1st life extension & 2nd life of vehicle hydrogen storage systems

Public report

Project within FFI Circularity
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FFI Fordonsstrategisk Forskning och Innovation

Content

<u>FFI in short</u>

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

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1. Summary

First life extension is the extension of the regulatory life for a tank installed in its original application. Second life is the usage in another application than originally intended. This pre-study addresses the prerequisites for the legislative difficulties for such extensions and gives a background to the legislative dependencies. The report focuses on carbon fibre reinforced composite tanks with an ambition to increase the lifespan and thereby reducing the overall emissions and contribute to the overall circularity goals. The focus for second life has primarily been on re-using vehicle mounted tanks in other less demanding applications. Also, transportable and stationary tanks have been evaluated. Some examples of adjustments related to life in the legislations were found and some are concluded to be ongoing. These adjustments were deeper investigated, partially by addressing how the revision of the legislations historically has been technically motivated.

No real examples of second life applications were found during this project. Although not fully approving re-use in new applications, some efforts in that direction were found within one ISO standard published one month before the completion of this report. Although not fully approving reuse in new applications, some efforts in that direction were found within one ISO standard published one month before the completion of this report. The fundamentals and limitations for this possibility are described further in this report.

Composites, as being very different to steel, needs to be managed differently and the behaviour of the material is further into detail explained. Repairs, reuse and inspection require special knowledge to be used for assessment of further service or not. The fundamentals for such operations are presented and the theoretical background is introduced.

During the project an international survey was made, and several actors were interviewed. These actors were able to present methods of qualifying carbon composite tanks for extended use beyond their originally regulatory lifetime. Typically, such qualification is made 5-years at a time. The project was finalized by a public seminar with the purpose to share the knowledge and to invite the participants to a dialogue, addressing future challenges and opportunities. The results from the dialogue have been included into the report.

2. Sammanfattning på svenska

Livstidsförlängning för en vätgastank kan typiskt ske genom förlängning av den ursprungligt bestämda livslängden eller genom återanvändning av tanken i en helt annan applikation. Väldigt få studier adresserar livstidsförlängning av tryckkärl för de högtrycksapplikationer som blir relevanta för vätgaslagring. Denna förstudie utgår från existerande regelverk och ger en introduktion till hur dagens kravställning är utformad och hur regelverken inbördes hänger samman. Från detta arbete går det att få en bild av de utmaningar som finns för att kvalificera en tank för flera applikationer.

För att öka förståelsen kring de påkänningar en tank förväntas utsättas för och vad de kvalificeras för med hänsyn till säkerhetsmarginaler, ges även bakgrunden till de kravnivåer som ligger till grund för typgodkännanden av fordonstankar.

Tankens andel av kostnaden för ett energilagringssystem är väldigt stor och de tekniska förutsättningarna för fortsatt användning, efter nuvarande livslängd som oftast bestäms av regelverken är goda. I rapporten ges en inledning till kompositer och deras speciella beteende som kräver andra angreppssätt än tex stålmaterial. För att kunna använda en tank i en annan applikation än den ursprungliga finns det uppenbara hinder som knyter till typgodkännanden och hur de är utformade för olika applikationer. I denna studie har inga exempel hittats där en tank återanvänts i en annan applikation än den ursprungliga. Trots att potentialen för ett sådant återbruk skulle vara uppenbar. I studien har det också genomförts en global omvärldsanalys och exempel på livstidsförlängning presenteras. Denna förlängning blir möjlig (typiskt med 5 år i taget) genom att använda sig av detektions- och provmetoder som ännu är tidiga i sin utveckling. Framtida möjligheter, utmaningar och förslag till fortsatta studier presenteras och resoneras kring. Det kan konstateras att framtidens beslutsunderlag är i hög grad beroende av hur man väljer att samla in och behandla data knutet till de individuella tankarna.

