ESCALATE

Powering European Union Net Zero Future
by Escalating Zero Emission HDVs
and Logistic Intelligence

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Refuelling Solutions and Protocols

Project deliverable D4.2

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Project Executive Summary

ESCALATE, an EU funded Research and Innovation project, has been awarded funding under the HORIZON-CL5-2022-D5-01 call, highlighting its significance within the academic and scientific community. The primary objective of ESCALATE is to showcase and demonstrate the efficacy of high-efficiency zero emission heavy-duty vehicle (z-HDV) powertrains, with a targeted increase of up to 10% in their overall efficiency. Specifically tailored for long-haul applications, these powertrains are designed to provide an impressive range of 750+ kilometers without the need for refueling or recharging, while simultaneously ensuring consistent performance during daily operations over a period of six months or more under real-world conditions.

To achieve these ambitious goals, ESCALATE focuses on the development of meticulously designed modular building blocks, which are intended to attain a Technology Readiness Level of 7 or 8. These modular components will serve as the foundation for three distinct types of z-HDVs, namely battery-HDV (b-HDV), fuel-cell-HDV (f-HDV), and range extender-HDV (r-HDV). The utilization of innovative business model innovations will be instrumental in optimizing the integration and utilization of these standardized and modular building blocks, further enhancing their efficiency and effectiveness.

Moreover, the ESCALATE project aims to contribute valuable insights to the scientific community through the production of three comprehensive white papers. These papers will delve into various aspects of z-HDV technology, with one white paper focusing on defining a clear pathway to reduce well-to-wheel greenhouse gas emissions specifically from heavy-duty vehicles. The formulation of this pathway will be informed by rigorous analysis, utilizing both empirical results and policy assessments, thereby establishing a robust foundation for future efforts in reducing the environmental impact of HDVs. Through its multifaceted approach, ESCALATE strives to advance the knowledge and understanding of high-efficiency z-HDV powertrains, foster technological innovation, and contribute to the ongoing efforts of EU aimed at achieving sustainable and environmentally friendly transportation systems.

ESCALATE partners

Participating countries:

- Belgium
- Denmark
- Germany
- Spain
- Estonia
- France
- Finland
- Greece
- Poland
- Portugal
- Austria
- Türkiye
- UK

List of partners:

- Fev Europe Gmbh & Fev France (FEV) - *Project coordinator*
- University Of Surrey (USR) - *Technical coordinator*
- Mercedes-Benz Turk As (MBT)
- Brussels Research And Innovation Center For Green Technologies (BRING)
- Teknologian Tutkimuskeskus VTT Oy (VTT)
- Virtual Vehicle Research Gmbh (VIV)
- Aristotelio Panepistimio Thessalonikis (AUTH)
- Polis - Promotion Of Operational Links With Integrated Services, Association Internationale (POLIS)
- Inegi - Instituto De Ciencia E Inovacao Em Engenharia Mecanica E Engenharia Industrial (INEGI)
- Deutsches Zentrum für Luft- und Raumfahrt (DLR)
- Rheinisch-Westfaelische Technische Hochschule Aachen (RWTH)
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- Engie Energie Services (ENGIE)
- Commissariat A L Energie Atomique Et Aux Energies Alternatives (CEA)
- Fev Tr Otomotiv Ve Enerji Arastirmave Muhendislik Limited Sirketi (FEV TR)
- Ai4sec Ou (AI4SEC)
- Ballard Power Systems Europe As (BLRD)
- Kempower Oy (KEM)
- Hydrogen Europe (HEU)
- Ergtech Spolka Z Ograniczona Odpowiedzialnoscia (ERG)
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Deliverable executive summary

As detailed in the project executive summary, ESCALATE aims to showcase and demonstrate high-efficiency zero emission heavy-duty vehicle powertrains, especially targeting long-haul applications. Since **reducing energy cost and recharging time is crucial to develop low-emission heavy-duty mobility**, part of ESCALATE project focuses on this topic. Thus**, this deliverable D4.2 “Refueling solutions and protocols” recaps the key public results of ESCALATE partners work about green hydrogen refueling system solutions**, while its counterpart D4.3 recaps the work done on battery electrical charging solutions.

Indeed, existing hydrogen stations in Europe are slow to refuel large<<<<< quantities, and thus are not yet adapted to heavy-duty vehicles. Fleet managers are expecting safe high-flow and high-capacity stations with validated appropriated fueling protocols and high connectivity, while keeping a reasonable hydrogen price at the pump. This document thus investigates the path to **future green hydrogen refuelling solutions and protocols** to develop new hydrogen fueling stations relevant for heavy-duty usage. Thus, it **contributes to enabling the deployment of hydrogen for heavy duty applications.**

In order to do so, **the first step is to understand the end-users needs** in detail. This document elaborates on previous ESCALATE work on requirements conducted in ESCALATE WP2 to give more specific requirements from two distinct perspectives: the developer of a fleet management and routing optimization tool, and the fleet manager responsible for the operational efficiency of the fleet. The two perspectives meet at the need for data such as: the hydrogen price, the station availability and the refuelling time, among many others. Finally, example on how these values might be used to optimize fleet management is also explained by showing results of RWTH simulation tool.

After specifying all the requirements from fleet management in order to get an appropriating network of hydrogen stations, a focus is done on the safety aspects all stations must respect. Indeed, all energy transfer operations include risks. So the specific regulations to prevent any accident linked to hydrogen in the European Union and more specifically in Finland, France, Germany and Turkey (countries that will receive ESCALATE hydrogen trucks) are listed. It is underlined that there is still a lack of harmonized regulations and standards for hydrogen technologies and applications, which is an important barrier to their deployment.

Then, the process of refuelling itself is deeply investigated. First, **a detailed state of the art of the current hydrogen refuelling protocols is presented**, insisting on how they work. The new Technical Informative Report SAE J2601-5 s particularly important, as it is to the authors’ knowledge, the only current public protocol published that allows to fuel 700 bar heavy-duty vehicles at high flow. Other protocol concepts as the ones defined by the PRHYDE European project are also recapped. Then, to understand what refuelling performances are to be expected with the ESCALATE pilots, **refuelling simulations** were conducted using ENGIE’s HyFill model and **SAE J2601-5 protocols**. It was shown that **if the truck and the station both have low pressure drops components, refuelling can be achieved in less than 7 minutes for each of the hydrogen pilots**, given current design hypotheses. **However, if the truck or the station design cause high pressure drops at high flow, it will prevent to reach a satisfying state-of-charge in a short time,** and the fueling time will need to be significantly extended to reach a good state-of-charge. Finally, the **communication** aspects between truck and station are particularly investigated and emphasis is placed on the possibilities for more advanced future communications.

Eventually, a first study on hydrogen infrastructure optimization was conducted. The main sources of energy consumption on a station were clearly pointed out. The impact of the station architecture on various parameters on the refuelling time and the energy consumption of the station have shortly been studied, underlining the need for a careful design of the hydrogen infrastructure in order to meet the fleet requirements in terms of performance while limiting the energy costs. Architecture impact on performance and costs aspects will also be investigated in next task T4.4.

At the end (section 7), a general recap of the recommendations for stations and trucks to be able to conduct high-flow refuelling that can be derived from the work done and presented in this report is presented. In particular, design phases of stations and truck is particularly important to minimize pressure drop, optimize station capacity and take into account thermal effects, therefore allowing a good performance. Connectivity and standardization are also two main topics to tackle for hydrogen mobility industry.

Thus, **this ESCALATE deliverable recaps key topics and insights that may give guidance to build hydrogen heavy-duty vehicles and stations**. Work on infrastructure optimization and cost is to be continued and detailed further later in the project.

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List of abbreviations and acronyms

Acronym	Meaning
AFIR	Alternative Fuel Infrastructure Regulation
AFNOR	Association Française de NORmalisation (French Standardization Association)
ALK	Short for alkaline technology (relative to electrolyzers)
API	Application Programming Interface
ATEX	Explosive Atmospheres
APRR	Average Pressure Ramp Rate
CEP	Clean Energy Partnership
CEN	European Committee for Standardization
CHSS	Compressed Hydrogen Storage System
CO_2, CO2	Carbon Dioxide
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EU	European Union
FC	Fuel Cell
FC-HDV	Fuel Cell Heavy-Duty Vehicle
FM	Flow Maximum (maximum flow allowed)
GA	Grant Agreement (*includes the project plan and the initial objectives*)
H_2, H2	Hydrogen gas (dihydrogen)
HDV	Heavy-duty Vehicle
HHV	Higher Heating Value (of hydrogen in this deliverable)
HRS	Hydrogen Refueling Station
IrDA	Infrared Data Association
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LHV	Lower Heating Value (of hydrogen in this deliverable)
MAT	Mass Average Temperature
NO_x	Oxides of Nitrogen : nitric oxide (NO) and nitrite dioxide (NO_2) *(are atmospheric pollutants)*
NWP	Net Working Pressure: *maximum pressure allowed at 15°C. In ESCALATE project, NWP of the pilots is 700 bars*
OEM	Original Equipment Manufacturer
PCV	Pressure Control Valve (*the valve that controls the fueling ramp)*

PED	Pressure Equipment Directive
PEM	Short for Proton Exchange Membrane technology (relative to electrolyzers)
PRR	Pressure Ramp Rate
SAE	Short for SAE International
SOC, SoC	State of Charge (of hydrogen vehicle or tank)
TBD	To Be Determined, *the placeholder for the parameter not yet defined*
TEN-T	Trans-European Transport Network
TIR	Technical Informative Report
TVL	Tank Largest Volume *(volume of the biggest tank of the tank system)*
WG	Working Group
WP	Work Package
APRR	Symbol for APRR (MPa/min if not specified otherwise)
$\dot{m}$	Symbol for mass flow (g/s if not specified otherwise)
T	Symbol for temperature (°C if not specified otherwise)
t	Symbol for time (s or min)
P	Symbol for temperature (bar if not specified otherwise)
ρ	Symbol for density (kg/m3 if not specified otherwise)

1 Purpose of the deliverable

1.1 Intended audience

The primary audience of the deliverable consists of the ESCALATE project partners, containing all members participating in the consortium. Secondly, the audience includes representatives from the Commission Services responsible for overseeing the project. Lastly, the target group is the broad audience. It includes policymakers, stakeholders, researchers, and industry professionals in the field of sustainable transportation and zero-emission technologies.

1.2 Structure of the deliverable and links with other work packages and deliverables

WP4 investigates the refuelling and grid-friendly charging solutions. The initial requirements and preliminary specifications were prepared in cooperation with the WP2 (T2.1) and WP3 (T3.1) requirements definition work, as well as with project OEM partners. This work resulted in the deliverable D4.1: “Requirements and specifications of single and multi-energy stations” [1]. Hydrogen refuelling and electrical charging were then studied more closely respectively in task T4.2 *Green H2 refuelling system solutions* (leading to this deliverable D4.2) and in task T4.3 *Grid-friendly fast charging station to 1MW* (leading to deliverable D4.3). Finally, the task T4.4 “Cost-effective refuelling and charging infrastructures” will summarize and deepen the findings of the WP4 from the insights learned from previous tasks. Figure 1 illustrates the flow of the tasks. The current task T4.2 also gives guidelines for the refuelling of the hydrogen pilots trucks of ESCALATE during their operation test phases, for the WP6.

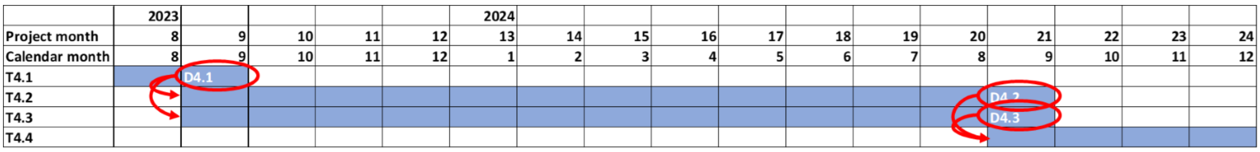

Figure 1 – Illustration of interdependency of tasks T4.1, T4.2, T4.3 and T4.4 within WP4.

2 Introduction

In Europe, one of the most emitting sectors is transportation: today trucks, buses and coaches are responsible for more than 25% of the greenhouse gases emissions from road transport and for over 6% of total European Union greenhouse gases emissions [2]. **Hydrogen is a promising way to decarbonize this sector,** and to reach the ambitious objective of reducing the CO_2 emissions of new heavy-duty vehicles by 90% in 2040 compared to 2019 levels [2]. Indeed, hydrogen combines the advantages of electric vehicles, such as **no CO_2, no NO_x, no particulate matter emissions**, and the advantages of fossil fuels vehicles such as a **large driving range** and a **very fast refuelling**, which are very appreciated for logistic purposes**.** However, **one of the challenges to develop this sector is the availability of hydrogen distribution infrastructures close to customers, at a reasonable cost and giving satisfying performances** (fuelling time, final SOC, …).

As of today, existing European hydrogen refuelling stations are not really adapted to heavy-duty vehicles: the refuelling flow is too low, the pressure drops are too high, the station storage is too small to fuel commercial fleets. Lack of guidelines, lack of validated refuelling protocols and lack of connectivity are also identified as gaps to bridge in order to unlock hydrogen potential for trucks. This **deliverable aims at** investigating these various aspects by **identifying current and future green hydrogen refuelling solutions and protocols to help develop new hydrogen fuelling stations relevant for heavy-duty usage**.

To do so, after reminding the ESCALATE project context, the deliverable first **focuses on the end-user requirements** to state clearly the objectives to be reached and features to be integrated by hydrogen stations. Then, a **review of the safety regulation framework in Europe is carried out.** After that, an **important emphasis is done on refuelling protocols**. An exhaustive **state-of-the-art** of the existing refuelling protocols is presented, **explaining why protocols are necessary, what are the existing ones and which of them could be relevant for heavy-duty vehicles**. Then, **some refuelling simulations of ESCALATE pilot 1 and 2** are done, to illustrate the functioning of such protocols. Study of possibilities for new **advanced communication during refuelling** is also conducted. Moreover, a small study **on energy consumption of stations and architecture impact on performance** is summarized. Eventually, **recommendations for future high-flow stations and high-flow trucks are presented**, based on the previously identified gaps and issues.

3 Context and end-user requirements

3.1 Hydrogen HDV in ESCALATE project

As mentioned in the introduction, hydrogen might be a relevant way to help decarbonize heavy-duty transportation. This aspect is investigated in the scope of the ESCALATE project, where three out of the five pilot trucks use hydrogen as power storage. These three pilot trucks are:

- **Pilot 1 (P1): ~ 60kg of hydrogen at 700 bar**, that aims at being fueled in 20 minutes
- **Pilot 2 (P2): ~ 65kg of hydrogen at 700 bar**[1], that aims at being fuelled in 10-15 minutes at the French station (long-haul trip), and in 15-25 min at the Turkish station (daily trip)
- **Pilot 5 (P5) (virtual) : ~80kg of hydrogen at 700 bar**.

The challenges and solutions to fuel these pilots trucks (with an emphasis on pilot 1 and 2 that will be fuelled in real-life during ESCALATE project) will be detailed in this report. More generally, this document will help to **understand the current needs, challenges, state-of-the-art and next steps for the hydrogen fuelling stations ecosystem in Europe**. Indeed, refuelling infrastructure is a key topic when speaking of hydrogen heavy-duty mobility, that should be tackled in the same timeline as vehicles manufacturing.

3.2 Fueling stations

3.2.1 General arrangement of a fuelling station

The purpose of a hydrogen refuelling station (HRS) is to supply hydrogen to the tanks of fuel cell electric vehicles. The basic principle of hydrogen refuelling is **to transfer hydrogen from high-pressure stationary storage to the on-board vehicle storage tanks**. Typical storage is 5 kg for passenger vehicles, 20 to 40 kg for buses and above 50 kg for trucks. In ESCALATE, only trucks are considered.

The nominal working pressure (NWP) of hydrogen within the truck tanks can vary, but the **two standards widely used are 350 bar (“H35”) and 700 bar (“H70”).** The lower pressure level allows lower specifications and less complex components for the vehicle and the station, thus reducing costs. The energy consumption for compression and cooling requirements is also lower than for H70 refuelling. However, the energy density in 700 bar vehicles is higher, allowing higher driving range for the same storage volume. The station must be adapted to the NWP of the truck it is fuelling.

The main components for most of the stations are detailed below and sketched on Figure 2. Here, a station using cascade tank-to-tank refueling is depicted, which is a very common station architecture. This concept requires hydrogen to be stored at a pressure level above the final pressure in the vehicle at least in the highest-pressure bank of the storage. Hydrogen is then **transferred from the stationary storage tanks into the vehicle storage tank(s) by the simple control of a valve, until the final pressure in the vehicle is reached.** The elements constituting that kind of station are:

- **A hydrogen source**: hydrogen can be produced on-site through an electrolyzer (for instance, producing at around 20 bar), trucked-in (for instance by trailers at 200-500bar) or even transported through pipelines.

[1] Pilot 2 design and H2 mass are not fixed yet, the values displayed might still change.

- **One or multiple compressor(s):** they are used to increase the pressure of the source, to reach a higher pressure than the final pressure of the vehicle tank.

- **High pressure storage** (up to 900 - 1100 bar for H70 stations): to store the high-pressure hydrogen from the compressor.

- **One or multiple dispenser(s):** to transfer the hydrogen from the storage to the vehicle. Multiple elements such as pressure control valve, optional heat exchanger, mass flow meter, break-away, hose, nozzle are part of the dispenser, each of them having a well-defined function to dispense hydrogen easily and safely.

- **Cooling system(s)** (can be optional): to pre-cool the hydrogen before it is dispensed into the vehicle. Indeed, hydrogen undergoes a **Joule-Thomson expansion** when flowing from the station high-pressure tanks. Hydrogen has the particularity of having a negative Joule-Thomson coefficient at common temperatures, which implies that its expansion goes with an increase of its temperature. Moreover, as it fills up, hydrogen within the vehicle tank is **compressed** and therefore heats. These two sources of hydrogen heating make it **often necessary to cool down the gas** before its introduction in the tank to prevent the temperature within the vehicle from exceeding 85° while keeping a satisfying speed.

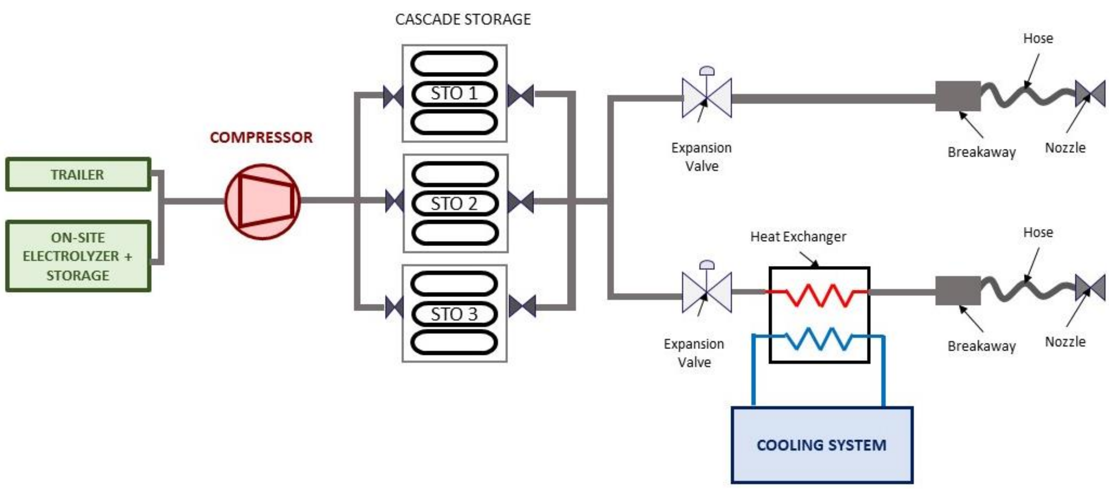

Figure 2 – Scheme of a hydrogen refueling station (ENGIE).
Lot of variations around this architecture exist.

3.2.2 ESCALATE fuelling stations

As of now, it is foreseen to use the following stations to fuel the pilots:

For Pilot 1 (route Helsinki – Jyväskylä), situation of the planned HRS investment projects in Finland has been confirmed. Pilot 1 plans to rely on one or several public HRSs. First Finnish planned HRS for operation in 2024 by P2X [3] was cancelled. The first actual HRS in Finland will be in summer 2025 in Jyväskylä, by Vireon. The planned location of the HRSs is suitable for Pilot 1 hydrogen refuelling. 700 bar refuelling capacity of the station is confirmed.

For Pilot 2, there are two different requirements:

- First, a high-flow refuelling must be done in France. The fuelling should reach 170g/s to meet ESCALATE KPI. This very ambitious goal cannot be met in most commercial stations functioning today, that distributes hydrogen only up to 60g/s or 90g/s peak.
- Secondly, classical refuelling should be done in Turkey, during the phase of daily operation.

