheating. The SoC should approach as much as possible 100%

Table 4: Generic use cases and estimations for associated refuelling performance metrics as a benchmark for hydrogen refuelling

Vehicle segment	Compressed hydrogen storage system (CHSS) capacity [kg]	Fuelling time [min]	Corresponding max. anticipated average H_2 flow [kg/min]
N1 commercial vehicle (included for comparative purposes)	2-10	3-5	2
N2 commercial vehicle	10-40	10	4
N3 commercial vehicle	40-80	10	8
M2 passenger carrier	10-40	8	5
M3 passenger carrier	30-100	12	8
Train, low case	150	10	15
Train, high case	500	15	33[13]
Inland ship, bulk carrier	4,500	60	75[14]
Inland ship, push barge	900	60	15
Inland ship, day cruise	300	30	10
Inland ship, river cruise	20,000	120	167
Transport system, low	300	30	10
Transport system, high	1,500	60	25

Note: SOC should approach as much as possible 100%

In summary, the required flowrates for different applications vary considerably. These requirements need to be taken into account when designing the corresponding hardware for refueling, such as nozzles, receptacles, hoses, breakaway couplings, control valves, metering devices, etc. It is likely that not all the requirements can be met by one size of product. Therefore, it makes sense to take these requirements and group them into similar performance brackets. A good example for this can be seen with current light duty nozzles (up to 60 g/s) and bus refueling nozzles (up to 120 g/s). Work has already started on nozzles that can support up to 300 g/s.

These metrics are performance based on the respective usage and therefore does not presuppose any technical choice of vehicle manufacturer to reach them, such as type of tank (Type 3 or Type 4) and pressure level. Nevertheless, protocol development work inside PRHYDE project will take the different choices such as Type 3 and Type 4 tank as well as pressure levels of 35 MPa, 50 MPa and 70 MPa into account.

[13] It is likely that such a system would have at least two independent tank systems. Accordingly, half the flowrate can be assumed.

[14] It is currently unsure whether these applications are feasible to refuel with gaseous hydrogen in their current operational scheme. It is well possible that options can be found to shorten the distances between fills or switch to alternative modes of supplying molecules, such as swappable containers, liquid hydrogen (LH_2), ammonia (NH_3) or other alternatives.

4 ECONOMICS

Achieving good performances for liquid fuels refuelling is generally not as constraining as for gaseous fuel in terms of technical and cost challenges. Major costs include critical component and equipment such as compressor, storage and cooling system eventually needed due to compression heating at high flow rate.

As a consequence, it has to be kept in mind that the trade-off between cost and performance is key and therefore that the refuelling protocol should achieve performance targets while not exceeding the necessary flow rate and cooling needed to do so.

ANNEX 1: EXTERNAL STAKEHOLDER INPUT

In order to gather information from stakeholders external to the project, the PRHYDE consortium developed a set of surveys which interested parties were invited to complete and return to the project. Additionally, webinars were held on the 24th March and 23rd April 2020, to disseminate information about the project, but also, and equally importantly, to gather relevant information from those involved in the refuelling of heavy duty vehicles, or development of the vehicles themselves. Further information on the webinars and the surveys is available in PRHYDE Deliverable D6.3.

The section below includes a summarised feedback gathered from the surveys and, where applicable, webinars, that is relevant to this document, with analysis to be carried out as part of the development of the PRHYDE project refuelling approach.

Feedback received from participants of the workshops and survey responders on ideal targets for future refuelling protocol performance was as follows:

- The ideal performance target would be performance parity with fossil fuel refuelling;
- For road applications, feedback on ideal refuelling times ranged from 5 min to 15 min depending on companies and usage;
- Feedback on ideal train refuelling times ranged from 7 min to 30 min;
- For Crew Transfer Vessel (CTV), 200 kg of compressed gas should be transferred in less than 30 min;
- “Economic analysis and customer survey” will be required to find an appropriate balance between the cost of precooling and the convenience of fast filling.

What is PRHYDE?

With funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), the PRHYDE project is aiming to develop recommendations for a non-proprietary heavy duty refuelling protocol used for future standardization activities for trucks and other heavy duty transport systems applying hydrogen technologies.

Based on existing fuelling protocols and current state of the art for compressed (gaseous) hydrogen fuelling, different hydrogen fuelling protocols are to be developed for large tank systems with 35, 50, and 70 MPa nominal working pressures using simulations as well as experimental verification. A broad industry perspective is captured via an intense stakeholder participation process throughout the project.

The work will enable the widespread deployment of hydrogen for heavy duty applications in road, train, and maritime transport. The results will be a valuable guidance for station design but also the prerequisite for the deployment of a standardized, cost-effective hydrogen infrastructure.

Further information can be found under https://www.prhyde.eu. For feedback on the PRHYDE project or the published deliverables, please contact info@prhyde.eu.

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