I studiens sista skede hölls ett öppet seminarium där deltagarna bjöds in till presentationer och en dialog kring framtida utmaningar och möjligheter. Resultaten från dessa samtal har inkluderats i rapporten.

3. Background

In the effort to reduce green-house gas emissions from road transport, hydrogen fuelled vehicles are being developed by many vehicle manufacturers using either fuel cell electric or internal combustion engine propulsion, Volvo Group (2024), Toyota (2024), Hyundai (2024), M. e. a. Yazdi (2023). Hydrogen vehicles have been under development for around 25 years with efforts focused on developing the technologies to a sufficient level of maturity and reliability for commercialization. Now large-scale commercialization is near, efforts are being made to improve circularity in the context of hydrogen vehicles, M. e. a. Yazdi (2023), which contain components quite different from those of conventional or full-electric vehicles, such as fuel cell stacks and compressed hydrogen storage systems. Automotive compressed hydrogen storage systems include containers and fire protection systems i.e. thermally activated pressure relief devices (TPRD) are typically based on "Type 3" or increasingly "Type 4" composite containers (pressure vessels) with nominal working pressures of either 35 MPa or 70 MPa. These pressure vessels are fully over-wrapped with a carbon-fibre/resin composite material to provide the structural strength and use thin metal (Type 3) or high-density polymer (Type 4) liners to contain hydrogen. Today, the actual life is regulated by pre-determined lifetimes stated in governing legislations such as the UNECE R134 or the GTR 13. So far there has been no known guidance for a prolonged usage for these tanks such as first life extension or for use in a secondary application different from the original one. Currently, vehicle regulations are restricting or affecting the prerequisites for an extended service life.

Life Cycle Analysis, LCA, show that one of the largest contributors to emissions during production of hydrogen vehicles with hydrogen stored as a compressed gas are related to the hydrogen storage system and the fuel cell stack, M. Johansson (2024) This pre-study intends to investigate other circularity pathways for road vehicle hydrogen storage systems with a primary focus on the composite containers and their fire protection systems. Potential circularity pathways include first life extension such as re-manufacturing or reuse of components for the original application, and second life with re-purposing of components for use in alternative applications.
The pre-study aims to consider technological challenges with the materials such as service and environmental deterioration (impacts, scratches, chemical exposure, fatigue,

ageing etc), opportunities such as smart monitoring, safety challenges and re-certification, to enable the identification of future research activities supporting this less researched aspect of the circular economy. Relevant regulations and standards should be investigated to see if there are any blockers or enablers related to these circularity pathways. The pre-study is based on a literature review, international benchmarking, and a workshop where initial ideas and concepts will be prioritized for future research that will contribute to reducing the overall lifetime emissions of hydrogen vehicles. Potential concepts to be investigated include assessment of remaining service through smart monitoring, environmental and damage assessment, technical inspections and non-destructive testing (NDT).

International benchmarking was the intended source of information by gathering and analysing international experience and best practice. In the project, representatives from industry (Volvo Technology, Toyota Sweden, Storstockholms Lokaltrafik and Scandinavian Scalable Advanced Composites) collaborated with the research institutes RISE and Lindholmen Science Park. The project partners bring knowledge from the whole life cycle of the products, from design, testing to use of hydrogen storage systems. This wide expertise enabled the project to identify possibly missing and fundamental implementations needed to include circularity in the design phase.

This project aimed to identify and address the prerequisites needed for extending the first life or re-purposing of composite hydrogen storage systems for vehicle use, as it is reasonable to believe that the technical life is longer than the life required by regulations. These circularity pathways are desirable as the systems have relatively high manufacturing costs and life cycle emissions. One of the fundamentals for this project was that there is no known research, regulations or standards for how such life extension or re-purposing would be accomplished. Although, existing regulations influence the possibilities for such efforts to a large extent.