Exact station locations for P2are still to be determined, various possibilities are currently being studied by ESCALATE consortium.

3.3 End-user requirements

The transition to hydrogen as an alternative fuel source for fleet vehicles **requires a comprehensive understanding of end-user requirements for hydrogen refuelling stations**. This chapter aims at **delineating these requirements from two distinct perspectives: the developer of a fleet management and routing optimization tool, and the fleet manager responsible for the operational efficiency of the fleet.** The insights gathered are intended to inform the design and implementation of hydrogen refuelling infrastructure to better support fleet operations.

3.3.1 Developer's Perspective

From a developer's point of view, the primary focus is on integrating hydrogen refuelling stations within a fleet management and routing optimization tool. This involves several key requirements that the hydrogen refuelling station operator must fulfil and data it must provide to enable effective simulation and optimization of refuelling times.

Real-Time Data Access

For accurate route optimization and refuelling simulations, the following real-time data from hydrogen refuelling stations is crucial:

- **Station Operational Status:** Whether the station is currently operational or undergoing maintenance.
- **Queue Lengths and Waiting Times:** The number of vehicles currently waiting at the station and the estimated waiting time.
- **Average Refuelling Time:** The typical duration required to refuel a vehicle, which is essential for precise time calculations.
- **Hydrogen Availability:** Current hydrogen stock levels and the rate at which hydrogen is being replenished.
- **Price:** The current price of hydrogen at the station.

For more detailed simulations and therefore more accurate refuelling time predictions, additional data is optimal, including:

- **Number of Tanks:** The total number of hydrogen storage tanks at the station.
- **Pressure at 100% SOC (State of Charge) of Each Tank:** The pressure levels when each tank is fully charged.

- **Hydrogen Mass at 100% SOC of Each Tank:** The amount of hydrogen in kilograms when each tank is fully charged.
- **Precooling Temperature:** The temperature at which hydrogen is precooled before refuelling.
- **APRR (Average Pressure Ramp Rate):** The rate at which pressure is increased during refuelling.
- **Live SOC (State of Charge) of Each Tank:** The current SOC of each tank in real-time.

Standardized Data Formats and API Access

To facilitate seamless integration into the fleet management software, the refuelling station operator should provide:

- **Standardized Data Formats:** Consistent data formats (e.g., JSON, XML) for all real-time and historical data.
- **API Access:** Robust and well-documented APIs that allow the software to query real-time data and receive updates.

Predictive Data Analytics

Beyond real-time data, predictive analytics can significantly enhance route optimization. Requirements include:

- **Historical Data:** Access to historical data on refuelling times, queue lengths, and operational statuses to identify patterns and predict future trends.
- **Predictive Models:** Information on expected refuelling demands based on time of day, day of the week, and other relevant factors.

Reliability and Uptime

For effective simulation and route planning, the refuelling station must maintain high reliability and uptime. This includes:

- **Minimal Downtime:** Ensuring that the station is operational as much as possible, with scheduled maintenance communicated in advance.
- **Redundancy Measures:** Backup systems to handle data transmission and station operations to minimize disruptions.

Security and Privacy

To protect sensitive data and ensure compliance with relevant regulations, the following measures are required:

- **Data Encryption:** Secure encryption protocols for data transmission between the refuelling station and the fleet management software.
- **Access Controls:** Robust access control mechanisms to prevent unauthorized access to data.

User Support and Documentation

Comprehensive support and documentation are essential for smooth integration and troubleshooting:

- **Technical Documentation:** Detailed API documentation, data schema descriptions, and integration guides.
- **Support Services:** Responsive technical support to assist with integration issues and provide timely updates on system changes.

3.3.2 Fleet Manager's Perspective

From the fleet manager's perspective, the requirements focus on the practical aspects of maintaining and operating a hydrogen-powered fleet. The primary concerns include:

Accessibility and Convenience

Hydrogen refuelling stations must be strategically located to ensure accessibility and convenience for the fleet. Key considerations are:

- **Proximity to Routes:** Stations should be located near major routes or hubs where fleet vehicles commonly operate.
- **Operational Hours:** Stations should operate during hours that align with fleet schedules, including early mornings, late evenings, and weekends.

Efficiency and Reliability

To maintain operational efficiency, refuelling stations must be reliable and efficient in their operations. This includes:

- **Fast Refuelling Times:** Minimizing the time required to refuel each vehicle to reduce downtime.
- **High Capacity:** Ensuring stations can handle multiple vehicles simultaneously, especially during peak times.
- **Consistent Supply:** Guaranteeing a steady supply of hydrogen to avoid disruptions.

Cost Management

Cost is a significant factor for fleet managers. Refuelling stations must provide competitive and transparent pricing, along with support for managing costs. This involves:

- **Pricing Models:** Offering flexible pricing models such as volume discounts or subscription plans.
- **Expense Tracking:** Tools for tracking refuelling expenses across the fleet.
- **Incentives and Grants:** Information on available incentives or grants for using hydrogen fuel.
-

Combined Requirements for Optimal Operation

Combining the perspectives of both developers and fleet managers, several overlapping requirements emerge that are critical for the success of hydrogen refuelling infrastructure:

- **Data Integration:** Seamless integration of refuelling data into fleet management tools.
- **Strategic Placement:** Ensuring refuelling stations are conveniently located and accessible.
- **Operational Efficiency:** Maintaining high reliability and fast refuelling times.
- **Cost-Effectiveness:** Offering competitive pricing and support for cost management.

Understanding and addressing the end-user requirements for hydrogen refuelling stations is crucial for the successful adoption of hydrogen-powered fleets. **By integrating real-time data, optimising routes, and ensuring efficient and cost-effective operations, both developers and fleet managers can work together to create a robust hydrogen refuelling infrastructure.** This chapter thus provides a foundation for designing refuelling stations that meet the needs of all stakeholders, thereby supporting the broader goal of sustainable and efficient fleet management. As a conclusion to this part, **the main requirements identified in ESCALATE project** (in WP2) **for hydrogen fuel cell trucks infrastructure are summarized and quantified below** by the ESCALATE partners depending on their current vision, needs, industry and regulation knowledge (for instance, some of these requirements can be found in AFIR regulation [4], that must be applied by EU countries since April 2024). It is distinguished what the industry should aim to, and what is currently acceptable.

Table 1 - Main requirements for hydrogen station to fuel heavy-duty vehicles

Category	Requirement	Ideal value	Acceptable value
Station characteristics	Type of dispenser	H70HF, H70MF, H70 H35HF, H35	H70 H35
	Ability to see available dispenser online	Yes	No
	Protocol used clearly stated	Yes	No
	Communication during refueling	Yes	No
	Quality of hydrogen dispensed	EN 17124 requirements ISO 14687 requirements	EN 17124 requirements ISO 14687 requirements
	Range of ambient temperature at which station works	-40°C to 50°C	-25°C to 45°C
	Station dispensing capacity	>1 ton/day	1 ton/day
	Online API	Yes	No
Station availability	Waiting time when arriving at station	< 10 min	30 min
	Global availability of station	> 98%	> 90%
	Ability to see station availability online	Yes	Yes
	Possibility to book a timeslot	Yes	No
	Capacity to see station live SOC	Yes	No
Location	With respect to TEN-T corridors	< 5 km from exit	< 10 km from exit

	Distance max between two stations	<100 km	< 200 km
Price of H2	Price per kg	3-6 €/kg by 2030 for green H2 (depending on country)	10-15 €/kg by 2030 for green H2 (depending on country)
	Access to live price online	Yes	No
Fueling performance	Fueling time (60 kg truck), incl. connecting time	<12 min	< 20 min
	Final SOC	> 95%	> 85%
Billing	Subscription necessary	No	Yes
	Card payment	Yes	Yes
	Automatic invoicing	Yes	No
Safety	Following EU standards	Yes	Yes
	Drivers are trained on how to react in case of filling disruption	Yes	No (rely on onsite instructions displayed)

3.3.3 Tool for logistic planification

In Task 5.4 of the ESCALATE project, **a model for fleet routing optimisation is developed by RWTH as an innovative fleet management tool for the integration of ZEV in current fleets.** The optimisation model is designed to maximise operational efficiency for a diverse vehicle fleet comprising Internal Combustion Engine Vehicles (ICEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs). The **model takes into account various input parameters, including vehicle locations, vehicle types, job requirements, charging station locations, and hydrogen refuelling stations (HRS) locations.**

The primary objective of the model is to optimise routes for the entire fleet for the upcoming day of operations. This optimisation process simultaneously considers the most efficient paths between job locations, the assignments and sequence of jobs to vehicles, as well as the strategic planning of charging and refuelling stops for BEVs and FCEVs, respectively. By incorporating these factors, the model ensures that vehicles can complete their assigned tasks while minimising downtime for energy replenishment.

The optimisation **is driven by a Total Cost of Ownership (TCO) objective function**, which **takes into account various factors such as vehicle costs, fuel/energy costs, vehicle efficiency, maintenance requirements, and time constraints. This approach ensures that the generated routes not only maximise the number of completed jobs but also minimise overall operational costs for the fleet.**

The model's output provides optimised routes for each vehicle in the fleet, detailing the sequence of jobs to be completed, along with scheduled charging or refuelling stops. This comprehensive routing solution enables fleet operators to deploy their vehicles in the most cost-effective and efficient manner while meeting the day's operational demands.

To assess the economic viability of transitioning a fleet to Fuel Cell Electric Vehicles (FCEVs), a series of simulations using the fleet routing optimization model was conducted. At first, **a baseline simulation using only Internal Combustion Engine Vehicles** (ICEVs) was determined to establish a reference point for traditional fleet operations. Following this**, multiple simulations with a fleet composed entirely of FCEVs were ran, varying the price of hydrogen (H2) per kilogram across these scenarios**. By comparing the ICEV-only results to the FCEV simulations with different H2 prices, the goal is to quantify how changes in H2 fuel costs and refuelling speeds affect the overall Total Cost of Ownership (TCO) and operational efficiency of an FCEV fleet. The following results demonstrate the model's sensitivity to H2 price fluctuations and provide crucial insights into the economic conditions necessary for a successful transition to a hydrogen-powered fleet.

The job scenario was the same for all simulations. For each simulation, the fleet routing optimisation had a fleet of 6 vehicles, which were all the same. In Figure 3 a map is visualised showing **the fleet operation for the fleet consisting of 6 ICEV. It is apparent that the optimisation only took 3 vehicles to fulfil the jobs.**

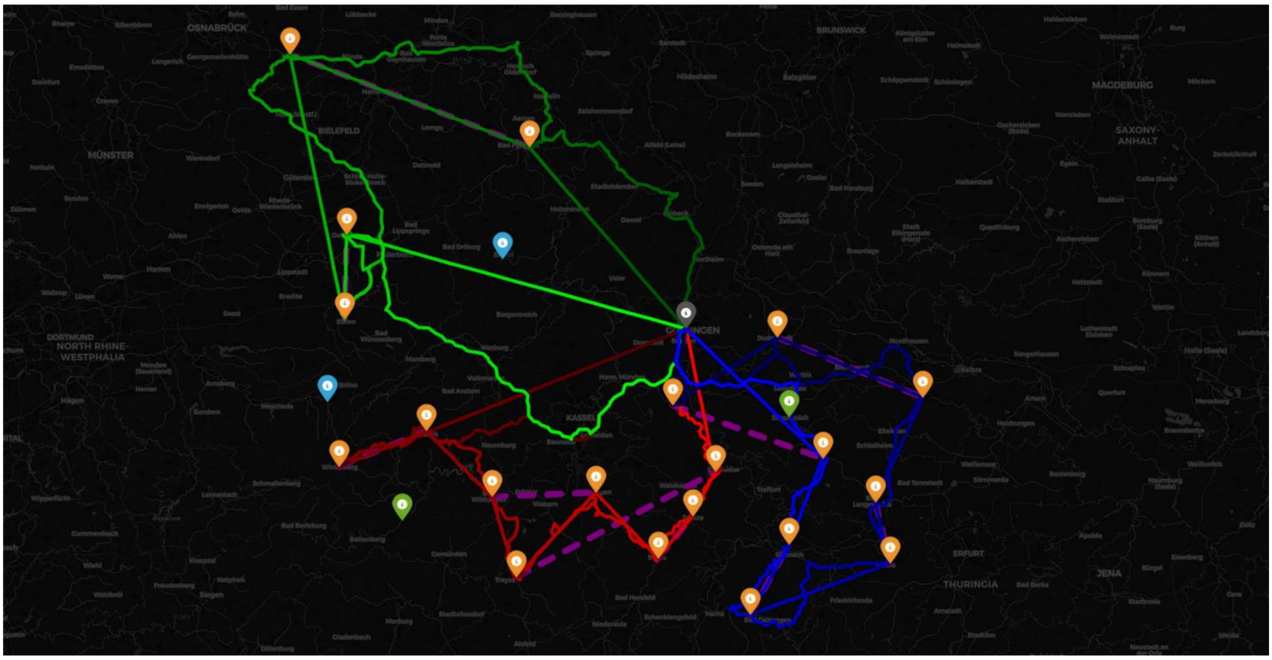

Figure 3 - Map showing the optimized routes for the baseline scenario (depot: grey, customers: orange, HRS: blue, charging point: green, vehicle tours are lines colored dark (shift start) to light (shift end), jobs with pickup and delivery in dashed magenta)

The TCO for the fleet operation of ICEV is shown in Figure 4. Since the optimisation model only took 3 vehicles to fulfil the jobs, the TCO only considers these 3 vehicles for the calculation. The TCO are given in absolute values for the one-day operation. **The TCO sum of all vehicles needed is 1675 EUR**.

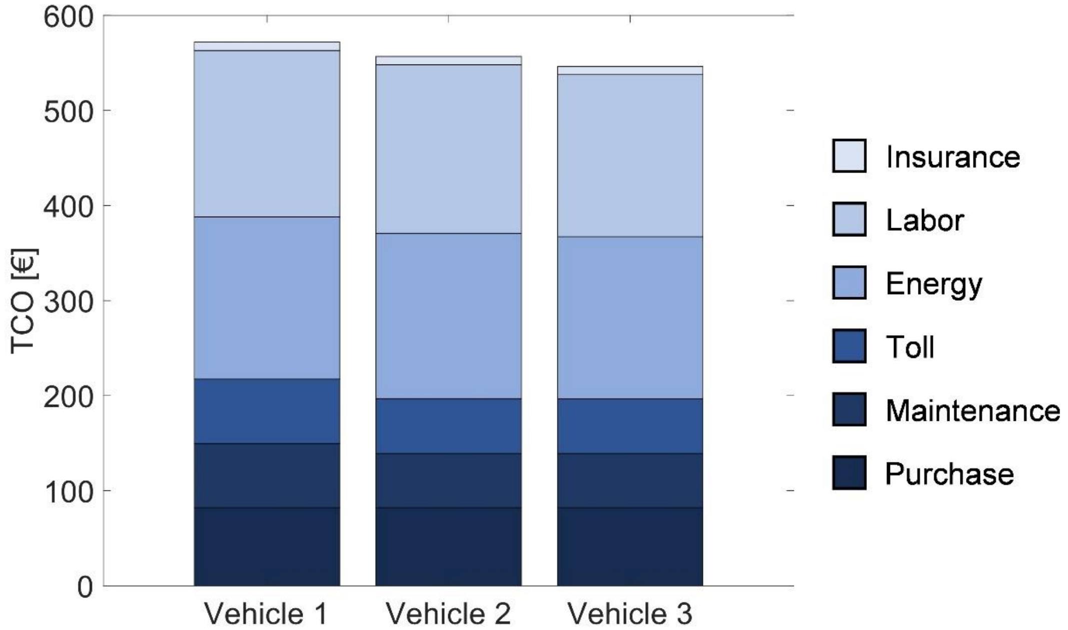

Figure 4 – TCO of each vehicle for the fleet operation with ICEV

Figure 5 shows the solution of the fleet routing optimisation model, which requires 4 FCEV to fulfil the same jobs. The assumption for this fleet operation is, that there is **no HRS infrastructure in the depot** and that vehicles start with a state of charge of 50% at the depot (because of the way back to the depot in the previous shift). **For this simulation, the hydrogen price is set to 12.5 EUR/kg and the vehicles refuel with a max mass flow of 120 g/s.**

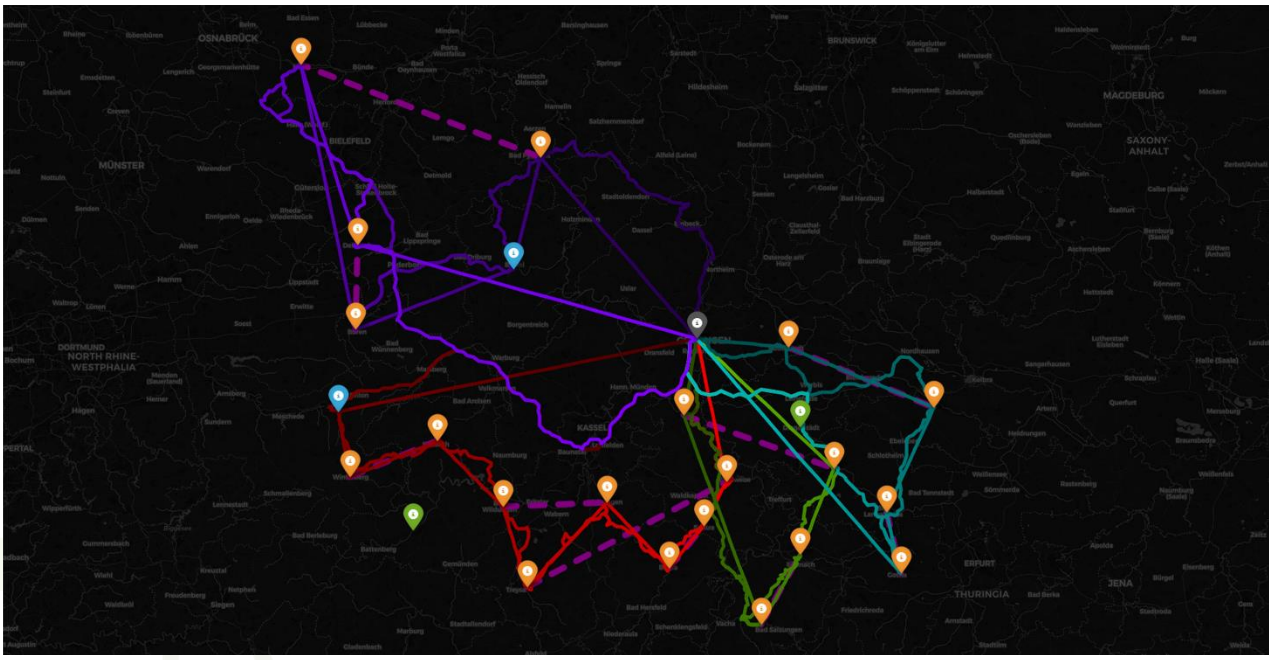

Figure 5 - Map showing the optimized routes for the fleet operation with FCEV (reference case hydrogen)

A hydrogen price of 12.5 EUR/kg and max refueling mass flow rates of 120 g/s are considered(depot: grey, customers: orange, HRS: blue, charging point: green, vehicle tours are lines colored dark (shift start) to light (shift end), jobs with pickup and delivery in dashed magenta)

The TCO for this fleet operation is shown in Figure 6. Because of the higher retail prices of FCEV at the moment, the ‘Purchase’ block is greater than for the ICEV. The fleet operation was assumed to take place in Germany, therefore there are no toll costs for FCEV. **The TCO sum of all vehicles in this operation is 3531 EUR.**

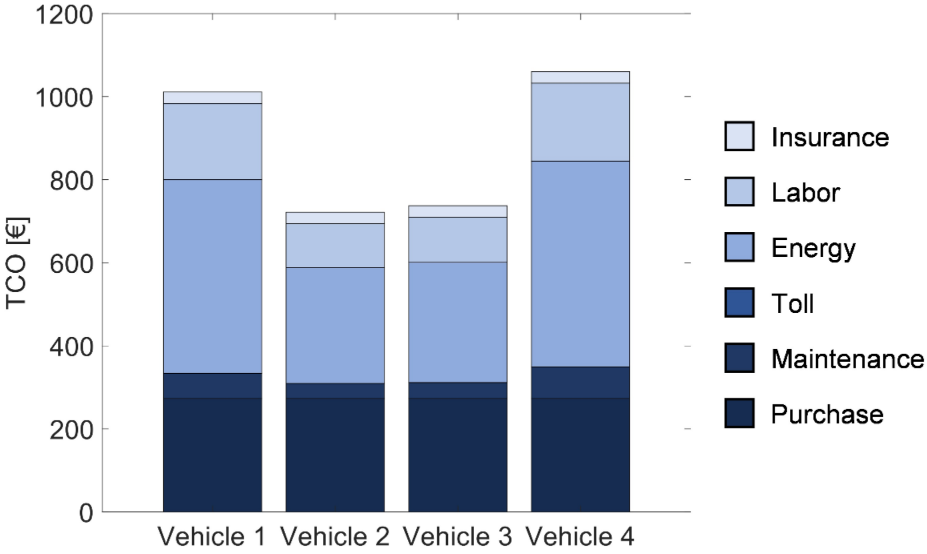

Figure 6 – TCO of each vehicle for the fleet operation with FCEV, a hydrogen price of 12.5 EUR/kg and max refueling mass flow rates of 120 g/s

Figure 7 shows the optimised routes for a fleet operation with a **lowered hydrogen price of 4.5 EUR/kg.** A reason for the different routes compared to the previous operation could be that the optimisation model is based on a metaheuristic and therefore it is not guaranteed, that the optimal solution is found every time.