Different forms of degradation, inspection or repair techniques should be identified and considered to be able to manage evaluations of residual strength and life extension. While the pre-study also should review the actual limitations in the existing regulations that might affect such work. The study should also address how the systems could be re-purposed for different applications (e.g. at a lower pressure in a stationary application).

4. Potential

At Volvo several life cycle assessments have been performed. The results indicate a high environmental impact of the carbon fibre-based hydrogen storage tanks (a significant part of the complete vehicle). Moreover, the hydrogen storage tanks are also one of the most expensive components in the hydrogen vehicles. Therefore, a deeper understanding of how to prolong the life of the tanks, second use in next vehicles and second life in other applications is highly valued, both considering the cost aspect as well as environmental impacts (Johansson M, 2024).

Hydrogen storage is widely recognized as one of the key cost drivers limiting broader adoption of hydrogen in the transport sector. Therefore, a significantly improved total cost of ownership (TCO), combined with increased confidence in long-lasting and reliable storage solutions, could contribute to positive market development and support the transition toward more sustainable transport systems.

For users - whether in industry, transport, or energy systems - the longer tank lifetime may reduce the need for replacements and avoid costly production stops. This in turn can improve the overall economy of hydrogen systems and strengthen their competitiveness compared to conventional alternatives (Eriksson K, 2025).

The potential of recycling was not intended to be considered in the project as it is already the subject of significant research. However, it has to some extent been mentioned in the report as it is expected to be a future cost competitor to second usage.

5. Results and deliverables

This study approached the topic of life extension by starting to evaluate existing legislative requirements. The benefit from such approach is that there is a lot of "built-in" experiences and proven data in the legislations. This is a conservative way of managing safety as most uncertainties that may affect safety already are indirectly included and the outcome is to some extent already known.

5.1 Regulatory and governing background

Today's regulations addressing pressure vessels have their origin from the experiences made from accidents with steam boilers in the 19th century, these accidents lead to the work that resulted in the ASME Boiler and Pressure Vessel Code. Later this was followed by the European counterpart, the pressure directive PED that exist along its counterpart for transportable vessels, TPED. Over the years, several different types of pressure vessels emerged as the technology allowed new inventions. Metal vessels were later accompanied by composite material vessels for reasons such as lighter weight and design flexibility. The legislations have therefore constantly evolved, adopting to these new technologies to allow for a safe technical progress. For our applications in this study the legislations were formed to govern the so-called type IV-vessels, carbon fibre reinforced tanks with a permeation resistant polymer liner. The first commercial applications were developed within the space industry in the 1960s and later the regulation adopted to compressed natural gas, CNG, pressure vessels for vehicle use starting in the 1980s. It is typically these regulations that have been the foundation for the hydrogen type IV-tanks we are using today.

This historical recap has some relevance when reading todays legislations. There have been some simplifications that can be traced to the reforming of the existing requirements for CNG application, such as the UNECE R110, rather than directly developing new regulations for hydrogen. Therefore, there might be some ideas inherited from the basis of CNG that will be adjusted in upcoming revisions. One example of difference would be the requirements of the procedure when refuelling hydrogen in comparison to CNG. For 700 bar hydrogen refuelling there are stricter requirements of safety such as digital communication between the vehicle and the fuelling station adding e.g. extra protection

for over pressurization and secondary pressure effects of process temperatures for fast re-fuelling. According to the SAE re-fuelling protocol J2601 a basic data handshake is necessary. During this handshake the tank temperature, pressure, tank ID, allowable fill level, and safety checks are communicated. Without this handshake it is not possible to refill the vehicle. There are no such basic requirements when refuelling CNG. Hydrogen, as being more flammable and being kept at higher pressures might in fact be safer from this perspective due to these extra legislative layers of safety.

As circularity is a fairly new initiative, the concept is about to find its way into the legislative documents. This study has identified some of the key issues related to life extension and second life and may contribute to further development. Future adjustments of the restrictions in and in between the legislations may enable further possibilities for circularity, or block them.

5.1.1 Legislations and standards

There are several governing documents that addresses the demands and qualification of pressure vessels. As this study focuses on type IV-tanks there are several similarities within these documents that applies for qualification. But there are still differences that make the qualifications difficult to combine. There are also regional aspects to account for. The hierarchy and dependencies of the governing documents may initially be difficult to grasp. There are a few legislative categorisations and terminology that may need an introduction to better understand the overall view.

Directives consist of "goals" such as formulated general safety objectives. It is up to the individual country to device their laws on how to reach these goals. These directives come to effect when they are chosen by the individual member state to be incorporated into domestic laws.

In contrast to the directives there are regulations. These have a binding legal force throughout every member state and apply on a set date in all the member states. Often, the regulations are issued by international intergovernmental organizations such as the UN. The purpose with the regulations is typically to e.g. ensure health, protect the environment etc.

There are also standards that states requirements and technical provisions, but they are of voluntary adoption. However, they may be legally binding if they are incorporated into the law. The work developing the standards are usually led by the industry. The purpose is to state technical specifications and criteria for e.g. uniformity, quality, performance and safety. There are also guidelines to consider. These are voluntary and consists of recommended or best practices for achieving specific objectives. These may be seen as complementary to the standards, often giving advice of how to interpretate specific parts of the standards. The hierarchy for the governing terminology is interpreted in figure 1.
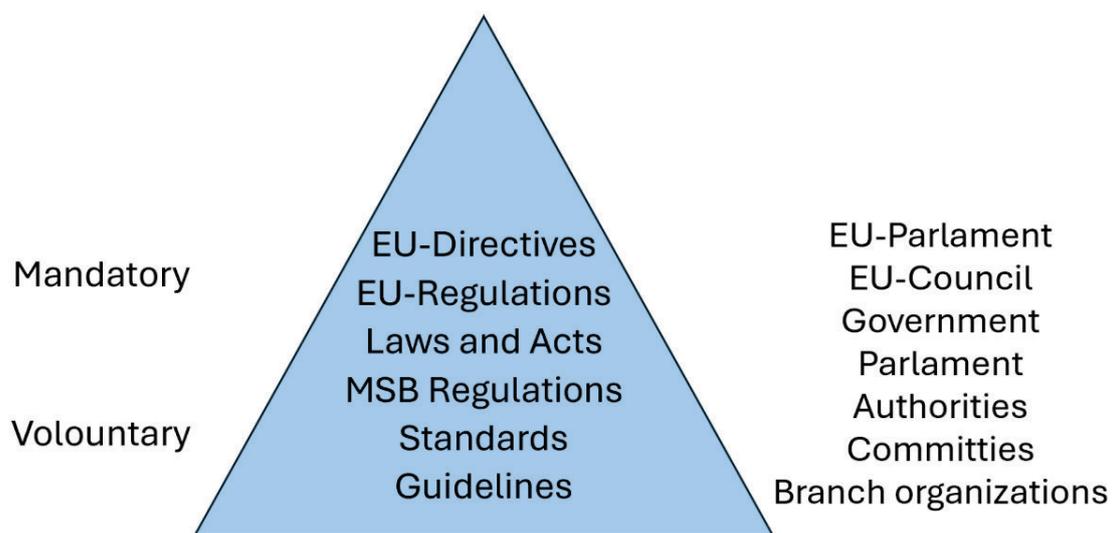
Figure 1   *Illustration of the relation of legislations and their governing organizations.*

There is also a concept called harmonization. If a standard fulfils the requirements in a directive, the standard is harmonized against the directive. European harmonized standards are found at the European Commission website (European Commission, 2024).

The most fundamental directives for essential safety requirements for pressurized stationary systems is the PED, Pressure Equipment Directive for the European Union and the ASME Boiler & Pressure Vessel Code for the US, Canada and to a large extent Asia. For transportable pressure vessels in the EU market the TPED, Transportable Pressure Equipment Directive is governing.