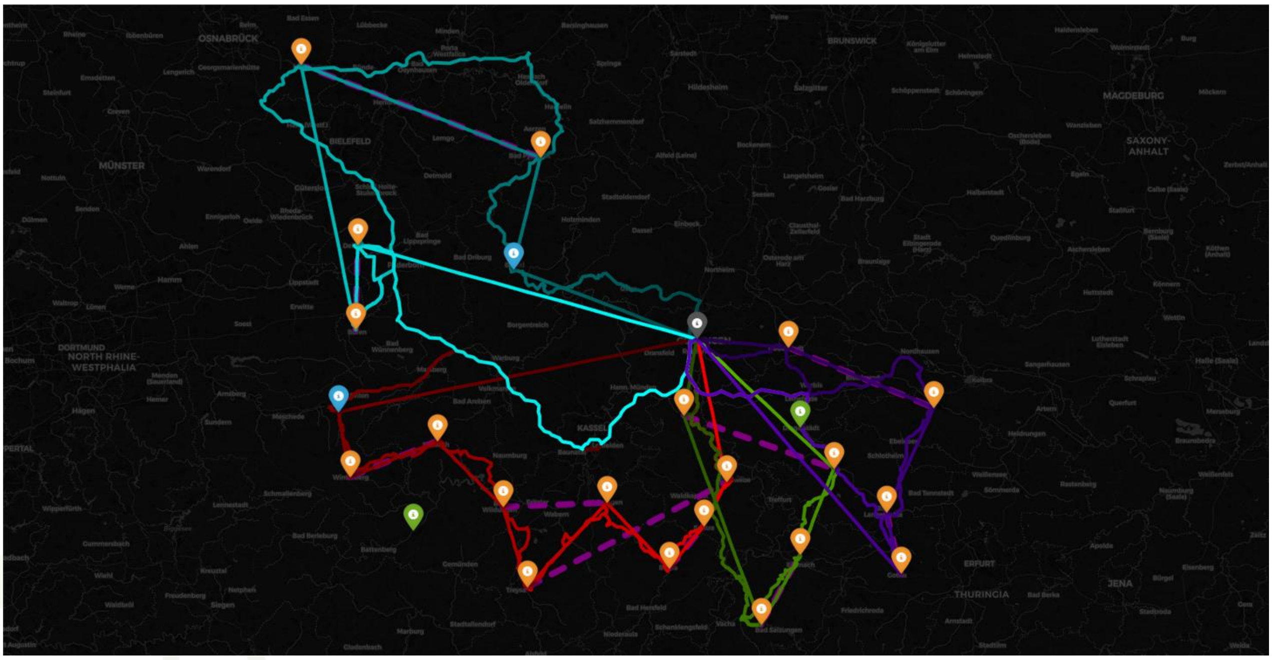

Figure 7 - Map showing the optimized routes for the fleet operation with FCEV (low hydrogen price scenario)

A hydrogen price of 4.5 EUR/kg and max refueling mass flow rates of 120 g/s are considered (depot: grey, customers: orange, HRS: blue, charging point: green, vehicle tours are lines colored dark (shift start) to light (shift end), jobs with pickup and delivery in dashed magenta)

Figure 8 shows the TCO for the fleet operation with a lower hydrogen price of 4.5 EUR/kg. **The TCO sum of all vehicles is 2552 EUR, to be compared to 3531 EUR with the higher hydrogen price and 1675 EUR of the ICEV fleet.**

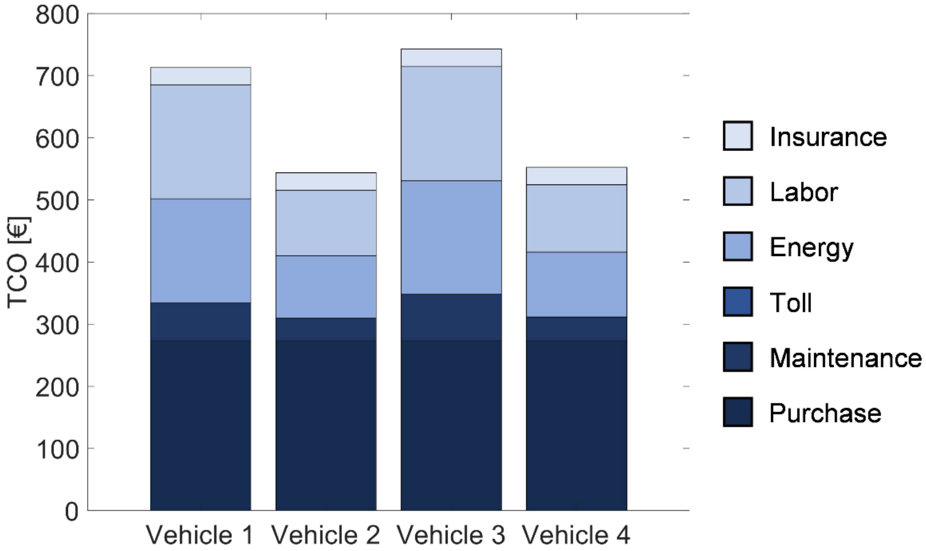

Figure 8 – TCO of each vehicle for the fleet operation with FCEV, a hydrogen price of 4.5 EUR/kg and max refueling mass flow rates of 120 g/s

Following the analysis of hydrogen price impacts, another simulation was conducted to investigate the operational and economic effects of varying hydrogen refuelling speeds. **In this scenario, the hydrogen price was back at 12.5 EUR/kg and the max mass flow rate was set to 300 g/s instead of 120 g/s in the previous simulations.** The fleet operation for this scenario is shown in Figure 9.

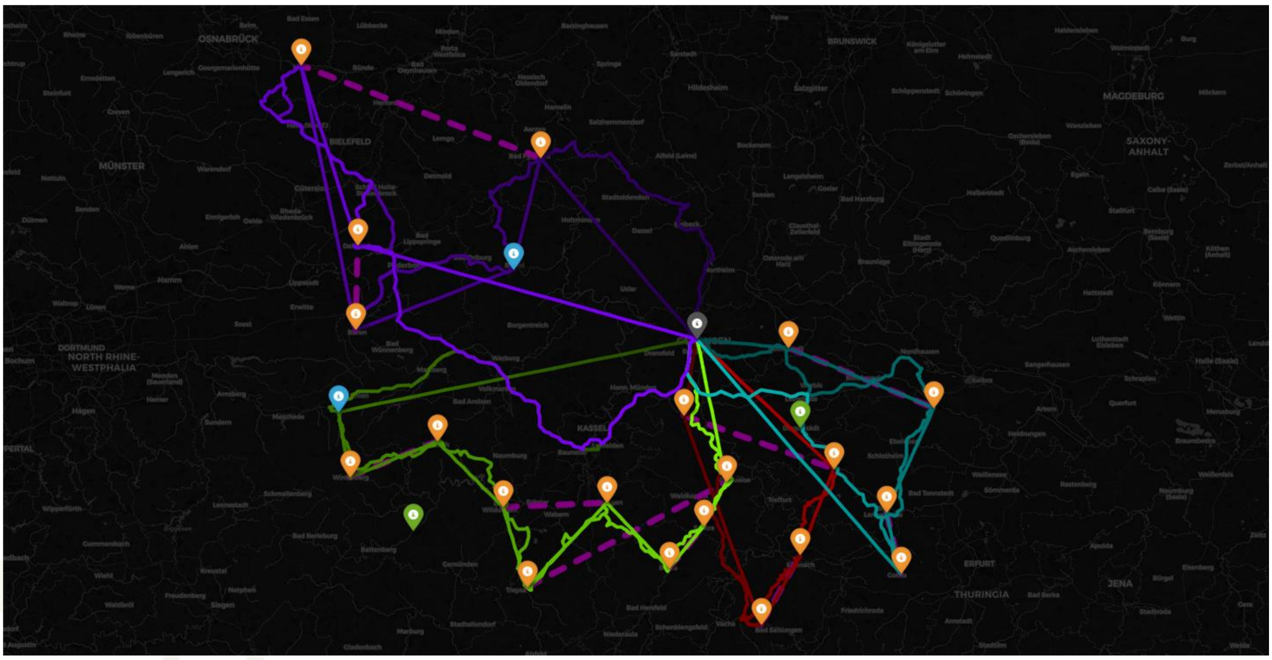

Figure 9 - Map showing the optimized routes for the fleet operation with FCEV (high-flow hydrogen refueling scenario)
A hydrogen price of 12.5 EUR/kg and max refueling mass flow rates of 300 g/s are considered (depot: grey, customers: orange, HRS: blue, charging point: green, vehicle tours are lines colored dark (shift start) to light (shift end), jobs with pickup and delivery in dashed magenta)

The TCO for the fleet operation with FCEV and a max mass flow rate of 300 g/s when refuelling is shown in Figure 10. **The TCO sum of all vehicles is 3526 EUR compared to 3531 EUR of the operation with a max mass flow rate of 120 g/s.** The reason for the lower TCO is the shorter required work time. **It is important to note, that this is specific to this fleet operation. In another scenario, the lower refuelling time could lead to a lower number of vehicles required to fulfil the scenario. The size of the FCEV chosen as part of the fleet can also influence the results.**

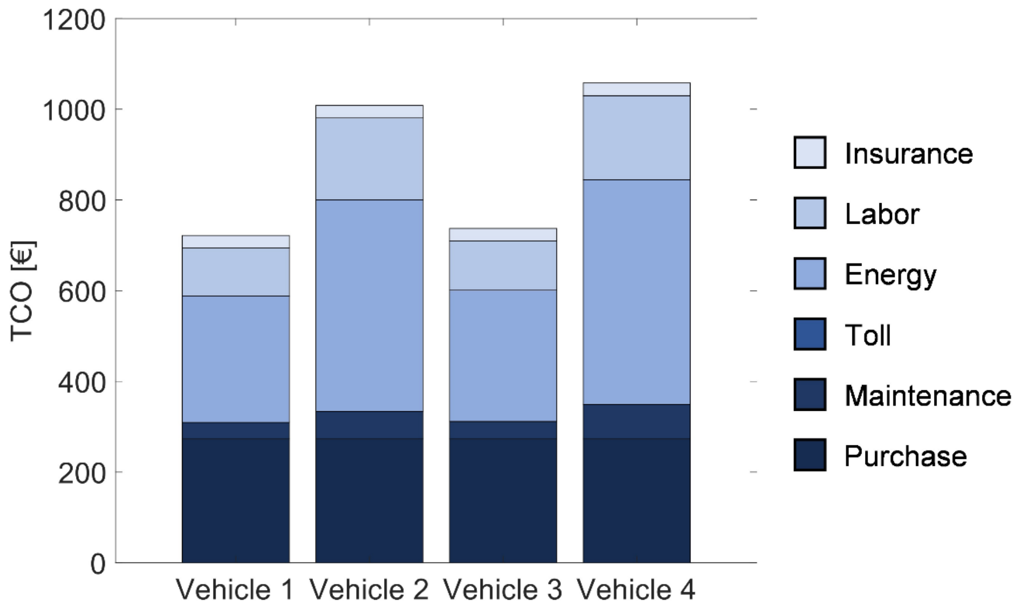

Figure 10 – TCO of each vehicle for the fleet operation with FCEV, a hydrogen price of 12.5 EUR/kg and max refueling mass flow rates of 300 g/s

As a conclusion, this part allows to understand what are the main aspects about refuelling that are of interest for fleet owners. It must be noted that performance criteria such as the driving range (that depends on final SOC reached during refuelling), the time taken to refuel and of course the cost are of primary importance. Such aspects will be investigated in the rest of this report. Finally, safety is always the first priority. This topic is investigated in next part.

4 Safety regulatory framework for refueling

Safety regulatory framework is investigated in this part. Both EU and national level regulation (Finland, France, Germany Turkey) are detailed.

4.1 Safety regulations in EU

The EU has implemented directives and regulations that apply to the safety of hydrogen refuelling stations, including the Seveso- and ATEX-directive. **The relevant directives and regulations regarding hydrogen refuelling and hydrogen refuelling stations are listed in Table 2**.

Table 2 Relevant directives and regulations for HRS safety within the EU.

Legislation	Description
Directive 2012/18/EU	The Seveso-directive focuses on major accident hazard prevention. As hydrogen is classified as a dangerous substance, hydrogen storage and processing are included in the scope of the directive.
Directive 2014/34/EU	The ATEX Equipment Directive sets safety requirements for the equipment and protective systems in explosive atmospheres.
Directive 1999/92/EU	The ATEX Workplace Directive includes minimum safety requirements to ensure safety of workers
Directive 2014/68/EU	The Pressure Equipment Directive (PED) concerns the design, manufacture, and conformity of pressure equipment of greater pressure than 0.5 bar. The directive includes technical specifications to ensure the safety of pressure equipment.

Directive 2012/18/EU, also known as the Seveso-directive focuses on the prevention of major accidents involving dangerous substances. As hydrogen is classified as a dangerous substance, certain obligations apply. Although, the obligation within the directive only applies to quantities of hydrogen that exceed 5 tonnes. The so-called upper-tier establishments handle more than 50 tonnes of hydrogen. Operators are obliged to notify competent authorities of the details of the establishment, including name, place, amount of substance, activity, and the surrounding environment. Other obligations include the deployment of a major accident prevention policy, safety reporting and internal emergency plans for upper-tier establishments, siting-related risk mitigation supervised by the authorities with new establishments, developments e.g. transport routes or modifications related to the establishment, and obligation for public consultation on specific individual projects.

The Pressure Equipment Directive (PED) 2014/68/EU applies to design, manufacture, and conformity of pressure equipment with a maximum allowable pressure greater than 0.5 bar. Hydrogen is considered as a Group 1 fluid which consists of dangerous fluids e.g. flammable gases. Because of this most equipment related to storage, production, and distribution of hydrogen are susceptible to the technical requirements of PED to ensure the safety of the equipment.

EU parliament and the council have issued **directives for the explosive environments (Ex, ATEX).** The directives define the basic procedures and refer to standards for further details and procedures. Additionally, European Commission releases implementing decisions for further refinements or updates of the link between the standards and the legislation (directives). The EU member states implement the directives in their own legislation. Also, national additions and standards are possible and are in use.

The main European Ex regulations are 2014/34/EU (EU, 2014): Equipment and protective systems intended for use in potentially explosive atmospheres, and 1992/92/EC: Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres. The 2014/34/EU covers the equipment which are intended to be used in the explosive atmospheres, and it is the relevant directive concerning this study.

Regulation (EU) 2018/1804 on the deployment of alternative fuels infrastructure (AFIR) is also a key regulation when it comes to alternative fuel infrastructure and refuelling of hydrogen. While it is not safety-specific, AFIR refers to several, usually European, standards and norms, and the implementation of the regulations is accomplished by following such standards.

4.2 Safety standards

There are several standards and standard categories related to the ATEX and other safety topics. **The most important standards for the study are in EN (European Standard, *"Europäische Norm"*) category**. Such standards are usually released and approved by CEN (European Committee for Standardization) or CENELEC (European Committee for Electrotechnical Standardization). Many of them are also adopted as national standards with additional prefixes.

Furthermore, **many international standards by ISO (International Organization for Standardization) and IEC (the International Electrotechnical Commission) are approved and harmonized as European Standards.** There are also national standard bodies, such as DIN (*Das Deutsche Institut für Normung*) in Germany, AFNOR (*Association Française de Normalisation*) in France, SFS (*Suomen standardit ry*) in Finland, BS (*British Standards*) in the UK, and TSE (*Türk Standartları Enstitüsü*) in Turkiye ; and specific product area standards, such as VDA (*Verband der Automobilindustrie*, automotive standards).

4.2.1 Hydrogen storage and usage

Hydrogen refuelling stations (HRS) are covered with several standards and regulations. The most important ones for ESCALATE refuelling stations are the gaseous hydrogen refuelling standards, including ISO/TR 15916:2015 (Basic considerations for the safety of hydrogen systems).

Moreover, regulation (EU) 2018/1804 on the deployment of alternative fuels infrastructure (AFIR) recommends outdoor hydrogen refuelling points dispensing gaseous hydrogen used as fuel on board motor vehicles to comply with standard EN 17127:2020 but insists on complying at least to the interoperability and fuelling algorithm requirements in that standard. In addition, AFIR insists hydrogen refuelling points to comply with hydrogen quality specifications in standard EN 17124:2022 and refuelling connectors of gaseous hydrogen to comply with standard EN ISO 17268:2020. However, technical specifications for refuelling connectors for heavy-duty vehicles are missing from AFIR. They are currently being discussed by ISO workgroups.

4.2.2 ATEX standards

Table 3. ATEX standards for evaluating the locations for the refueling equipment.

Standard code	Standard name	Function when evaluating location
EN IEC 60079-0	Explosive atmospheres - Part 0: Equipment - General requirements	General requirements

EN IEC 60079-10	Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres	Area classification and selection the right operating classes
EN IEC 60079-29-2	Explosive atmospheres - Part 29-2: Gas detectors – Selection, installation, use and maintenance of detectors for flammable gases and oxygen	

Table 3 gives the overview of the main relevant ATEX standards for hydrogen refuelling: the general requirements including the equipment classes, the area classifications, and gas detectors, which are relevant for hydrogen handling.

In the EN IEC 60079-0:2019 and EN IEC 60079-10-1:2021, the equipment is divided into 3 ATEX classes (1, 2, and 3). Furthermore, there are 3 ATEX zones for explosive environments due to the vapours from liquids and gases (0, 1, and 2). The suitability of the equipment classes for each ATEX zone are presented in Table 4. For example, the equipment with ATEX class 1 is suitable for all ATEX zones, whereas the equipment with ATEX class 3 is suitable only for the ATEX zone 2.

Each of the ATEX equipment classes have their own conformance requirements in EN IEC 60079-0, 2019. The requirements are shown in Table 4. The requirements are the most stringent for class 1 equipment.

Table 4. ATEX requirements.

ATEX equipment class number/ Category	ATEX class name	Suitability for ATEX zone	IEC protection level (EPL)	Conformance requirements for the equipment class
1G	very high	0, 1, 2	Ga	Certificate, type tests + production quality assurance OR product inspection
2G	high	1, 2	Gb	Certificate, for electric equipment same as class 1
3G	normal	2	Gc	Internal inspection by manufacturer (CE)

4.3 National safety regulations

The national safety regulations for Turkiye, Germany, France, and Finland are addressed here, because Pilots 1 and 2 are planned to be refuelled in these countries. Pilot 1 is a multi-energy pilot with both battery and fuel cell energy sources, whereas Pilot 2 uses exclusively fuel cell. Pilot 1 will be tested in Finland, and Pilot 2 is planned to be operated between France and Germany, as well as in Turkiye.

4.3.1 Finland

Several laws regulate hydrogen and hydrogen safety in Finland. These include the chemical safety legislation, ATEX, pressure equipment legislation, rescue legislation, environment legislation, and building legislation. The most relevant legislation is presented here.

The chemical safety legislation of Finland (390/2005) states that the hydrogen refuelling stations are under the supervision of rescue authorities *(pelastuslaitos*) in case the amount of hydrogen at the HRS is less than 2 tonnes. More than 100 kg of stored hydrogen should be reported to the rescue authorities. After exceeding 2 tonnes the handling and storage is considered large-scale and therefore the responsibility moves to the Finnish Safety and Chemical Agency (*Tukes*). In this case a permission is required for the operation. The construction of distribution pipes for hydrogen always requires a permission from Tukes.

Decree (856/2012) on the safety requirements of handling and storing dangerous goods industrially includes safety requirements for the placement of the facility but also for, e.g., ventilation and leak detection.

In Finland the EU ATEX directive 2014/34/EU is validated to law 1139/2016. There is also a government decree 1439/2016 for further details of the legislation. The directive 1992/92/EC is validated as a Finnish government decree Vna 576/2003.

All the EN IEC-60079 series standards, EN ISO/IEC 80079-34:2020 and EN 13617-1, 2021 are adopted as SFS standards, and some of them are also translated in Finnish.

In addition, there is the Finnish national standard SFS 3352, 2014, giving guidelines for the practical Ex zones in the areas of the service stations, which could also be partially applicable to the hydrogen refuelling. Finland has fully adopted the European standards, and the only main addition is the SFS 3352, 2014, which mainly gives some practical details concerning the ATEX classification at the fuelling stations.

Any specifications given in the Regulation (EU) 2018/1804 on the deployment of alternative fuels infrastructure (AFIR) must be complied with in Finland as in other EU member states. AFIR states that the minimum capacity of the refuelling station must be either 1 or 2 tonnes of hydrogen depending on the frequency of the heavy-duty traffic and equipped with 700 bar refuelling.

4.3.2 France

There are multiple directives, standards and norms that needs to be followed when building and operating a hydrogen station. It can be noted that all the related EN standards are adopted either directly or as French translations as French national standards by AFNOR, with NF prefix.

First of all, the ATEX directive 2014/34/EU must be applied and is validated in French decree Décret n°2015-799. In addition, the text "*Arrêté du 28 juillet 2003 relatif aux conditions d'installation des matériels électriques dans les emplacements où des atmosphères explosives peuvent se présenter* » should be followed, as well as the Directive 1999/92/EC of the European Parliament and of the Council of 16 December 1999 on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.

The pressure equipment directive 2014/68/UE (Décret n°2015-799) must also be followed when relevant, as well as the machinery directive 2006/42/CE (Décret n°2008-1156), electromagnetic compatibility directive (Décret 2015-1084), and low voltage directive 2014/35/UE (Décret n°2015-1083).

Depending on the size of the station and the quantity of hydrogen it contained, the hydrogen station can fall in the scope of the French regulation for *"ICPE – Installations classées pour la protection de l'environnement"* (Facilities classified for environmental protection). If it does, the French ICPE code must be followed. For hydrogen, the most impactful are ICPE 4715 (*Arrêté du 12 février 1998*) and IPCE 1416 (*Arrêté du 22 octobre 2018*, soon to be revised).

Moreover, the distribution of hydrogen at the station must follow the *« Arrêté du 8 décembre 2017 relatif aux caractéristiques de l'hydrogène en tant que source d'énergie pour le transport »*. Measurement of distributed hydrogen is regulated by the « *Arrêté du 30 octobre 2009 relatif aux ensembles de mesurage de masse de gaz compressé pour véhicules* », that relies on the compliance with OIML R139 recommendations (2018 version).

Additionally, as it is stated by the AFIR (REGULATION (EU) 2023/1804), the H2 stations built from now should comply with EN 17127:2020 (interoperability, protocol), EN 17124:2022 (quality), EN ISO 17268:2020 (connectors).

Finally, French Environmental and Labor codes must obviously be followed at all times when building and operating a hydrogen refueling station.

4.3.3 Germany

In Germany the EU directive 2014/34/EU is validated to law *Elfte Verordnung zum Produktsicherheitsgesetz 1 (Explosionsschutzprodukteverordnung - 11. ProdSV) - § 2 Begriffsbestimmungen (Bundesministerium der Justiz, 2021)*. It refers directly to the EU directive.

All the related EN standards are adopted either directly or as German translations as German national standards by DIN.

Also, DIN NA104 working group has released a technical rule DIN SPEC 26056 Hazardous area at storage tanks and its equipment, 2016. The rule specifies the potentially explosive atmospheres in storage tanks as well as in and around pipelines, fittings, plant components, in and around pumps, in and around chambers, shafts and other rooms below ground level and around aboveground storage tanks outdoors.

In addition to these regulations, hydrogen refuelling stations in Germany are categorised according to their hydrogen storage capacity or whether on-site electrolysis is provided. Depending on the stations category, different authorisation procedures must be carried out and additional regulations to those stated above have to be considered. If the hydrogen storage capacity is less than three tons, the HRS is authorised in accordance with the *Betriebssicherheitsverordnung – BetrSichV*. If the capacity exceeds three tons or if on-site electrolysis is provided, in addition to the *BetrSichV* the authorization process also includes the *Bundes-Immissionsschutzgesetz – BImSchG.* These two directives describe the approval procedure for the hydrogen refuelling station and require an inspection by an external organisation, such as the Technical Inspection Agency (TÜV). The inspection is mainly based on three directives: the ISO 19880-1 as standard for gaseous hydrogen fuelling stations, the DIN EN 17127 as standard for the outdoor hydrogen refuelling stations for dispensing gaseous hydrogen and the TRBS 3151 as standard for prevention of fire, explosion and pressure hazards at petrol stations and gas filling systems.

4.3.4 Turkiye

Turkish Standards Institute has accepted and published the standard numbered TS ISO 19880-1:2021-09 for fuel stations (hydrogen gaseous) on 30.09.2021, which was approved by ISO on 04.03.2020. There is no registration, application or framework for the hydrogen refilling station operating according to official records or licensed by the energy market supervisory board (information was requested with the official application). Within the scope of this project, it is aimed to establish a hydrogen filling station and make the country and the hydrogen ecosystem gain experience.

Related to ATEX issues, regulation on the Protection of Workers from the Dangers of Explosive Atmospheres (Number:28633) has been prepared. It is based on Article 30 of the Turkish Occupational Health and Safety Law No. 6331 dated 20/6/2012 and in parallel with Directive 1999/92/EC of the European Parliament and of the Council dated 16/12/1999.

4.4 Recommendations for future regulations targets

Lack of standards related to hydrogen technologies and applications is currently an important barrier to invest in technologies and applications, and to their deployment [5]. Situation will be this even until 2030, because only then the standardization in the subject area will be comprehensive according to the European road map [6].

Therefore, it seems particularly important to continue identifying the gaps in the legal and administrative framework and **also to learn and accumulate knowledge about the best practices in safety in the**

context of hydrogen refuelling station, in order to be able to build relevant future regulation and guidelines.

It may be interesting at this point to mention the ongoing work of the **MultHyFuel European project, aiming to "contributing to the harmonization of existing laws and standards based on practical, theoretical and experimental data as well as on the active and continuous engagement of key stakeholders**" [7]. This European project[2] is currently ongoing and is especially working on tackling this problematic of lack of regulation and lack of harmonization between the approaches chosen among the various EU countries. MultHyFuel partners are in the process of establishing guidelines for multifuel stations, especially about safety barriers, separation distances and hazardous area classifications. It is thus highly recommended to take into account their work while drafting new standardization documents or while harmonizing them. [8]

[2] The MultHyFuel project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101006794. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research

5 Refueling protocols

5.1 State-of-the-art of refuelling protocols

5.1.1 Refuelling protocols

To fuel hydrogen vehicles, specific automated procedures to control refuelling process called "fueling protocols" or "refuelling protocols" need to be followed. Such protocols **ensure that safety limits are respected during refuelling, while ensuring satisfying performances** [9].

Why are protocols necessary?

The point of refuelling is increasing hydrogen quantity and consequently hydrogen pressure in the vehicle tanks, in order to provide it the fuel to drive. However, these tanks have a maximum pressure limit, generally 43.75 MPa (for H35 vehicles) or 87.5 MPa (for H70 vehicles). Therefore, the **first goal of the fuelling protocol is to prevent the tank pressure to exceed this maximum operating pressure.** The protocol is also in charge of preventing overfilling, which occurs when the state of charge exceeds 100%[3].

Moreover, it can be observed hydrogen is heating when dispensed, mostly due to :
- Inverse Joule-Thomson effect during gas expansion between high-pressure storage in the cascade and fuelling line
- Thermal exchanges with the ambient air after hydrogen is cooled in the heat exchanger
- Compression in the vehicle storage.

However, hydrogen tanks in vehicles are allowed to be operated only between -40°C and 85°C [4]. Therefore, **the protocol must ensure the gas temperature always stays within these limits** and does not heat too much. This is done via controlling the rate of pressure increase.

Protocol must also ensure the flow rate stays within the allowed limits.

Finally, the **last goal of the protocol relates to customer satisfaction, and aims at providing good performance in terms of fuelling time and final state of charge**. For instance, a customer would want its vehicle to be fuelled as fast as possible. But if there are high pressure drops in station and vehicle fuelling lines, it can conduct to low final SOC if the fuelling goes too fast, which is not satisfying either. Therefore, the fuelling protocol will try to find the best way to conduct the fuelling while keeping within the safety limits.

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[3] $SOC = \frac{\rho(P,T)}{\rho(NWP,15°C)}$.
If SOC is more than 100%, a change in temperature could induce a resulting pressure exceeding the maximum operating pressure, which needs to be prevented.

[4] See Regulation n° R134 where extreme temperatures are -40°C and 85°C;

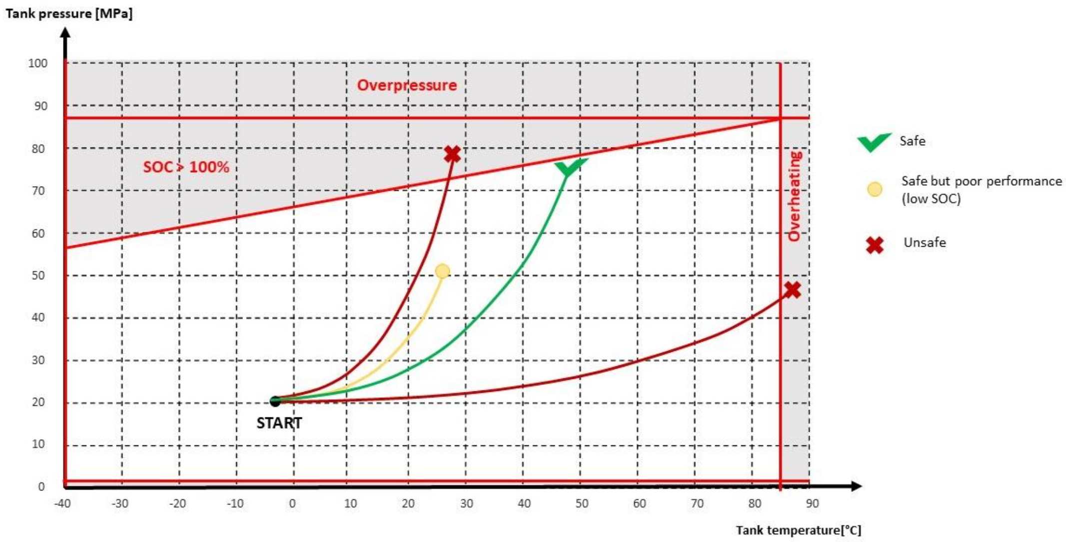

Figure 11. Boundary conditions for H70 fueling.

The boundary conditions for H70 refuelling are represented in Figure 11. Fuellings are represented in the (temperature, pressure) space. The green fuelling is safe in terms of thermodynamical conditions reached, and ends with a satisfying SOC. In yellow is represented a safe fuelling but reaching a low SOC. In red are represented unsafe fuelling, leading either to overheating or to overfilling.

Moreover, **when vehicle and station are equipped, communication from vehicle to station can be used using infrared technology**. Among other data, it transmits the values of pressure and temperature in the vehicle tanks all along the refuelling process, allowing to improve fueling performances. However, today, **safety of the fuelings do not rely on communication.**

Thus, it can be summarized the following:

Fueling protocols are necessary to ensure fueling performance and safety:

Objectives:

- Fuel as fast as possible
- Reach a state of charge close to 100%

Constraints

- Gas temperature stays between -40°C and 85°C
- Gas pressure stays below 43.75 MPa (H35 fueling) or below 87.5 MPa (H70 fueling)
- State of charge stays below 100%
- Mass flow stays below maximum mass flow rate allowed (60 g/s, 90g/s, 120 g/s or 300 g/s)

In order to meet such objectives while respecting the constraints, fuelling protocols often prescribe the temperature of hydrogen delivered, the fuelling speed (in terms of pressure increase per unit time for instance), and the stop criteria to respect.

How are protocols established?

To define a fuelling protocol, there are some main steps to follow:

- First, **the use cases for the protocol should be carefully defined**. It includes the thermodynamic safety limits (for instance, the minimum and maximum pressure, gas temperature, mass flow, ambient temperature,…), the ranges of vehicles to which the protocols can be applied, the kind of stations that can apply it, the type of communication that may be used, …

- Then, the structure of the protocol is defined. A **validated thermodynamic model is used to derive the parameters** of the fuelling protocols. For instance, such parameters can be a target pressure to end the fuelling, a ramp rate to apply for the pressure increase, a delivery temperature to respect, … The values of these parameters can vary with respect to ambient conditions or vehicle type and initial state. Risk assessment and fault management should be taken into account in the design of the protocol.

- Finally, the **protocol should be tested**, to verify it is safe and gives the expected results.

The new ***ISO/DIS 19885-1*** *- Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 1: Design and development process for fuelling protocols* [10]**, give some details and requirements on how to define, design, verify and validate the fueling protocols**.

5.1.2 Publicly available protocols at the beginning of ESCALATE project

Protocols can be distinguished between prescriptive and non-prescriptive ones. Non-prescriptive protocols, such as SAE J2601-2 [11], establish the boundary conditions for safe and performant refuelling, but do not explain how to reach them. On the contrary, prescriptive protocols give precise and specific guidance on how to fuel. Among them, there are some "private" protocols, owned and applied by private actors as station manufacturers, but there are also standardized prescriptive protocols. As far as the members of consortium are aware, the public prescriptive protocols used widely in Europe at the beginning of ESCALATE project (beginning of 2023) are:

- **SAE J2601** [12]
- **CEP/Wenger protocol** [13]

The use cases for which they can be applied are given below in the Table 5 and Table 6. The protocols should not be used outside of its expected range because it can lead to overfilling or overheating.

Table 5 – Main prescriptive protocols used in Europe for H35 vehicles in 2023

Total vehicle capacity	1.2 – 6 kg	6 – 20 kg	20 – 42.5 kg	> 42.5 kg
H35 vehicles	**SAE J2601** **Table-based** Individual tanks ~1 to 6 kg Cooling T40, T30 or T20 60 g/s max	/	**CEP/ Wenger protocol** Individual tanks 4 to 8.5 kg Cooling: down to -40°C 120 g/s max	/
	SAE J2601 **MC formula** Individual tanks ~1 to 6 kg Cooling -17.5°C to -40°C 60 g/s max			

Table 6 - Main prescriptive protocols used in Europe for H70 vehicles in 2023

Total vehicle capacity	2 – 10 kg	> 10 kg
H70 vehicles	**SAE J2601** **Table-based** Individual tanks 2-10 kg Cooling T20, T30 or T40 60 g/s max	**SAE J2601 - DEGRADED PERFORMANCE** **Table-based Cat D** Individual tanks 2 to 10 kg Cooling T20, T30 or T40 60 g/s max
	SAE J2601 **MC Formula** Individual tanks 2-10 kg Cooling -17.5°C to -40°C 60 g/s max	**SAE J2601 - DEGRADED PERFORMANCE** **MC Formula Cat D** Individual tanks 2 to 10 kg Cooling -17.5°C to -40°C 60 g/s max

Note : In the major existing refueling protocols, there is also an Japanese national standard JPEC-S 0003, that is very close to SAE J2601. See [9] *for more detail.*

Currently there are two main fueling methodologies:

A- Table-based fueling (SAE J2601 and CEP/Wenger)

This fueling method is based on two key parameters:

- **APRR** (Average Pressure Ramp Rate) : the constant pressure ramp rate applied by the dispenser to fuel the vehicle
- $\mathbf{P_{target}}$: the target pressure: the fueling stops when this pressure is reached by the dispenser (or when SOC=100% is measured if the fueling is a communication fueling).

In SAE J2601, these parameters are already computed and are given in tables (except for SAE J2601 category D where APRR should be calculated with a formula). They are chosen at the beginning of the fueling depending mainly on:

- The pressure class and the size of the vehicle storage
- The range of hydrogen injection temperature (there are various categories)
- The presence or absence of infrared communication between station and vehicle
- The ambient temperature
- The initial pressure of the vehicle storage.

Options as “top-off” and “cold dispenser” can be applied in SAE J2601, more detail about it can be found directly in the protocol.

B- MC formula fueling (SAE J2601)

This fueling method allows to improve the fueling time and to limit the constraints on the cooling. Indeed, the fueling temperatures are no longer classified into categories, but the protocol considers the exact value of the temperature delivered along the fueling via the mass average temperature.

- t_{final} parameter is used to compute the pressure ramp rate (PRR). t_{final} can be computed thanks to a formula given in the protocol.
- The end of the fueling is also when P_{target} or P_{limit} are reached by the dispenser, (or when SOC=100% is measured if the fueling is a communication fueling). P_{target} is either read in tables or computed at each step of the fueling using equations based on thermodynamic modeling.

The formulas to compute these parameters or the table where to read them depend mainly on:

- The pressure class and the size of the vehicle storage
- The hydrogen injection temperature through the **MAT** (mass average temperature, detailed explanation on how to compute it is in the standard)
- The presence or absence of infrared communication between station and vehicle
- The ambient temperature
- The initial pressure of the vehicle storage.

Main limitations

The main limitations for these protocols identified by ESCALATE consortium are:

- **Lack of widely used protocol to fuel efficiently large H70 vehicles** (SAE J2601 category D is quite slow over around 30 kg): the speed is not yet sufficient to reach fossil fuel parity for heavy-duty vehicles
- **Lack of widely used protocol for large H35 vehicles** between 6 and 20kg, and over 42.5kg.
- Protocols are built on v**ery conservative hypotheses:** there is often an important **margin**, and speed could have been higher in most of the refuellings.
- There is **no protocol to fuel H70 vehicles warmer than –17.5°C**

How to improve these aspects?

- **SAE J2601-5**, that did not exist at the beginning of the project, is a very good answer to most of the previous limits mentioned: i**t enlarges the scope of the vehicles targeted and allows warmer temperatures** than in SAE J2601. This document is described in the next part 5.1.3.
- **Customized protocols** that are derived specifically for a vehicle can also greatly improve the performance by limiting the margins. For instance, it can take advantage of the presence of type III tanks, or use the precise geometry of the tanks or the piping arrangement. As an example, **PRHYDE protocols** are based on customized tables (see paragraph 5.1.4)
- Fuelling efficiency can also be increased and safety can be improved by **decreasing the HRS command response time**, which can be up to 5s in most cases according to SAE J2601.

5.1.3 SAE J2601-5 protocols

SAE J2601-5 [14] was published on February, 2024. It aims at bridging the existing gaps and giving refueling protocols on a far **more exhaustive range of vehicles.** Table 7 and Table 8 below show how this new SAE document gives prescriptive protocols to fuel efficiently ranges of vehicles that were not previously covered by any widely spread prescriptive protocol. It is especially important for **heavy-duty vehicles**.

Table 7 - SAE J2601-5 positioning among main H35 protocols

<table>
<tr><th>Total vehicle capacity</th><th>1.2 – 6 kg</th><th>6 – 20 kg</th><th>20 – 42.5 kg</th><th>42.5 – 180 kg</th><th>> 180 kg</th></tr>
<tr><td rowspan="3">Protocols for H35 vehicles</td><td>SAE J2601
Table-based
Individual tanks 1 to 6 kg
Cooling T40, T30 or T20
60 g/s max</td><td rowspan="2">/</td><td rowspan="2">CEP/ Wenger protocol
Individual tanks 4 to 8.5 kg
Cooling -40°C to ambient
120 g/s max</td><td rowspan="2">/</td><td rowspan="3">/</td></tr>
<tr><td>SAE J2601
MC formula
Individual tanks 1 to 6 kg
Cooling -17.5°C to -40°C
60 g/s max</td></tr>
<tr><td>/</td><td colspan="3">SAE J2601-5
MCF-HF-G
Individual tanks 50 to 1000 L (1.2 to 24 kg)
Cooling -40°C to 20°C
120 g/s max
Methods to improve performance (K0, PRR Taper)</td></tr>
</table>

Table 8 - SAE J2601-5 positioning among main H70 protocols

<table>
<tr><th>Total vehicle capacity</th><th>2 – 10 kg</th><th>10 - 201 kg</th><th>> 201 kg</th></tr>
<tr><td rowspan="4">Protocols for H70 vehicles</td><td>SAE J2601
Table-based
Individual tanks 1-10 kg
Cooling T20, T30 or T40
60 g/s max</td><td colspan="2">SAE J2601 - DEGRADED PERFORMANCE
Table-based Cat D
Individual tanks 1 to 10 kg ?
Cooling T20, T30 or T40
60 g/s max</td></tr>
<tr><td>SAE J2601
MC Formula
Individual tanks 1-10 kg
Cooling -17.5°C to -40°C
60 g/s max</td><td colspan="2">SAE J2601 - DEGRADED PERFORMANCE
MC Formula Cat D
Individual tanks 1 to 10 kg ?
Cooling -17.5°C to -40°C
60 g/s max</td></tr>
<tr><td rowspan="2">/</td><td>SAE J2601-5
Cat D HF
Individual tanks 50 to 800 L (2 to 32.1 kg)
Cooling -40°C to -17.5°C, depends on category
60 g/s max (can be 90 g/s max with COM FM in OD)</td><td rowspan="2">/</td></tr>
<tr><td>SAE J2601-5
MCF-HF-G
Individual tanks 50 to 800 L (2 to 32.1 kg)
Cooling -40°C to 0°C
60 g/s max (can be 90 g/s max with COM FM in OD) or 300 g/s max
Methods to improve performance (K0, PRR Taper)</td></tr>
</table>

*Important note: **SAE J2601-5 is a technical informative report (TIR) and not yet a standard, mostly because it needs more experimental validation.** Therefore, it is advised to be cautious while applying this protocol on a vehicle on which it has not yet been tested.*

Description:

The protocols in SAE J2601-5 were built using conservative assumptions about pressure drop and heat loss in the various components constituting the fueling line. These assumptions were drafted based on an industry survey on the current and future technical specifications of the stations and vehicles. Hypotheses chosen can be found in Appendix A of SAE J2601-5 [14], and some of them are summarized in a presentation of the TIR done by the Clean Energy Partnership [15]. Then, fuelings simulations were conducted using the H2Fills model (by NREL).