For this study, the primary focus has been on vehicle mounted, transportable and stationary application as this is likely to be interchangeable with regards to the storage volumes and pressure levels. Furthermore, the expectation is that these applications will be the dominating ones by sales volume in the nearest foreseeable future. During the study, the approach from a regulatory perspective developed towards primarily investigating the possibility of extending the life of or reuse tanks from vehicles. The technical lifetime of hydrogen vehicles and the assumption that the tanks have a significantly longer technical life makes it natural to see this market as "donors". A stationary installation will not share the same prerequisites for reusability, and it is unlikely that a stationary tank will have the potential to be used on a vehicle. Table 1 introduces a list of the standards considered primarily relevant for this study, although there are several more that address pressure vessels in various applications.

The automotive related regulations that primarily are addressed within the scope of this study are:

- GTR13 (Global Technical Regulation) that governs vehicle mounted tanks and components.

- UNECE R134 is the European counterpart.

- ISO 19881 Gaseous hydrogen — Land vehicle fuel containers

For the transportable tanks:

- EN 17339:2024 Transportable gas cylinders – Hoop wrapped and fully wrapped carbon composite cylinders and tubes for hydrogen

- ISO 11119-3:2020, Gas cylinders — Design, construction and testing of refillable composite gas cylinders and tubes — Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners or without liners

For stationary tanks:

- EN 17339 Transportable gas cylinders – Hoop wrapped and fully wrapped carbon composite cylinders and tubes for hydrogen

- ISO 19884 Gaseous Hydrogen - Pressure vessels for stationary storage

Table 1   *Examples of hydrogen tank legislations relevant for the European market.*

Document	Hydrogen	CNG	Vehicle	Transportable	Stationary
GTR 13	X		X		
UNECE R134	X		X		
UNECE R110		X	X		
EN 17339	X			X	
EN 17533	X				X
ISO 19881	X		X		
ISO 19884	X				X
ISO 11119	X	X		X	

There are more legislations covering these different types of applications, however the primary focus in the project was to evaluate the governing documents with relevance for European markets.

For this study it is relevant to specifically mention ISO 17533:2025 Gaseous hydrogen — Cylinders and tubes for stationary storage. As this partially addresses one of the fundamental difficulties within the scope of second life. This standard suggests a service life of 30 years or a pre-determined set of cycles. What makes it interesting for this study is the latest revision (approved April 7, 2025) adds the concept described in the standards Annex A and specifies an option for the safe use of new cylinders and tubes that are qualified to other applications (e.g. for transport of dangerous goods). Although this does not allow for second life usage, as it is only applicable to entirely new cylinders, this may be one of the first regulatory initiatives in that direction. The ISO 17533 only allows for re-assessment of qualification if the tank was previously approved according to one of the following standards:

- EN 12245
- EN 12257
- EN ISO 9809-1
- EN ISO 9809-2
- EN ISO 9809-3
- EN ISO 9809-4
- EN ISO 11120
- ISO 11515
- ISO 11119-1
- ISO 11119-2

ISO 17533 could serve as a predecessor to future initiatives for similar transfers in between approvals.

There are different ways of defining lifespans between different legislations. The lifespans for the relevant legislations included in this study are listed in table 2.

Table 2   Life limitations in legislations.

Document	Life limitations
GTR 13.2	Max 25 years
UNECE R134	Max 25 years
EN 17339	Min 15, maximum 30 years or "Non-limited life"
EN 17533	Max life 30 years or no of cycles
ISO 19881	Min 10, maximum 25 years
ISO 19884	Service life should not exceed 30 years
ISO 11119	Min 15 years of life. No limit to design life if test pressure is <60 bar

5.1.2 Rationale for type approval testing

The EN 17339 is the only standard found that is not declaring a definite maximum life limit for tanks relevant for higher storage pressures. Instead, the standard uses the phrase "non-limited life", without no further elaboration about the definition of the phrasing. Instead, the EN 17339 refers to EN ISO 11623 where procedures and intervals for periodic inspections for non-limited life are stated. The typical periodic inspection interval for composite cylinders is stated to be made every 5 years, although this can vary based on national regulations and specific usage conditions. The inspection typically includes internal and external inspection combined with hydrostatic testing and leak testing.