For **H70 refuelings**, two protocols are introduced:

A- ***Category D table-based protocol:***

This protocol controls fuelings with a constant pressure ramp rate (APRR) and a pressure target ($\mathbf{P_{target}}$) as described previously for table-based protocols. Here, the APRR is chosen as the **minimum between**:

- The **temperature-constraint APRR** read in tables depending on vehicle storages size, temperature category, ambient temperature
- The **flow-constraint APRR**, given by an equation depending on CHSS volume and maximum flow allowed.

Choosing the minimum ensures that neither maximum temperature nor maximum flow are exceeded.

Some new elements are introduced when compared to SAE J2601. Among them:

- The **lower bound of all temperature categories is now always -40°C** (for T40D : hydrogen is between -40°C and -33°C, for T30D : between -40°C and -26°C, T20D : between -40°C and -17.5°C)
- Minimum mass flow rate and fueling time indicator are introduced
- “Tank volume large” **TLV** parameter to communicate is introduced and can be used optionally (see below part 5.1.5)
- “Flow rate Maximum class” **FM** parameter to communicate is introduced: if allowed by communication, it is possible to fuel at 90g/s maximum flow rate instead of 60g/s

As noted in [15], the assumptions of the vehicle are very different between D-category from SAE J2601 and SAE J2601-5. It is advised not to use SAE J2601 category D anymore.

Finally, a sensitivity study of the flow constraint on the APRR was done in [15]. It shows **that in European climate conditions (-10°C to +35°C), T30D gives the best performance ratio.** Indeed, T40D has higher temperature constrained APRRs as the hydrogen is more pre-cooled, but above CHSS of 500L, the flow constraint value takes over and limits the fueling speed.

B- ***MC-formula-based protocol:***

This protocol controls fuelings with an adaptative ramp rate based on the MAT. The ramp rate is constantly updated during fueling with t_{final} values. The t_{final} values are the minimum between:

- The **temperature-constraint $\mathbf{t_{final}}$** read in tables and interpolated (there are 2 interpolation options)
- The **flow-constraint $\mathbf{t_{final}}$**, given by an equation depending on CHSS volume and maximum flow allowed.

Choosing the minimum ensures that neither maximum temperature nor maximum flow are exceeded. Some additional multiplicative constants account for possible deviations in station pressure or ramp, and for low initial pressure.

The end of the fueling can be controlled with different methods: either final pressure is found in tables or calculated with MC Method calculations.

Some new elements are introduced, when compared to SAE J2601 MC-formula. Among them:

- The possibility to fuel at **300g/s** maximum for adapted stations and vehicles (H70HF), or if allowed by communication (**FM** parameter), to fuel at 90g/s maximum flow rate instead of 60g/s for H70.
- The fuel temperature can be **between -40°C and 0°C.**
- Minimum mass flow rate and fueling time indicator are introduced
- **TLV** parameter to communicate is introduced and can be used optionally (see below part 5.1.5)
- The **maximum start-up mass is now 500g**.
- To allow for accurate enough measurement with large vehicles, a **new volume measurement method** is suggested.
- New features are introduced to allow for better performances:
    - **K_0 method:** K_0 method aims at computing an estimation of the CHSS pressure in the dispenser (called MP_{calc}) and comes from the work of Honda's researchers [16]. K_0 is a constant, that is computed during a non-fueling event. It allows to estimate CHSS pressure based on the assumption that the pressure drop between the station and the vehicle is proportional to the mass flow squared over the density. This method is particularly useful to improve SOC for non-communication fuellings.
    - **PRR Taper method:** PRR Taper comes from the PRHYDE SOC Taper method. It aims to allow the vehicle to reach a high SOC at the end of the fueling even if there are important pressure drops, and not to lose PRR control when the station is not able to follow the theoretical ramp rate. To do so, when a certain threshold pressure is reached, the time at which the CHSS reaches its pressure target and the time at which the dispenser hits its maximum value are estimated. If the time for the CHSS pressure to arrive at its target pressure is larger than the time for the ramp pressure to arrive at its maximum value, the PRR is reduced so that both points can be reached simultaneously. Formulas in the SAE explain how to implement it. Knowing the CHSS pressure is needed to apply PRR Taper. For non-com fuellings, it can be applied using MP_{calc} from K_0 method.

It can be underlined that, at the time of the writing, these methods have not been extensively validated with experiments on heavy-duty vehicles, and therefore should be tested carefully.

5.1.4 PRHYDE protocols

The **PRHYDE project** (PRotocol for heavy duty HYDrogEn refuelling), was a European project that ended in 2022. It aimed at developing recommendations for non-proprietary heavy-duty refuelling protocols. PRHYDE work is described in detail in their final report [17]. In PRHYDE project, **new fuelling concepts for heavy-duty vehicles** have been created. They allow:

- **Optimization of refuelling time**
- **Improvement of the final state-of-charge** of the vehicle
- **Taking advantage of the favourable initial conditions** and fuelling history.
- **Reduction of the energy consumed** during fuelling by reducing the precooling demand
- **Easy adaptation** to new vehicles or conditions, with a fixed framework and fuelling parameters values derived for each vehicle.

Various interesting achievements of this project are summarized here (summarized from [17]).

First, **experimental campaigns were conducted**. Two test phases took place, the first to produce experimental data in order to validate numerical models, and the second to test the implementation of the new protocols and the agreement of performance simulations with experiments. In these fuelling test campaign, the hydrogen tanks were heavily equipped with thermocouple trees containing up to 16 thermocouples. This allowed PRHYDE consortium to get a good overview of the thermal behaviour and thermal heterogeneities during refuelling. It can be noted that:

- There can be **important thermal heterogeneities** in tanks during refuelling (see Figure 12). During the experimental campaign, thermal differences as high as 27°C were observed between the hotter and the colder measurement point. This should be kept in mind when designing hydrogen storage systems (in order to maximize mixing in tanks with optimized geometrical characteristics of the tank and injector), and when creating refuelling protocols.

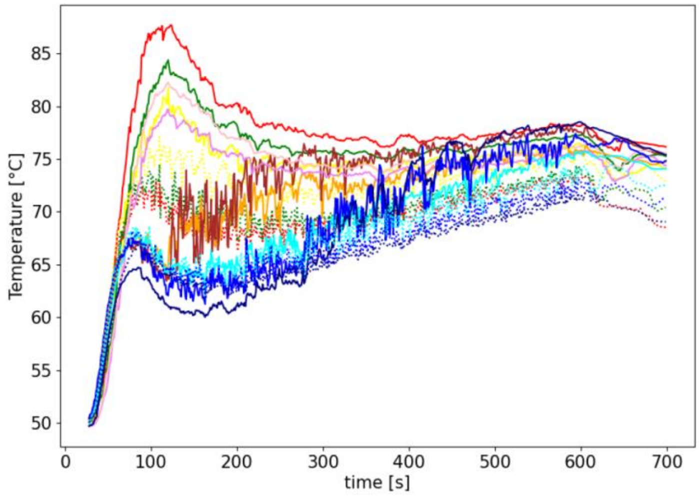

Figure 12 - Temperatures measured by the various thermocouple inserted in a hydrogen tank during refueling and stand-by, taken from PRHYDE report [17].
Important thermal heterogeneities within the tank can be observed.

- **Sometime, the OTV temperature measurement is impacted by the incoming pre-cooled gas and does not represent accurately the average temperature of the hydrogen in the tank** (see Figure 13). However, this temperature measurement is often the only one in the vehicle. According to PRHYDE report [17] , it can be due to several reasons and is likely specific to the OTV-tank combination. The existence of such an issue should be considered by the industry and actions should be taken to **ensure the temperature sensor(s) that are in the tank represent accurately the average gas temperature**, especially for advanced protocols relying on it.

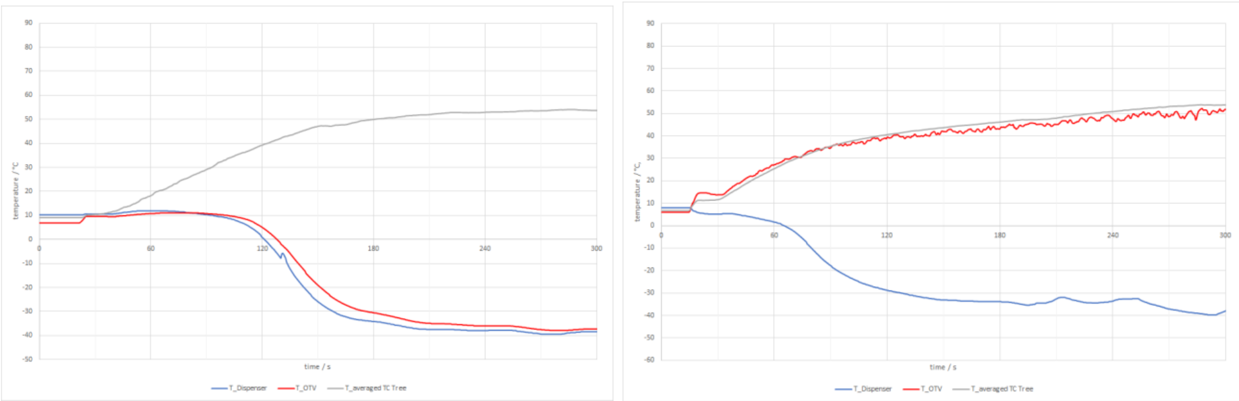

Figure 13 - Example of temperature measurements observed during PRHYDE test campaigns, PRHYDE report [17]. The temperature measured at the OTV is in red, the temperature of the hydrogen injected by the dispenser is in blue, and the average of the temperature measured by the thermocouple tree is in grey. On the left (1st OTV-tank combination), it can be seen that the OTV temperature follows the temperature of the pre-cooled hydrogen injected, and not the average temperature in the tank that is heating, which is not desirable. On the right (another OTV-tank combination), the OTV temperature is following the average temperature of the tank, which is the expected measurement.

Then, important simulation work was conducted during PRHYDE project. PRHYDE work relies mostly on **numerical simulation**, in order to be able to investigate quickly various possible ranges of parameters. Numerical models of partners and external associated entities were validated using experimental campaigns data and used in this project, and some CFD calculations were also investigated. Thus, this project was one of those that helped to validate HyFill model from ENGIE, that is also used in ESCALATE (see Figure 14).

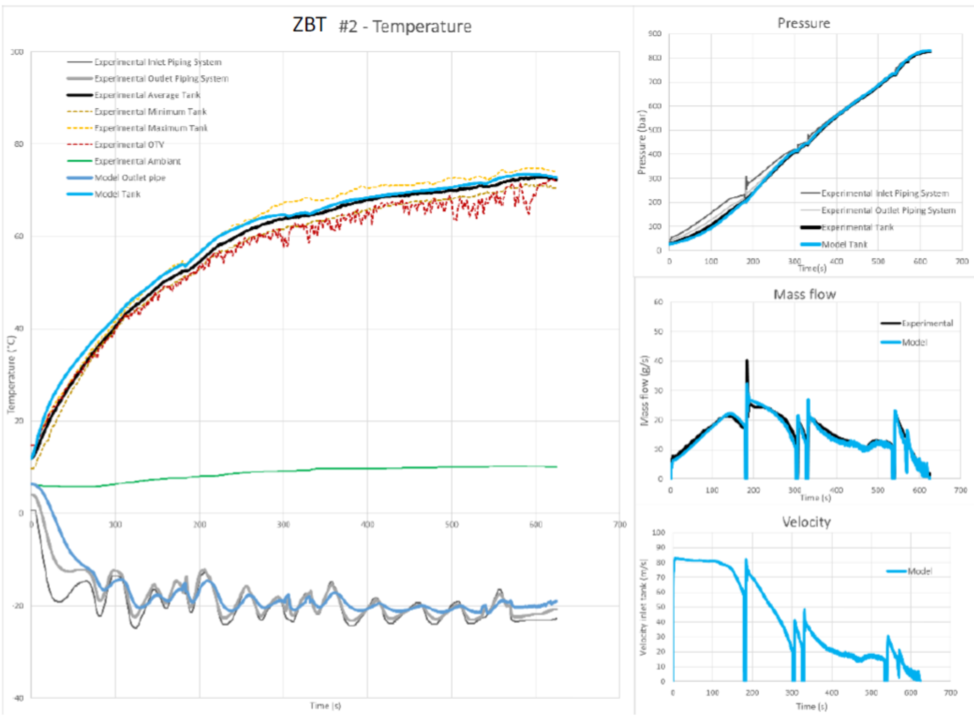

Figure 14 – ENGIE's HyFill model outputs and experimental measurements for test #2 on a type IV H70 tank at ZBT facility, taken from PRHYDE report [17].
Model and experiments show very good agreement (for instance, maximum temperature difference between simulated tank temperature and measured average temperature is 3.88° and final temperature difference is 0.3°C)

Finally, PRHYDE most important work was **the definition of new advanced protocols**. Four protocol concepts were created, as well as an additional feature called SOC Taper that can be used with every concept (it has evolved into PRR Taper in SAE J2601-5, see relating paragraph). The PRHYDE protocols are **based on the MC-Formula framework** : the fuelling is controlled using t_{final} parameters and MAT. Additionally, PRHYDE protocols limit the use of conservative hypotheses, that often lead to very important margins and therefore a loss of performance by using specific vehicle values. In order to do so, in PRHYDE framework, protocols are implemented into the dispenser, but **the dispenser get the numerical values of the fueling parameters such as the t_{final} values from the vehicle**, that communicates them to the station. More precisely, the four protocol concepts are:

- **"Static"** : there are two t_{final} tables derived specifically for the vehicle, the choice between both is made depending on the initial pressure of the vehicle.
- **"T_{gas} Initial"** : there are multiple t_{final} tables (>2) derived specifically for the vehicle. If the initial temperature of the vehicle does not show that a previous fueling just happened, the choice of the table is made depending on the initial pressure of the vehicle, to be able to take advantage of a high initial pressure. If a previous fueling just happened, table with the lowest initial pressure is used.
- **"T_{gas} Initial+"** : there are multiple t_{final} tables derived specifically for the vehicle. If the initial temperature of the vehicle does not show a previous fueling that just happened, the choice is made depending on the initial pressure and the initial temperature of the vehicle, to be able to take advantage of favourable initial conditions. If a previous fueling just happened, table with the lowest initial pressure is used.
- **"T_{gas} Throttle"** : there is only one t_{final} table derived specifically for the vehicle with a maximum allowed temperature strictly superior to 85°C (for instance, 95°C). During the refuelling, the pressure ramp is dynamically reduced depending on the vehicle temperature to prevent the gas from exceeding 85°C.

Thus, PRHYDE protocols **rely on a trusted communication between the vehicle and the station:** the station must rely on the data communicated via the vehicle to choose the fueling parameters and conduct the fueling, therefore it uses the communicated parameters for safety-relevant decision. This is not possible today with current state-of-the art communication as explained in next part 5.1.5, however this is a current topic of interest for industry.

5.1.5 Communication between station and vehicle : state-of-the-art and limitations

Communication between H2 dispenser and vehicle refueled are currently described in standards by the sole SAE J2799.

The widely used SAE J2799 is 2019 version [18]. It **covers one way data communication** from vehicles equipped with gaseous H2 tanks to H2 dispenser. **Communication system described is composed by an InfraRed emitter mounted on vehicle and by InfraRed receiver located in the nozzle dispenser**. The number of both, emitter and receiver, and their mandatory location are described by the standard so the data communication could be efficient and reliable.

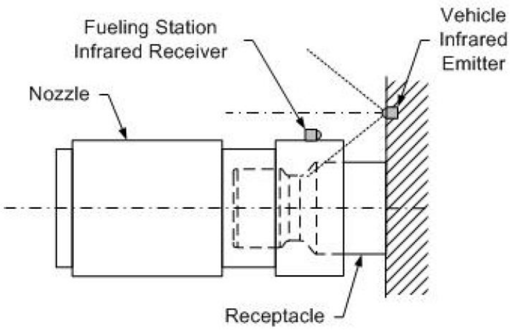

Figure 15 - Connector w. infrared communication links, from [18]

InfraRed communication is based on optical light pulse. Each occurrence or no occurrence allows the system to convert data to a hexadecimal signal which transmit information on ASCII format. The detailed bit frame and mandatory messages allowing reliable communication is also defined in the standard. The InfraRed interface used in it is based on dedicated IrDA specification IrPHY 1.4.

The exhaustive list of data transmitted in the 2019 version are : protocol identifier, soft version number, tank volume (at NWP), receptacle type, fueling command, measured inside tank pressure and temperature (see Table 9). It can be noted that an open spot is already implemented in the standard for future development and potential additional exchanged data. For each data transmitted the standard specifies the possible value or range and other format characteristics.

Table 9 - List of data transmitted and its associated format (from [18])

	Protocol identifier	Soft version nb	Tank volume (at NWP)	Receptacle type	Fuelling command	Meas. Inside tank Pressure	Meas. Inside tank Temp	Optional data
Tag	ID=	VN=	TV=	RT=	FC=	MP=	MT=	OD=
Units	NA	NA	Liter	NA	NA	MPa	Kelvin	NA
Format	NA	##.##	####.#	NA	NA	###.#	###.#	
Range	SAE J2799	[00.00 ; 99.99]	[0000.0 ; 5000.0]	{ H25 ; H35 ; H50 ; H70 }	{Dyna; Stat; Halt; Abort}	[000.0 ; 100.0]	[16.0 ; 425.0]	Up to 74 characters (except "|")
Example	|ID=SAE J2799|	|VN=01.10 |	|TV=0350. 0|	|RT=H70|	|FC=Dyna|	|MP=022.7 |	|MT=330.0 |	|OD=test|
Interval	100ms	100ms	100ms	100ms	100ms	100ms	100ms	100ms
Direction	Veh to HRS	Veh to HRS	Veh to HRS	Veh to HRS	Veh to HRS	Veh to HRS	Veh to HRS	Veh to HRS

The standard finally describes the tests to conduct, and the set-up associated to assess the full range of receiver/transmitter locations, powers, and sensitivities.

<u>New SAE J2799</u> [19] **:**

SAE J2799 have been revised very recently in order to accommodate for new parameters that are used in SAE J2601-5 (see previous paragraph). The main changes compared to the 2019 version are the following [15], [19] ..:

- A new version VN=02.00 is introduced
- The geometrical considerations for receiver and transmitters are updated

- The tank volume range is extended up to 9999.9L
- The optional data field is extended to up to 240 characters (excluding "|", "\", ",")
- The optional data field is structured:
  - It is divided in various blocks separated by "\" character
  - Each block begins with a header string, and is followed by one or multiple data fields separated by "," character
    Example of structure: *| OD= Header1, Tag1=Data1, Tag2=Data2 \ Header2, Tag3=Data3|*
  - In particular, header can be fueling protocol header, for instance CATDHF24 referring to SAE J2601-5 category D fueling protocol, or MCFHFG24 referring to SAE J2601-5 MC formula fueling protocol
  - Two tags are also defined: "FM" for maximum flow rate (can take 060, 090, 120, 300 values, in g/s) and "TVL" for largest tank volume, the volume of the largest tank of the system (in L)
    Example | *OD= CATDHF24, FM=090, TVL=0500 \ MCFHFG24, FM=090,TVL=0500* |

Paths of evolution of the communication during hydrogen fueling are multiple. The one that may be really beneficent to develop more advanced refueling protocols would be to allow **safe bidirectional communication between vehicle and H2 dispenser** to allow more efficient and faster refueling. Part 5.3 details this aspect.

5.2 Application of refuelling protocols on pilot 1 and 2

5.2.1 Challenges and order of magnitude

It can be noted that **most current stations and protocols use a maximum flow rate of 120g/s for H35 fuelings, and 60g/s for H70 fuelings**. These peak flow rates cannot be sustained during the whole fueling (the mass flow profile is generally "bell-shaped"). Thus, the **average flows that are reached during refuelling are generally between 1/2 and 2/3rd of the maximum flow rate** (see example on Figure 16).

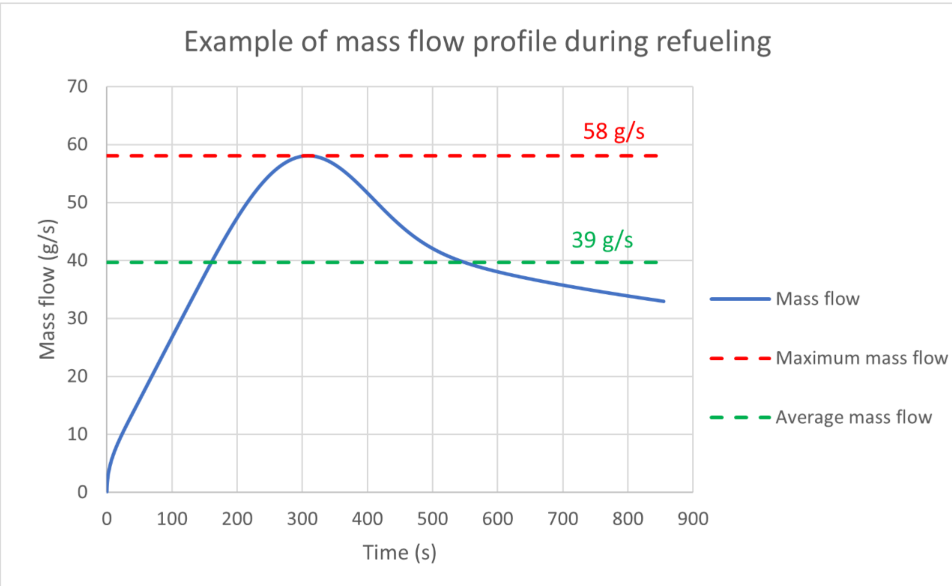

Figure 16 - Example of mass flow profile during a constant ramp rate refueling

For P1, objective of fueling 58kg in 20 minutes would require a flow of **48g/s on average. It does not seem easily achievable for a station with 60g/s maximum flow** because the average flow required seems too close to the maximum flow allowed, but it might be reachable with a station allowing to go up to 90g/s, if pressure drop in the truck is not too high.

For P2, fu**eling 65 kg[5] in 10 minutes would require 108 g/s on average**. This is of course not possible at all with a 60g/s classic H70 station : a special station allowing for higher flow will be needed. For the daily fuelings in Turkey, fueling 65kg in 25 minutes requires an average flow of 43 g/s. This is quite ambitious to reach such a fueling with a 60g/s station, and this objective may need to be relaxed a little, depending on the station used and the pressure drop in the truck.

Note : the trucks will not be completely empty at the beginning of the fueling, therefore the real average flows needed will be a little smaller. See the next parts of the report for more details.

5.2.2 Hypotheses for simulations

In order to anticipate the refuelling profiles, numerical simulations can be carried out. To do so, ENGIE **hydrogen station simulation model HyFill** has been used.

HyFill tool has been internally developed by ENGIE, to contribute to the understanding of hydrogen stations and hydrogen refuelling. Among all, it allows to simulate hydrogen refuelling at to compute the final thermodynamic state (temperature, pressure, SOC) of a vehicle's tanks. The model is pseudo-1D. HyFill has been validated on a large number of tank refuelling, including various sizes and pressure class. More detail about this model and its validation can be found in ICHS document [20], where HyFill is shown to be as performant as other industry-wide refuelling models as SOFIL from AirLiquide, H2FillS from NREL and H2-Fill from Wenger, or in the final report of the PRHYDE project [17], where the validation of HyFill over some examples is displayed (see also Figure 14).

To get specific results, detailed information is required about the stations and trucks that will be used for refuelling. Thus, data as tank geometrical and thermal characteristics, components pressure drops, piping arrangement, … must be available and entered as input in the simulation model. Howeve**r, no accurate information was available at this stage for the pilot 1 and pilot 2** trucks except basic information about their storage system (see Table 10).

Table 10 - Pilot 1 and pilot 2 CHSS information, used for refueling simulations[6]

Pilot	Tank type	Total volume (L) =V_CHSS	Total mass (kg)	Number of tanks	Individual tank size (L) =TVL
1	IV	~ 1440 L	~ 60 kg	4	~ 360 L
2	IV	~1645 L	~ 65 kg	4	~410 L

Thus, **hypotheses were mad**e for the other needed data. Especially, **various pressure drop hypotheses were considered**, to represent the variety of situations possible and assess their impact.

[5] Pilot 2 H2 mass is not fixed yet, the value displayed might still change.
[6] Pilot 2 design characteristics are not fixed yet, the values displayed in the table might still change.

- On the station side, two sets of hypotheses are made :
    - **High-flow station (HF station)** : the components of the station are fulfilling the hypotheses described in SAE J2601-5 (Appendix A.3.3) [14] for high-flow stations, allowing to fuel up to 300 g/s. This is what is expected for future stations targeting trucks.
    - **Low-flow station (LF station) :** station is equipped with current H70 components designed for 60 g/s maximum , that don't fulfil hypotheses described in SAE J2601-5 (Appendix A.3.3) [14] for high-flow stations. This is representative of most of today's existing station characteristics.
- On the vehicle side, two sets of hypotheses are also made :
    - **Low pressure drop vehicle (HF vehicle)** : the vehicle respects the pressure drops requirements presented in SAE J2601-5 (Part 1.3.2.8) [14]. This is what is expected for future hydrogen heavy-duty vehicles.
    - **High pressure drop vehicle (LF vehicle)** : the vehicle is designed so that there is significantly more pressure drop that the requirements presented in SAE J2601-5 (Appendix 1.3.2.8) [14], due to small pipes and small manifolds. This is representative of current cars or buses.

Specific values are kept confidential among ESCALATE project partners and cannot be detailed in this report.

For each of the two pilots, **refuelling simulations were made. They are all using the new TIR SAE J2601-5 protocol,** that is one of the only document prescriptive in how to fuel heavy-duty trucks in H70. The setup considered for the simulations is the following :

- Ambient temperature : 15°C
- Initial pressure of the tanks : 50 bar
- Initial temperature (gas, station and vehicle components) : 15°C
- Expected MAT : -30°C
- Communication is used (V_CHSS, TVL are transmitted and used by the dispenser to compute the protocol parameters)
- SAE J2601-5 [14] MC formula is used, without K0 method and using ending pressure table option
- It is supposed here that the station has enough storage to fill entirely the vehicle, and is able to follow the pressure ramp rate determined by the protocol.[7]
- Pressure drops varies depending on the simulation : **five cases are simulated for each pilot:**

1. HF station + HF vehicle, FM300, no PRR Taper

[7] For high flow stations, this might be a challenge : pressure drops between high-pressure storage and pressure control valve should be low to use as much hydrogen as possible, and the pressure control valve should be large enough and fast enough to follow the ramp rate.

2. HF station + LF vehicle, FM 300, no PRR Taper
3. HF station + LF vehicle, FM300, PRR Taper
4. LF station + LF vehicle, FM90, no PRR Taper
5. LF station + LF vehicle, FM60, no PRR Taper

For SISU pilot 1, it is currently planned to use a 60g/s or 90g/s station. Therefore, depending on the truck design, situations 4 or 5 are the most likely to happen during the test campaign. For BMC pilot 2, it is planned to do one high-flow refueling at a high-flow station in France. Ideally, if the truck design is with low pressure drops, the fueling will be represented by situation 1 to reach the 170g/s fueling KPI. However, we may encounter situation 2 or 3 if pressure drops of the truck are too high. For the daily refueling in Türkiye, situation 5 will likely be encountered. This assessment of the situation can still evolve depending on the final choice and design of the stations and pilots.

5.2.3 Results of simulations for P2

The main results for pilot 2 refuelling simulations are presented inTable 11.

Table 11 - Summary of main refueling simulations results for P2

Station	HF station	HF station	HF station	LF station	LF station
Truck (P2)	HF Vehicle	LF vehicle	LF vehicle	LF vehicle	LF vehicle
FM	300	300	300	90	60
PRR Taper on	No	No	Yes	No	No
Fueling time *(simulation result)*	6.2 min	6.2 min	12.6 min	16.9 min	25.4 min
Final SOC *(simulation result)*	99%	52 %	98 %	84 %	99 %
Final temperature *(simulation result)*	77°C	68°C	77°C	71°C	68°C
Maximum flow reached *(simulation result)*	234 g/s	129 g/s	100 g/s	75 g/s	55 g/s

The results of the simulations are also plotted in the following Figure 17, Figure 18, Figure 19, Figure 20, Figure 21.

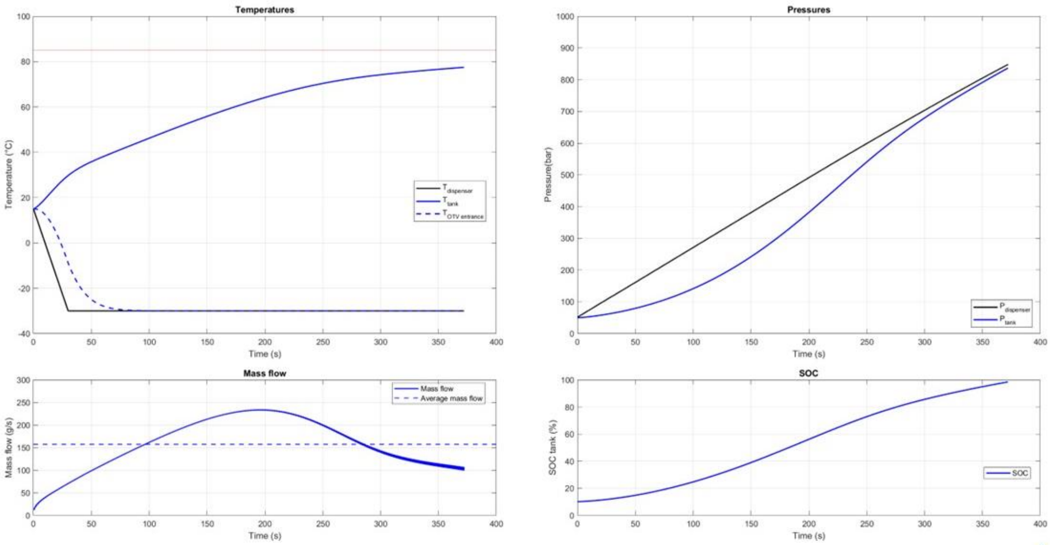

Figure 17 - P2 simulated refueling (with ENGIE HyFill model) – case 1 : HF station and HF vehicle (no PRR Taper)

At the top left, temperatures are plotted : in black is the temperature at the dispenser outlet, in dash blue is the temperature at the OTV entrance and in blue is the temperature in the tanks (it is supposed all tanks are perfectly similar and at the same distance from receptacle). At the top right, pressures are plotted : in black is the pressure at the outlet of the dispenser (it is supposed in these simulations that it follows perfectly the protocol ramp), and in blue is the pressure in the tanks. Pressure drops are the difference between both. At the bottom left is plotted the total mass flow rate, and in dashed line is shown the mean flow it represents when averaged on the complete fueling. At the bottom right is plotted the SOC in the tanks.

Figure 17 represents a **high-flow station coupled with high-flow hypotheses for P2** (case n°1). With this setup, the **performance of this refuelling is very satisfying**: it is very **short** (6.2 minutes) and gives **a final SOC very high** (99%). It can be noted that the temperature in the tanks (in blue, at the top left) always stays below 85°C, and the mass flow rate (in blue, at the bottom left) stays below 300g/s. **With such a refuelling, the ESCALATE KPI of reaching a flow superior or equal to 170 g/s is meet.**

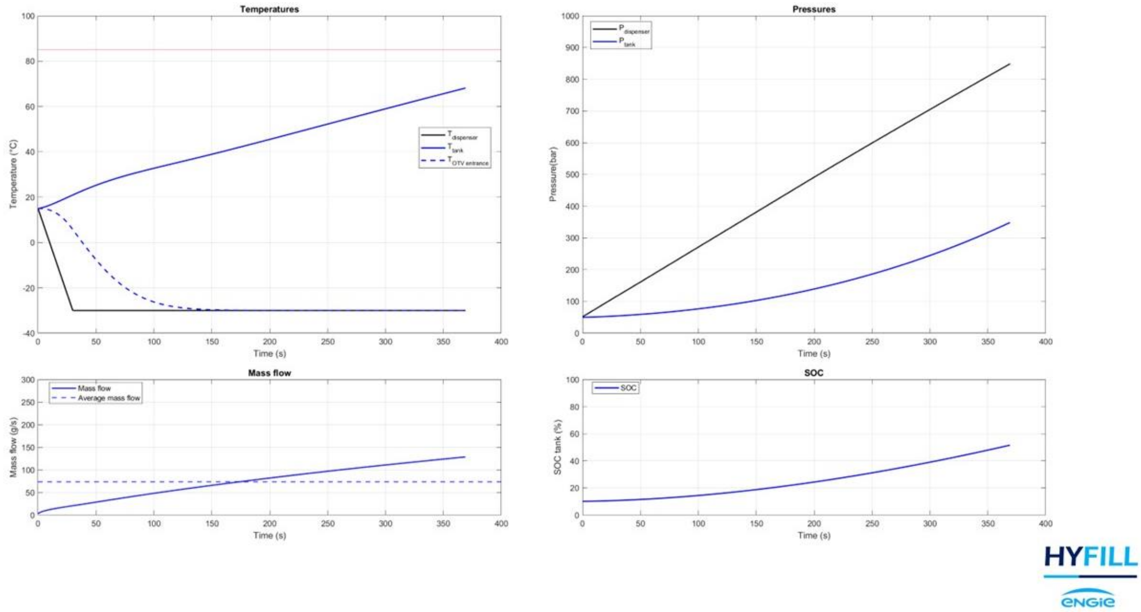

Figure 18 - P2 simulated refueling (with ENGIE HyFill model) – case 2 : HF station and LF vehicle (no PRR Taper)
See Figure 17 legend for explanation about the variables plotted.

Figure 18 represents a **high flow station coupled with low-flow hypotheses for P2** (case n°2) . With this setup, the **performance of this refuelling is not satisfying**: the fueling time is indeed as short as in case n°1 (6.2 minutes), however the final SOC is very low : it is only 52%. This is due to the very high pressure drop in the fueling line of the vehicle. Indeed, as it can be seen at the top right of the figure, the vehicle pressure (in blue) does not follow the dispenser pressure (in black). This is because the vehicle components are not well dimensioned and prevent the flow from going too high. Thus, it is **impossible to fuel both quickly and entirely vehicles with high pressure drop fueling line.** Finally, in addition to giving very poor performance, such a refuelling **does not allow to reach the 170 g/s KPI (**maximum here is 129 g/s).

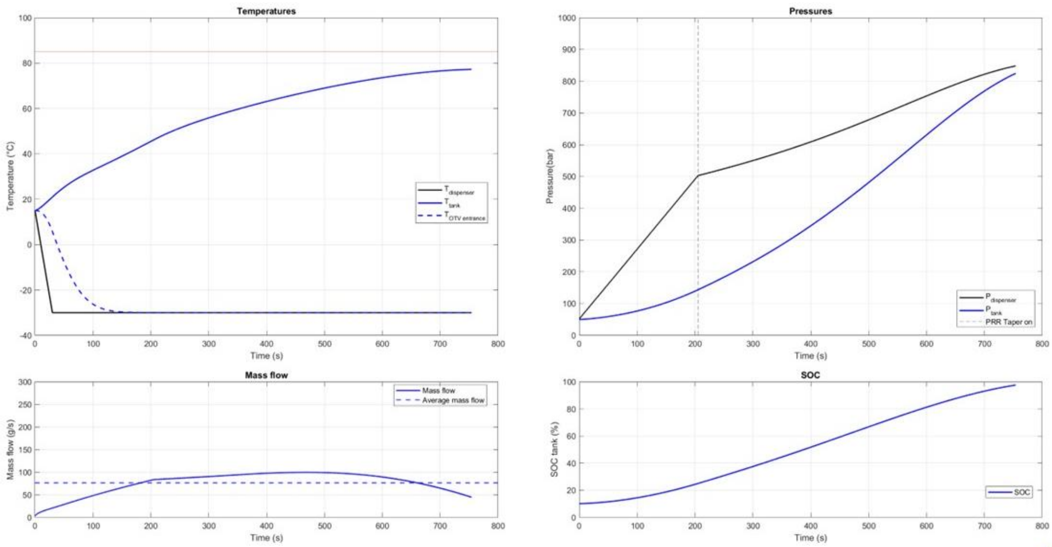

Figure 19 - P2 simulated refueling (with ENGIE HyFill model) – case 3 : HF station and LF vehicle (with PRR Taper)
See Figure 17 legend for explanation about the variables plotted. Note that the timescale of these graphs is not the same as in Figure 17 and Figure 18.

In order to **prevent high pressure drops from impacting too much the final SOC, the "PRR Taper" option** of SAE J2601-5 can be used. This is shown on Figure 19, that represent case n°3 refuelling (high flow station coupled with low-flow hypotheses for P2, PRR Taper option activated). With the **same vehicle and same station than in case n°2 but adding the PRR Taper feature, the final SOC is increased from 52% to 98%** : the final SOC is now very satisfying. However, the drawback is that **the refuelling time is twice**, going from 6.2 minutes to 12.6 minutes. Indeed, PRR Taper is made to handle important pressure drops by decreasing the ramp rate when it is detected that the vehicle pressure will not reach a satisfying value at the end of the refuelling. This decrease of the ramp rate allows the vehicle pressure to "catch up" with the ramp but increase the fuelling time. Moreover, the 170g/s KPI is not reached in this fuelling. Finally, it must be noted that PRR Taper has not yet been extensively tested. It might also be slightly complicated to integrate into stations' dispensers.

In the case the truck internal design is such as pressure drops are high at low flow, it might not be worth it to use a high-flow station. Examples of refuelling with a low-flow station and a high pressure drop pilot are displayed on Figure 20 and Figure 21.

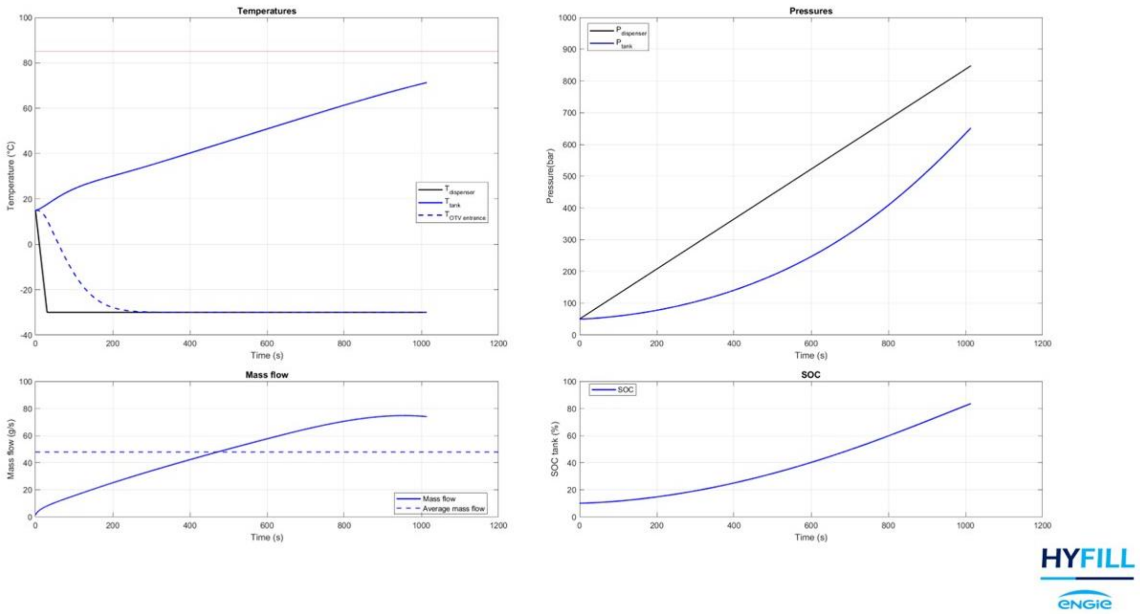

Figure 20 - P2 simulated refueling (with ENGIE HyFill model) – case 4 : LF station and LF vehicle, FM90 (no PRR Taper) See Figure 17 legend for explanation about the variables plotted. Note that the timescale of this figure is not the same as in the others.