To qualify a tank, a series of tests need to be made for type approval. This is necessary for commercial access to the market. For some of the legislations the background to why certain requirements have been formulated the way they are is described in a rationale. For vehicle tanks the rationale behind the GTR 13 is available and will partially be described in detail here. The European UNECE R134 and GTR13 are very similar when it comes to the parts of tank testing with almost identical requirements, so the rationale applies to both.

The qualification tests were developed to demonstrate capability to perform critical functions throughout service including fuelling/defueling, parking under extreme conditions, and performance in fires without compromising the safe containment of the hydrogen within the storage system.

The type approval testing is grouped into four design qualification categories (Ref GTR13):

5.1.1. Verification tests for baseline metrics
-Performance verification tests and in production quality control.

5.1.2. Verification test for performance durability
    - Qualification tests that verify that the system can perform basic functions of fuelling, defueling and parking under extreme on-road conditions without leak or rupture through-out the specified service life. These tests are performed with water.

5.1.3. Verification test for expected on-road performance
    - Qualification tests that verify that the system can perform basic functions of fuelling, defueling and parking under extreme on-road conditions without leak or rupture through-out the specified service life. These tests are primarily performed with hydrogen.

5.1.4. Verification test for service-terminating performance
- provides confirmation that the system performs safely under the service terminating condition of fire.

For the first baseline tests the purpose is to establish a statistical knowledge around the production process and thereby the ability to produce tanks with a predictive strength and strength distribution in combination with the expected cycle life.

For the durability tests, the purpose is to subject one individual tank for a series of tests. The tank needs to sustain these without losing its integrity under a specific threshold. This durability verification test includes the following sub-steps:

- Initial pressurization to 150% Normal Working Pressure, NWP
- Drop test that corresponds to the tank being dropped from 1.8 m in production or during a repair.
- Surface damage test simulating wear on the tank surface.
- Chemical exposure onto the damages. Several chemicals are included such as oil, acids, Methanol, nitrates, alcohols, chlorides, carbonates, gasoline and ammonia.
- The tank is then cycled, with the chemicals, to an elevated pressure of 125% NWP for 13200 cycles.
- The tank is then subjected to 10 over pressure cycles to 150% NWP, considered to be the worst-case scenario for a malfunction of the filling station.
- Static test, 85°C for 1000 hours at 125% NWP corresponds to 25 years of parking with a full tank and the accelerated testing is managed by the elevated temperature.
- Pressure cycling at -40°C, 80%, for 4400 cycles corresponding to low-temperature extreme conditions. As the maximum pressure is decreased for normal filling in service at these low temperatures the same applies during testing.
- Pressure cycling at +85°C and 95% humidity and 125% NWP for 4400 cycles to simulate the elevated temperature extreme.
- Static pressurization for 4 minutes at 180% NWP. Simulates the probability of stress rupture of composite strands (equivalent to 10 hours at 150 per cent NWP).
- Finally, the pressure is increased until rupture. The burst pressure should be above a 20% drop from the characteristic mean burst pressure, BP_0 obtained from the baseline test.