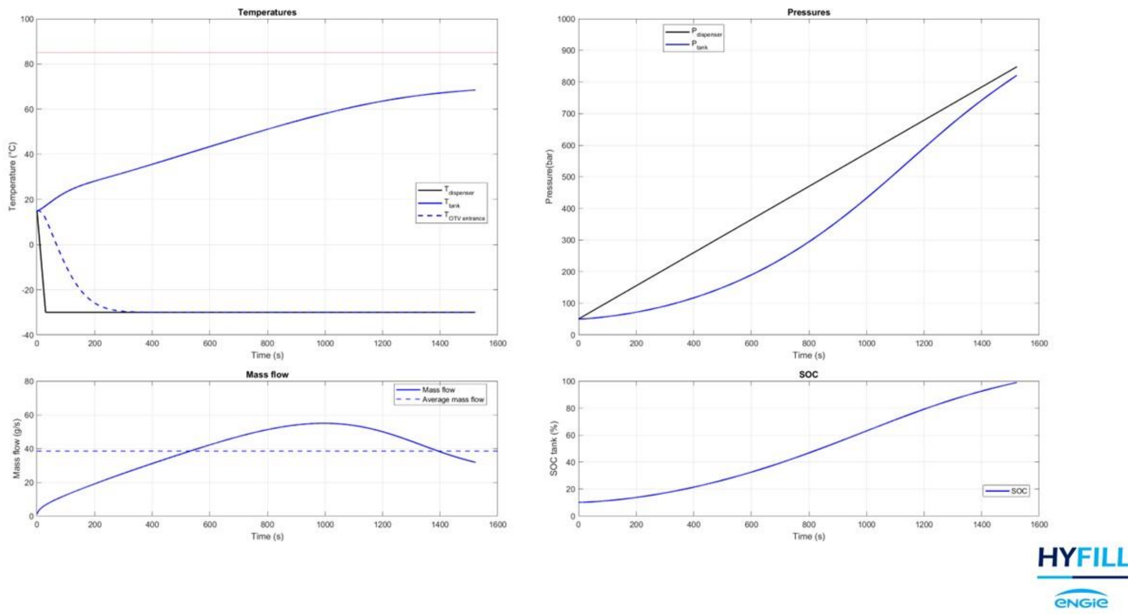

Figure 21 - P2 simulated refueling (with ENGIE HyFill model) – case 5 : LF station and LF vehicle, FM60 (no PRR Taper) See Figure 17 legend for explanation about the variables plotted. Note that the timescale of this figure is not the same as in the others.

Case n°4 and n°5 consider a low-flow station designed to reach 60g/s. Therefore, when **using a maximum flow (FM) of 60g/s** (see Figure 21**), the final SOC reached by the truck is very satisfying (99%). However, the refueling time is rather long: more than 25 minutes are necessary**. This might be too long for some fleet manufacturers, hence the need for high-flow stations. **Using a maximum flow of 90g/s** (case n°4, shown on Figure 20) **can improve this fuelling time to around 17 minutes.** However here, pressure drop begins to impact the final SOC that drops to 83%. The final SOC might be improved using a station especially sized for 90g/s and if the truck design is such that pressure drops are reasonable at this flow.

Thus, it can be underlined that **to reach very high performances, it is important to design truck and station so that the pressure drops are low** in the refueling line. However, **in case of high pressure drops, methods as PRR Taper can help keep a very acceptable fueling time and fueling performance**. Finally, current existing stations allowing to go up to 60 g/s or 90g/s maximum allow to perform full truck refueling but are not sufficient to reach fueling times below 15 minutes.

5.2.4 Results of simulations for P1

The main results for pilot 1 refuelling simulations are presented in Table 12.

Table 12 - Summary of main refueling simulations results for P1

Station	HF station	HF station	HF station	LF station	LF station
Truck (P1)	HF Vehicle	LF vehicle	LF vehicle	LF vehicle	LF vehicle
FM	300	300	300	90	60
PRR Taper on	No	No	Yes	No	No
Fueling time *(simulation result)*	4.7 min	4.7 min	10.8 min	14.8 min	22.2 min
Final SOC *(simulation result)*	98%	46%	98 %	83 %	99 %
Final temperature *(simulation result)*	80°C	67°C	78°C	72°C	69°C
Maximum flow reached *(simulation result)*	265 g/s	129 g/s	100 g/s	75 g/s	55 g/s

The main insights that we can draw from these simulations are the same as the ones detailed for pilot 2:

- **High flow station coupled with high-flow vehicle (case n°1) allows a very efficient refuelling:** the refuelling lasts less than 5 minutes, for a very satisfying final SOC of 98%
- On the contrary, when the **high-flow station is coupled with a low-flow vehicle (case n°2), the refuelling is not efficient at all**. It sill lasts less than 5 minutes, as the same protocol is used. However, the **final SOC is very low: 46%**. This is due to the very high pressure drop in the fuelling line of the vehicle: the pressure ramp of the station goes very fast, but the vehicle components are not well dimensioned and prevent the flow from going too high: t**he vehicle pressure does not catch-up with the dispenser ramp rate**. Thus, it is impossible to fuel quickly and entirely high-pressure drop vehicle.
- An option t**o prevent this situation of very low SOC at the end of the fuelling of a very high pressure drop vehicle is to use the PRR Taper option** of SAE J2601-5 (case n°3). This feature is indeed made to handle this kind of issue. Thus, **with PRR Taper, the final SOC is now 98% even**

with the high pressure drop created by the vehicle, which is very satisfying. However, the drawback is that the refuelling time is significantly increased: it takes 10.8 minutes, which is more that the double of the time taken when the pressure drop of the vehicle was reasonable. Moreover, PRR Taper might be more complicated to integrate in the stations' dispensers.

- Finally, the **refuelling simulation caped at 60g/s** (case n°5 : low flow station and low flow vehicle) shows also a ve**ry good final SOC** : there is no significant pressure drop issue within this range of flow. However **the refuelling is much longer**: it takes more than 22 minutes to reach 98.9% SOC. Using a maximum flow of 90g/s (case n°4) can improve this fuelling time to around 15 minutes. However here, pressure drop begins to impact the final SOC that drops to 83%. It might be improved using a station especially sized for 90g/s (here the LF station is simulated using reference 60g/s station design).

5.3 Advanced communication as a key enabler for more advanced protocols

5.3.1 Drawbacks & opportunities of bidirectional data exchange technologies.

In the context of H2 vehicle refueling and as mentioned in part 5.1.5, a communication can be established from vehicle to the dispenser as detailed in standard SAE J2799. The purpose of sharing information is to achieve a fuller tank.

The last revised version of the standard (2024) **describes only one way communication by using infra-red emitter/receiver devices**. In the future, **bidirectional communication could be used to better improve refueling and add safety features among others.** In this future evolution, the infra-red wireless data transmission might not be sufficient and more potential suitable technologies to exchange data could be found.

Purpose of bidirectional data exchange can be:

- 1st allow connection between vehicle and dispenser via a secured way (with action from user, fully automatic communication would be the next step)
- 2nd allow live data exchange from vehicle to dispenser and from dispenser to vehicle, that could be trusted for safety decisions.

Various possibilities of vehicle data communication are possible. There are usually defined:

- vehicle-to-vehicle (V2V)
- vehicle-to-network (V2N)
- vehicle-to-infrastructure (V2I)
- vehicle-to-pedestrian (V2P)
- vehicle-to-device (V2D)

Each of these possible communications have specific requirements depending on several factors which allow industrial and researchers to usually priories specific data communication technologies. Main requirements and their characteristics will be defined to reduce the possible technologies to use for bidirectional communication in between a vehicle and its H2 dispenser.

The typical use case for hydrogen mobility is a communication between a stopped vehicle next to H2 dispenser in a most likely protected environment (roof, not many obstacles…). **In H2 refueling, live bidirectional data communication in a secure way will be needed, with:**

- **low latency** (for safety matters)

- **a sufficient data transmission rate**
- **a low cost** (hardware + power consumption)
- **a certain resistance to interference** (obstacles, electromagnetic fields, fog, etc…)

There are mainly **two types of data communication, one is wireless, and the other is by wire. Wireless data communication could be based on two principles, light waves emission or radio waves emission**. Various well-known technologies were selected, and their advantages and drawbacks will be explained in relation with the H2 refueling use case. The protocol of communication between the two main communicators is not treated here, only the possible technologies allowing a potential protocol in the defined use case.

The main function needed is to **allow live bidirectional communications**, meaning that dispenser and vehicle can exchange both data which are not prewritten in advance. Thus, all technologies like NFC or RFID cannot be used since they do not allow live data transmission. However, we can notice that NFC could be a good way to implement a secure way of identification between dispenser and vehicle when connected.

One frequent characteristic for choosing appropriate wireless data transmission technologies is its transmission range. However, in this use case, the vehicle is stopped near the dispenser to allow the fueling hose to be plugged, therefore the range is not identified as a blocking point since the emitter /receiver could be installed very close (like they are defined for the moment by J2799 for infra-red data technology).

Moreover, the current J2799 specifies a transmission rate of 38kbits/s. Even if the communications are now bidirectional with additional information shared, the requested speed is not expected to excess 5 times the actual transmission rate which equals around 200kbits/s. Such a transmission rate is reachable for all the wireless technologies studied and therefore will not constitute a criterion even if great disparities exist between them.

Thus, both wireless technologies identified based on light waves (InfraRed and Li-Fi) could be suitable for the usage. As defined by the J2799, an emitter/receiver placed on both vehicle receptacle and on dispenser nozzle would be the ideal architecture to avoid the main drawbacks of these technologies which are its sensitivity to obstacles and ambient environment such as fog, ice, or direct sunlight.

Cellular based data transmission present lots of advantages but also lots of drawbacks. 3G could be excluded as a potential solution since it will stop being hosted in some countries like France, in near future (2028). 4G could have a latency rate up to 100ms in worst case which could be insufficient with safety features required for a safe H2 refueling. Only 5G remains and it presents a very high transmission rate with low latency and a good reliability since a relay tower can takeover instead of a another if it fails. However, the technology relies on 3rd parties' infrastructure which is not a fully independence. In addition, all countries are not equipped with 5G and even if, gaps in coverage still exist. All these elements make the cellular based data transmission not the best candidate for the application.

All other wireless data transmission technologies do not need an external infrastructure to work. They are all relatively cheap in term of hardware requested and in term of power consumption, nothing which cannot be handled by a standard automotive battery.

But some of them present major drawbacks. UWB for example could interferes with other radio-based services like GPS which could make it unsuitable for an automotive application. DSRC does not present same protocols, wide band and data transmission rates between USA, Japan et Europe which is likely to prevent a standardization of a refueling protocol based on this technology.

Bluetooth has all the requested requirements listed above. It also has the great advantage to be widely spread in car automotive industry. Most of the cars today are already equipped with a Bluetooth module which dramatically lowered the costs. An pearing is still mandatory though and could take some time (sources mentions time up to 40s in worst case).

Wi-Fi is also a good answer to the requirements. It is a widespread technology which is also used in car automotive, though far less than Bluetooth. Its higher consumption and its more expensive hardware might be a drawback, but Wi-Fi still answers all criterions and further studies must be conducted to assert if Wi-Fi is a viable solution compared to Bluetooth, especially in term of security.

Zigbee answers to all requirements but is not applied in automotive applications yet which could imply additional development cost. Moreover, its transmission rate is around 250kbits/s, which is very close to the minimum target we put in evidence at the beginning of the study.

Communication should be effective when the vehicle is stopped. This should not be a problem but it still interesting to have in mind that all radio waves wireless technologies are much more sensitive to electromagnetic fields than their equivalents light signal-based and it can be more difficult to solve EMC problems than for direct wiring.

It can be noticed that all wireless technologies are by definition reachable from outside which makes them subject to intrusion. In other words, the safest way to allow bidirectional communication is to connect it by wire. But it come with drawbacks like weight, services or design (a reliable electrical connection for both vehicle and especially dispenser is mandatory).

A summary of these pros/cons can be found in the tables below:

Table 13 : pros/cons for multiple bidirectional data communication technologies (part 1/2)

Connection type	**Wire**	**Wireless**					
Way of transmission	Electrical signal	Light waves		Radio waves			
Common name		IR	Li-Fi	ZigBee	UWB	Bluetooth (including Bluetooth low energy)	NFC (part of RFID)
Signification		Infra-Red	Light Fidelity		Ultra-wide band		Near field communication
IEEE standard referring			IEEE 802.11bb	IEEE 802.15.4	UWB/IEEE 802.15.3a	IEEE 802.15.1	ISO18092
Live bidirectional information transmission	Yes	Yes	Yes	Yes	Yes	Yes	No
Range		Short range		Short range			
Distance of reliable data transmission		10m	10m	20m	10m	10m	10cm
Requested power	Low	Low	Low	Low	Very Low power	Medium power (for non-low energy)	No power requested
Need of external infrastructure (besides car and dispenser)	No	No	No	No	No	No	No
Sensitive to fog, sunlight, ice	No	Yes	Yes	No	No	No	No
Sensitive to obstacles	No	Yes	Yes	No	No	No	No
Sensitive to electromagnetic field	Less than wireless based on radio waves	No	No	Might	Might	Might	Might
Security	Not reachable from outside	For wireless: Reachable from outside, possibly subject to intrusion					

Main advantages	Already widespread for multiple application in car	Widespread technologies Technology already defined in SAE J2799 for this specific use (to be adapted for bidirectional com)	High transmission rate		High data rate Low latency	Widely used in automotive industry, most cars are already equipped with a Bluetooth module	
Drawbacks	Wiring weight addition	Cleanness and ambient conditions around nozzle/receptacle must be supervised	Relatively new technology without any industrial automotive application yet Cleanness and ambient conditions around nozzle/receptacle must be supervised	Low transmission rate compared to other technologies No industrial automotive application yet	Could interfere with other radio services like GPS	Appearing mandatory (it's a piconet structure (master/slave type)) New nodes can take some time to connect	

Table 14 : pros/cons for multiple bidirectional data communication technologies (part2/2)

Connection type	**Wireless**					
Way of transmission	Radio waves					
Common name	RFID	Wi-Fi	DSRC	Cellular techno		
Signification	Radio frequency identification	Wireless fidelity	Dedicated short wave communication	5G	4G (including LTE)	3G
IEEE standard referring	ISO21451	IEEE 802.11a/b/g	IEEE 802.11p			
Live bidirectional information transmission	No	Yes	Yes	Yes	Yes	Yes
Range	medium range			Long range		
Distance of reliable data transmission	up to 100m	50m	1 km	Several kilometers		
Requested power	No power requested (for passive)	High power		High	High	High
Need of external infrastructure (besides car and dispenser)	No	No	No	Yes	Yes	Yes
Sensitive to fog, sunlight, ice	No	No	No	No	No	No
Sensitive to obstacles	No	No	No	No	No	No
Sensitive to electromagnetic field	Might	Might	Might	Might	Might	Might
Security	For wireless: Reachable from outside, possibly subject to intrusion					
Main advantages		Widespread technologies Quite high data transmission rate	Suitable for in vehicle communication, several experiences conducted for V2X communication One control channel out of 7 dedicated to high priority safety messages	Widespread techno Data transmission rate Reliable due to other tower takeover in case of one failure	Widespread techno Data transmission rate Reliable due to other tower takeover in case of one failure	

Drawbacks		Not as developed as Bluetooth in car automotive industry	Not same protocols, wide band, data transmission rates between USA, Europe and Japan	Depend on 3rd parties' infrastructure (not fully independent) Gaps in coverage	Depend on 3rd parties infrastructure (not fully independent) Gaps in coverage Latency rate could be in worst case up to 100ms	Will be stopped hosted in some country like France in a near future

To complete the study, we could take the example of electrical recharging which has similar requirements. Nowadays the standard ISO 15118 rules all problematics of bidirectional communication from secure connection to hardware/software requirements and automatic smart-charging.

5.3.2 Advanced communication benefit from electrical car protocol

It can be noticed that **the problematic of bidirectional data exchange is something already managed by some electrical vehicles**. "Plug & charge" feature is a function that allow an automatic energy exchange without any other action from the customer than plug the charging cable between the car and a dispenser. In that case electric car automatically identify and authorize itself to receive (or send for "vehicle to grid" connection) energy. The car should first need to send and receive information from the dispenser.

ISO 15118 is a standard which rules communication interface for bidirectional charging/discharging of electric vehicles, including that "Plug & charge" feature.

The vehicle and the dispenser establish a communication network via a secure TLS connection (Transport Layer Security, cryptographic protocol which provide communications security over a network). They exchange certificates provided beforehand via a certificate pool. The certificate linked to a vehicle contain all information allowing automatic billing.

The communication between vehicle and electrical charging station works either by:

- **PLC (Power Line Communication):** data exchange via electrical waves modulation through the charging cable (described in ISO 15118-3)
- **WLAN (Wireless communication from Local Area Network):** mostly referred to by Wi-Fi network, data exchange through wireless communication (referenced by ISO 15118-8) (mandatory for electrical induction charging)

Both the dispenser and the vehicle need a CPL/Wi-Fi module (depending on the chosen solution) to allow the communication. Moreover, an internet connection is used for the dispenser to exchange with the certificate pool and authenticate the vehicle certificate.

For H2 vehicle, a similar communication interface as the one already described in ISO 15118 could be used. The PLC way of communication would not work, but a dedicated wire within the H2 dispenser hose could be implemented for exchanging data. A wireless solution with the WLAN could also be used. It would be interesting to exchange information with ISO 15118 development team to understand why their study led to choose Wi-Fi for wireless communication over other technologies. A deeper study should also be led to identify the specifics needs of the H2 vehicles refueling. Although, it can be already assumed that the closer the chosen solution for H2 vehicles will be to ISO 15118 standard the better and easier it will be for the mobility industry because of the following advantages: one certificate pool covering both electric and H2 vehicles, easier development for both dispenser and car manufacturers if communication interfaces share same characteristic for H2 and electrical vehicles, etc…

Finally, it is worth mentioning that the hydrogen industry is currently tackling this topic of advanced bidirectional communication, and a new ISO workgroup has been created to advance on this subject (*ISO TC197/WG38 : Gaseous hydrogen - Fuelling protocols for hydrogen fuelled vehicles: communications between the vehicle and dispenser control systems*).

6 Optimization of the hydrogen infrastructure

6.1 Energy consumption on HRS

The main components consuming energy are :

- **The electrolyzer(s),** if any onsite, producing hydrogen from grid electricity and water. Typical hydrogen pressures at the output of the electrolyzer are 1 to 40 bar depending on the technology used.

- **The compressor(s),** to compress hydrogen from the low pressure buffer to medium and high-pressure storage. Typical medium pressure storage are 400-500 bar and typical high-pressure storage are 900-1000 bar.
  Nb : In some stations, there are two compressors with an intermediary storage (first compressor for low to intermediate pressure (~200 bar for instance),and second compressor from intermediate to high pressure).

- **The cooling system(s) of the distribution line(s),** that cools the hydrogen distributed to the vehicles. Cooling the hydrogen allow faster distribution rates. Typical temperatures to reach are -20°C to -40°C.

Other equipment consuming energy can be considered negligible (air compressor for air instrumented valves, instrumentation monitoring and control, …).

It can be estimated that the total consumption to produce and deliver green hydrogen to 700 bar light-duty vehicles is theoretically around 60-85 kWh/kgH_2 [21] . However, Genovese [22] studied the data from 4 years of refuelling in a small light-duty station (60 kg/day), delivering to 350 bar and 700 bar and found the average specific consumption was between 60 and 120 kWh/kgH_2, with peaks up to 280 kWh/kgH_2. This peak matches with a low demand, however the extreme value of this peak is not really commented and explained by the author. This might be because the system is not designed to operate at very low utilization rate and is therefore inefficient at such operating points.

No other analysis on the consumption of a hydrogen station over a long period of operation was found, showing the **current lack of knowledge on this topic.** This lack of knowledge makes it currently hard to optimize properly the design and operation of hydrogen refuelling infrastructure.

Details on the theoretical consumption of a hydrogen refuelling station can be found below.

<u>**Electrolysers**</u>

Electrolyzers currently installed in stations have a capacity between 0.1 MW and 5 MW. **Recent stations use electrolyzers from 1 MW to 5 MW**, corresponding to a production capacity approximately comprised between 400 kg and 2.1t of hydrogen per day at full load.

According to literature, the specific consumption of current commercial proton exchange membrane (PEM) and alkaline (ALK) electrolyzers is between 45 and 80 kWh/kg H_2 (generally included in **50-65 kWh/kg)** [23]**,** [24] [25] . 80 to 95% of this energy is used by the stacks [25]. Given as comparison, hydrogen LHV is 33.3 kWh/kg and HHV is 39.4 kWh/kg.

In stand-by mode, the electrolyzer does not produce any hydrogen but needs power to maintain the system temperature and pressure so that it can start production quickly when asked. The value of **stand-by power** consumption is often estimated to be between **1% and 5% of the nominal power of the electrolyzer for MW scale electrolyzers,** it can even range to more than 10% or 15% for smaller ones (several kW) [26], [27].

Specific energy consumption of an electrolyzer can depend on :

- Technology (PEM, ALK, pressurized or not …)
- Service life of the stack (number of hours it has already been running), as the end-of-life specific consumption is higher than the beginning-of-life specific consumption
- Turndown ratio (% of nominal production)
- Power converter, power 'quality'
- Operation history
- …

More precisely, how the specific consumption depends on the technology is investigated in Chatenet's article [28] . They give current and future targets for electrolyzer specific consumption depending on the technology. Their findings are summarized below:

Table 15 - Estimated specific consumption of various electrolyzers, from [28]

Electrolyzer technology	PEM (proton-exchange membrane)	Alkaline	AEM (anion-exchange membrane)	Solid oxide
Stack specific consumption today (kWh/kgH_2)	47-66	47-66	51.5-66	35-50
System specific consumption today (kWh/kgH_2)	50-83	50-78	57-69	40-50
Stack specific consumption targeted in 2050 (kWh/kgH_2)	< 42	< 42	<42	<35
System specific consumption targeted in 2050 (kWh/kgH_2)	< 45	< 45	<45	<40

Therefore, **current and future performances are close for alkaline, PEM and AEM electrolyzers. Specific consumption of solid oxide electrolyzer is better, but the technology is still today at a low level of maturity**. Moreover, solid oxide electrolysis is a high-temperature technology. It explains its high efficiency, but it can introduce other operational constraints, as a long start-up time.

Compressors

Compressors installed in stations are generally used to compress hydrogen up to 900 – 1000 bar. Mass flow is highly dependent on the inlet and outlet pressure, and can range between 10 and 100 kg/h for compressors installed in HRS. Future compressors are expected to exceed 150 kg/h. According to the few examples found in literature, the specific consumption of current hydrogen compressors observed in station is **between 1 and 10 kWh/kg H_2** [22] [29] [30] **for compression, with an average around 3-4 kWh/kg** [30] including cooling and auxiliaries for H70 stations (and around 1-5 kWh/kg [30] for H35 stations). However there is very little available data, and the exact conditions in which it is obtained is not clear.

From **a theoretical point of view**, thermodynamic behaviour of hydrogen is the following : isothermal compression of hydrogen from ambient pressure to 1000 bar requires 2.6 kWh/kg where an isentropic compression requires 8.6 kWh/kg [31]. These two figures represent thermodynamical theoretical consumptions, but actual compressors do polytropic compression, which energy requirement is between isothermal and isentropic. Moreover, small energy losses can be observed when converting electrical energy to mechanical energy in the compressor motor (typical efficiencies are around 90% [30]) and there are minor consumptions in auxiliaries, giving a total **specific consumption included between 2.9 and 9.5 kWh/kgH_2 for ambient to 1000bar compression. The higher the inlet pressure and the lower the outlet pressure, the lower the specific energy consumption will be.**

It can be noted that **the consumption of compressors is not straightforward to describe**, as they work between a low-pressure and high-pressure storage with **continuously varying inlet and outlet pressure**, therefore their consumption is also always varying.

Specific consumption of a compressor mostly depend on:

- Technology (booster, membrane, ionic, …)
- Design (number of stages, cooling system design, piston and sealings arrangements, … can change the energy consumed by the compressor)
- Inlet pressure
- Outlet pressure
- Compression ratio
- Flow rate

Finally, it must be highlighted that it is **quite complicated to find accurate data about HRS compressors energy consumption**, especially real-word, comparable data. This highlights a knowledge gap on this domain, that should be bridged to be able to design and optimize better hydrogen infrastructure.

Dispenser cooling system

The energy needed by the cooling system of a station is quite variable, as it is **highly dependent on the design of the chiller, heat exchanger and on the operating choices** (cooling temperature, mass flow, stand-by strategies, frequencies of refuelling …). As an example, a 700-bar light-duty station monitored during four years consumed between **1,2 and 27 kWh/kgH_2** [22] for precooling. In another study [32], the precooling electrical energy is reported to be in a range as wide as **0.5 – 50 kWh/kgH2** depending on design and use. However, it estimates that it highly depend on utilization : when a light-duty T40 – precooling station is highly utilized (more that 60% of its capacity), electricity consumption of the cooling unit is reported to be less than 1 kWh/kgH_2, it can be as low as 0.3 kWh/kgH_2 at full utilization while **it grows exponentially when the percentage of use decreases**. Therefore, it can be underlined that it is uneasy to predict the energy consumed by a refuelling station without knowing its utilization rate and the operating strategy of the cooling system. Specific energy consumption that can be targeted is around 1-2 kWh/kgH_2.

Specific consumption of a hydrogen cooling system in HRS can depend on:

- Technological choices
- Precooling temperature targeted
- Mass flow of hydrogen dispensed
- Stand-by strategy.

- Number of refuelling (if the cooling system is on all day, the specific consumption will be 10 times less if there is 10 refuelling than if there is 1 refuelling during the day. In other words, it means the consumption of the cooling system could be the same whatever the number of vehicles refuelled, depending on the operating strategy.)
- Ambient temperature
- Joule Thomson effect due to expansion of the gas from the high-pressure storage

How to optimize this consumption?

As hydrogen stations (especially the ones producing green hydrogen onsite) consume a lot of energy, it is highly relevant to try to optimize it. Energy management of stations might be done by trying to minimize total energy consumption, or to maximize use of renewables for instance. For a station that is already built, the main leverages for energy management of a station with onsite production are the following:

For the electrolyzer

- Choose when to produce or not depending on renewable electricity availability, on electricity price, on storage state and on hydrogen demand
- Efficiency can be better at low turndown ratio: choose wisely the turndown ratio (it could be interesting to produce on longer periods at lower power)

For the compressor

- Choose when to use the compressor, depending on electricity price, on storage state and on hydrogen demand.
- Choose source of hydrogen for compression (if various sources at various pressures are available)
- Choose in which storage to compress the hydrogen (if various target storages at various pressures are available).

For the dispenser cooling system

- Choose from which storage to use hydrogen depending on its pressure and temperature.
- Choose when to turn on, to turn off or to use standby mode depending on electricity price and demand.
- Choose what pre-cooling level to use if it can be chosen.

The other way to optimize energy consumption is to consider it when designing the station. Indeed, lots of design parameters can influence energy consumption. Next paragraph will give some insights on this topic.

6.2 Architecture of the HRS

When an HRS is built, many parameters should be considered to size it. Among them:

- The demand envisioned (expected daily demand profile, number of back-to-back refuelling to be able to conduct)
- The availability to be targeted (can lead to back-up plans for supply of H2, redundancies strategies,…)

- The performance to be targeted (the targeted fuelling time will have implications on components sizing, cooling levels, …)
- The budget, costs and price constraints.

In order to give some insights on the impact of station design, simulations were conducted with ENGIE's HyFill tool. **Seven station configurations were modelled and studied while refuelling the same truck in the same conditions**.

First, a reference station was created with the following characteristics:

- Two medium pressure banks (500 bar) containing 506,4 kg of hydrogen in total and three high pressure banks (1000 bar) containing 226,8 kg of hydrogen in total.
- Precooling hydrogen temperature of -30°C.
- Fuelling line pressure drop meeting SAE J2601-5 requirements (High flow station, 300 g/s capacity)
- Refuelling protocol : SAE J2601-5

Simulations showed that **the reference station was able to completely refuel the truck without reaching the temperature or pressure limits, in just under 5 minutes.**

Then, variations this station were implemented. Changes were on:

- Size and configuration of hydrogen storage
- Pressure drops in the dispenser and upstream dispenser
- Hydrogen precooling temperature.

to evaluate the impact of architecture on the performance of hydrogen refuelling stations and the capacity to meet its demands. The truck used for simulation is a fictive representative truck containing 56kg of hydrogen split in four type IV tanks.

The second station hydrogen storage is the double of the reference station storage: station 2 counts four MP banks and six HP banks. Since the reference station had no problems to finish refuelling, as expected, this new station with the extra banks also managed to finish the process, in the same time and with same energy performance for one refuelling. However, the **performance of station 2 will be better for back-to-back refuelling.**

Station 3 was created to evaluate the effect of an increase pressure drop in the dispenser. **This may represent a station where the dispenser components (valves, nozzle, hose, break-away, heat exchanger, pipe diameter, …) are not adapted to high-flow. It can be seen that this station is not able to complete the refuelling before the dispenser pressure reached its limit**. Therefore, the final SOC for this station was 53,5%, which is very low. Note that the energy consumption is consequently lower (48% of the one of the reference station), however as the fuelling is not complete the comparison is not really meaningful. Still exploring further pressure drop impact, **station 4 was created to evaluate the effect of high pressure drop between the storage and the dispenser, which might be due to long and thin piping, or small valves, filters, … It also failed to complete refuelling**, because at the end of the fuelling, the station does not manage to supply high-pressure hydrogen as the pressure of the dispenser is way lower than in the storage due to pressure drop. Thus, final SOC is 70 %. **This underlines the high impact of pressure drop** (whether before or in the dispenser) in the station capacity to fuel quickly heavy-duty vehicles.

The fifth station uses a higher precooling temperature of -10°C . Consequently, and according to the protocol, the pressure ramp rate is slower order to avoid reaching the temperature limit of 85° C. Thus, the temperature inside the vehicle tanks experiences slower growth, but it leads to a notable increase in refuelling time. In this case, the energy consumption of precooling was greatly reduced, with a 88% reduction in the peak energy consumption of the reference station, and the total energy consumption during the refuelling is only 62.3% of the one of the reference station. However the refuelling time was more than 24 minutes (around 5 times as long as for the reference station). Thus, there is a **trade-off between cooling energy consumption and refuelling time**: either cold precooling is used and the refuelling is fast, or a higher temperature precooling is used, consuming less energy but leading to a significant increase in the refuelling time.

The last two stations explore only the distribution of the storage tanks in the cascades, maintaining the same total hydrogen mass per pressure level and same total volume. The sixth station has only one bank MP with 506,4 kg and two banks HP with 113,4 kg each while the seventh station has four banks MP with 126,6 kg each and six banks HP with 37,8 kg each. The simulations showed that, although the stations had the same parameters and the same total amount of hydrogen stored, station 7 had a superior energy performance, consuming 8% less energy than the reference station, while station 6 consumed 6% more than the reference station. This is due to a difference in the Joule-Thomson effect created by the heating of the hydrogen while being expanded in the PCV, that varies depending on upstream storage pressure and temperature. In addition, after refuelling, the seventh station still had two high-pressure banks that were not used, so there is still a good margin to continue operating, while the sixth station does not have any more full storages, even though both had consumed the same total hydrogen mass. This is because **the factor that limits the use of a bank is usually not the amount of hydrogen mass available, but the pressure in each bank**. Indeed, since the pressure of the stored hydrogen needs to be higher than the dispenser pressure to flow to the vehicle, the minimum storage pressure needed upstream increases during the refuelling. In other words, it does not matter if there is an available bank with a huge amount of hydrogen if the amount of mass that can be used from it is limited or zero because its pressure is close or below the dispenser pressure. Splitting this huge bank into multiple smaller ones will allow to take better advantage of the high pressure in each. **Thus, for a given constant hydrogen quantity, it is better to split it in more banks for energy consumption and for back-to-back capacity. However, it comes with an increased CAPEX cost and piloting complexity.**

Table 10 shows a recap of the main results of the comparison between the stations.

Table 10 - Recap and station results

Station	Reference Station	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
Changes compared to reference station	-	Doubled hydrogen quantity by doubling number of storage tanks	Increased pressure loss in piping (fueling line assembly)	Increased pressure loss in piping (between storage and dispenser)	Cooling temperature at -10°C	Same hydrogen quantity as reference station but splitted in less banks	Same hydrogen quantity as reference stations but splitted in more banks
Fueling time	4.9 min	4.9 min	5 min	5 min	24.8 min	4.9 min	4.9 min
Final SOC	99.9 %	99.9 %	53.5 %	70 %	99.9 %	99.9 %	99.9 %
Cooling energy consumption	C_{ref}	C_{ref}	49% of C_{ref}	84.6% of C_{ref}	62.3% of C_{ref}	106% of C_{ref}	92% of C_{ref}
Cooling energy consumption peak	P_{peak_ref}	98% of P_{peak_ref}	40 % of P_{peak_ref}	70 % of P_{peak_ref}	11,7 % of P_{peak_ref}	105 % of P_{peak_ref}	97 % of P_{peak_ref}
Remaining H2 in MP storage	94,8%	97,3%	98,4%	97.7%	93,9%	95,2%	94,6%
Remaining H2 in HP storage	90,2%	95,4%	93,6%	91.2%	92,1%	89,3%	90,6%

		(not all HP banks have been used, some are still full)	(not all HP banks have been used, some are still full)		(not all HP banks have been used, some are still full)	(fullest HP bank after refuelling is at 890 bar)	(not all HP banks have been used, some are still full)

To conclude this part, hydrogen infrastructure optimization can be done through cost, energy, and design studies. First elements have been given about sources and amount of energy consumption in HRS, and a lack of specific and reliable data on this topic has been pointed out, underlying this is a current relevant research topic. A short study about architecture impact of energy and performance has also been conducted. **Studies about hydrogen infrastructure optimization will be continued and deepened in task *T4.4 - Cost-effective refuelling and charging infrastructures* of ESCALATE project.**

7 Recommendations for high-flow refuelling

The previous results shed light on various very important recommendations that should be implemented as much as possible.

7.1 For the station

Very important points to take into account while designing, building and operating a hydrogen refuelling station for heavy-duty vehicles are the following:

- First, **pressure drop in the refuelling line of the dispenser should be as low as possible**. As shown in part 5.2, important pressure drops in the dispenser do not allow to reach high flow. Thus, it is impossible to reach a high SOC in a short time with high pressure drops either the final SOC of the vehicle will be very low, or the fuelling time will be long. It is therefore recommended to build stations following SAE J2601-5 requirements (Appendix 1.3.3) [14].

- Then, **pressure drop between the high-pressure storage and the dispenser should also be as low as possible**. Indeed, if the upstream pressure drop is too high, hydrogen at the dispenser inlet will be at a much lower pressure than in the storages. Each bank will then be less exploited, so more high-pressure storage will be needed to fill the same amount of hydrogen in the vehicle. Thus, it will lead to an increase in cost to have the same fuelling capacity than a station with lower pressure drops. It is therefore recommended to limit this pressure drop as much as possible by using large pipes, valves, and other appropriated components if any.

  → Thus, these two first points underline that **all station components must be designed for high flow (300 g/s).** This includes piping size, valves, pressure control valves, heat exchanger, flow meter, filters, pressure and temperature sensors, break-away, hose, nozzle. Some of these components are not yet available on the market, yet many manufacturers are currently working on it (see for instance RHeaDHy European project[8] [33]).

- Moreover, it **is advised to implement as much standardized high-flow protocols and protocol options as possible**. This will allow the station to handle every kind of vehicle in the more efficient and safe way possible. For instance, high-flow stations using SAE J2601-5 should implement PRR Taper feature to be able to handle vehicle pressure drop higher than expected, or K0 method to be able to fuel efficiently even without communication. Back-up with low flow protocols could also be considered, as well as back-up with ambient temperature feelings in case the cooling system has an issue. When more protocols will be available, having a lot of them at the station will maximize the probability of finding a common allowed protocol between station and vehicle.

- **High-flow refuelling stations should use communication between station and vehicle** to improve the fuelling performance. They should implement current infrared communications for the moment (see part 5.1.5 for more details). It is likely that in the future, other sorts of more advanced communications will be available (see part 5.3).

- In addition, the **station should be fully designed**.

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  - First, a **good balance between compressor capacity and total cascade size** should be stricken to be able to meet the daily refueling needs without under- or over-dimensioning the equipment.
  - **Cascades arrangement must be investigated particularly**, as the total volume but also the arrangement of this volume into several pressure levels and several pressure banks has a big impact. For instance, it has been shown in part 6.2 that the same hydrogen quantity split differently among banks do not give the same refuelling performance.
  - The **pressure control valve response time should be sufficient**. Indeed, unlike light-duty vehicles, the refueling of heavy-duty vehicle implies frequent switches among cascades: the pressure control valve response must be quick enough to follow the set-up points despite the frequent brutal changes in the upstream pressure when switching banks. (NREL has alerted of this issue in a presentation [34], showing the consequences of a control valve too slow)
  - **Precooling temperature choice must be done via balancing additional cost versus gain in performance.** Indeed, it was shown in part 6.2 that releasing the precooling constraint from -30°C to -10°C can lead to a 20 min increase in the refueling time, which is clearly non negligible. Moreover, as for the station components, **the cooling system should be dimensioned for 300 g/s refuellings** in order to refuel hydrogen at the desired temperature during the whole high-flow fueling.

- **Connectivity of the station** is also an important aspect that should not be neglected. As detailed extensively in part 3.3, end-users and especially fleet managers need fully accurate and updated data about the refuelling station state. It should be taken into account from the start when designing new high-flow capacity station, to ensure the need of the users are fully met.

- Finally, as high flow refuelling stations are not yet available and widespread, a lot of standardization work is ongoing. Stations manufacturers, owners, operators and users should follow carefully the progress of these standardization discussions in order to be aligned with the future standards and also to feed the committees with their knowledge. Thus**, future high-flow stations must meet future high-flow standards (that are currently under development).**

7.2 For the trucks

Very important points to take into account while designing, building and operating a hydrogen truck and concerning the interface with the refuelling stations are the following:

- The refuelling must be taken into account from the design phase. It is **crucial to design the truck refuelling line with low pressure drops even at high flows**. This means **using components as receptacles, manifolds, piping, OTVs, filters, check-valves that are large enough and made to allow 300g/s refuelling**. Indeed, **if the design is such that too much pressure drops are induced, it will never be possible to fuel the truck at high flow (and to reach a high SOC in a short time), whatever the station.** A relevant objective to respect when building H2 trucks is to target SAE J2601-5 pressure drop limits (Part 1.3.2.8) [14].

- **High-flow trucks should use communication during the fuelling** to improve its performance. They should implement current infrared communications for the moment (see part 5.1.5 for more details). It is likely that in the future, communication will be more and more important and that other sorts of more advanced communications will be available (see part 5.3).

- **Truck storage system should be design thoughtfully to take into account thermal evolution:**

- First, it has been shown that **there can be particularly important thermal heterogeneities in the tanks** during refuelling (see part 5.1.4). **The design of the tanks (aspect ratio, OTV injector characteristics) should be chosen carefully in order to limit this stratification as much as possible.** Indeed, fuelling protocols are calculated doing the hypotheses of uniform temperatures, and do not consider the peaks that can appear locally.
- Moreover, **the temperature sensor(s) should be placed carefully so that they measure representative temperature values** (average or peak)**, and not the injection temperature.** It has been seen designs were the temperature measurement gave values corresponding to the hydrogen injection temperature, and not at all to the heating of the tank occurring during refuelling (see part 5.1.4). In this case, the temperature measurement is not useful, the truck computed SOC is incorrect, the truck cannot know if the temperature limit is approached or overpassed, and if there is COM, the communicated temperature is also incorrect.

- Finally, as for stations, trucks OEM and users should carefully follow the progress of the standardization discussions in order to be aligned with the future standards and also to feed the committees with their knowledge. Thus**, future high-flow trucks must meet current and future high-flow standards.**

8 Conclusions

This **deliverable D4.2 "Refueling solutions and protocols" recaps the key public results of ESCALATE partners work about green hydrogen refueling system solutions,** in order to show the path to new hydrogen, stations adapted to heavy-duty vehicle refueling.

To do so, the fleet managers' needs were deeply investigated to understand **what requirements the hydrogens stations should fulfill**. The importance of reaching a high state of charge with low waiting times and reasonable costs was underlined, coupled with the important need for connectivity. **Safety requirements and regulations** to respect have also been detailed. Then, an **extensive state of the art of existing hydrogen refueling protocols was conducted, showing that the high-flow protocols are not yet fully mature but new promising solutions are emerging**. **Refueling simulations** for pilot 1 and pilot 2 were conducted, underlying the **need for a good design with low pressure drops for both stations and vehicles**. The importance of **working on communication between vehicles and stations during the refueling phase** has also been underlined. Finally, some insights were given on hydrogen refueling station energy consumption, and on the impact of the architecture of the station on refueling performance and energy consumption.

Thus, **this ESCALATE document summarizes major insights and guidelines to pave the way for hydrogen heavy-duty mobility development in Europe**. Further work on refuelling and charging infrastructure for low-emission heavy-duty will be conducted in task T4.4 and recapped in D4.4, and a practical evaluation of the refuelling and charging of the ESCALATE pilots in the light of the detailed requirements and recommendations will be conducted during and after the testing phase of the project.

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