Verification test for performance durability (hydraulic)
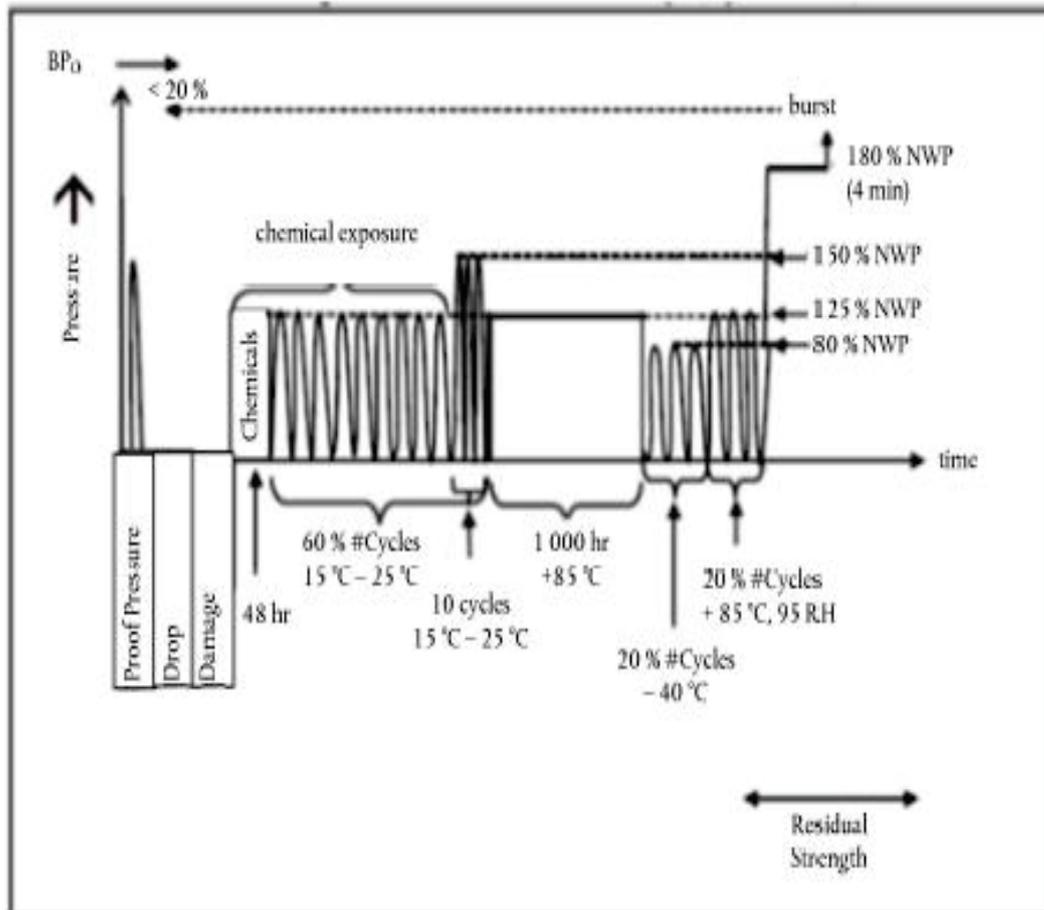
Figure 2   Illustration of the test sequence for durability performance, from UNECE R134.

The on-road performance tests are instead of liquid performed with hydrogen, still on one same tank, and consists of the following sub-steps:

- Initial pressurization to 150% for establishing safety for the upcoming tests as they will be made with compressive flammable gas. This test does not intend to rupture the tank.
- Extreme temperature pressure cycling and ambient temperature cycling. The extreme conditions expected during operation are stated to -40°C/80% NWP and +50°C/125% NWP. Cycling at these temperatures and ambient are distributed during a total of 500 pressure cycles. The hydrogen gas cycling is interrupted by permeation testing.

- 30+ hour of permeation testing at 115% NWP and +55°C. The purpose is to quantify the leakage rate of hydrogen through the entire system of materials, connections and couplings.
- Static pressurization for 4 minutes at 180% NWP. Simulates the probability of stress rupture of composite strands (equivalent to 10 hours at 150 per cent NWP)
- Finally, the pressure is increased until rupture. The burst pressure should be above a 20% drop from the characteristic mean burst pressure, BP_0 obtained from the baseline test.


Verification test for expected on-road performance (pneumatic/hydraulic)
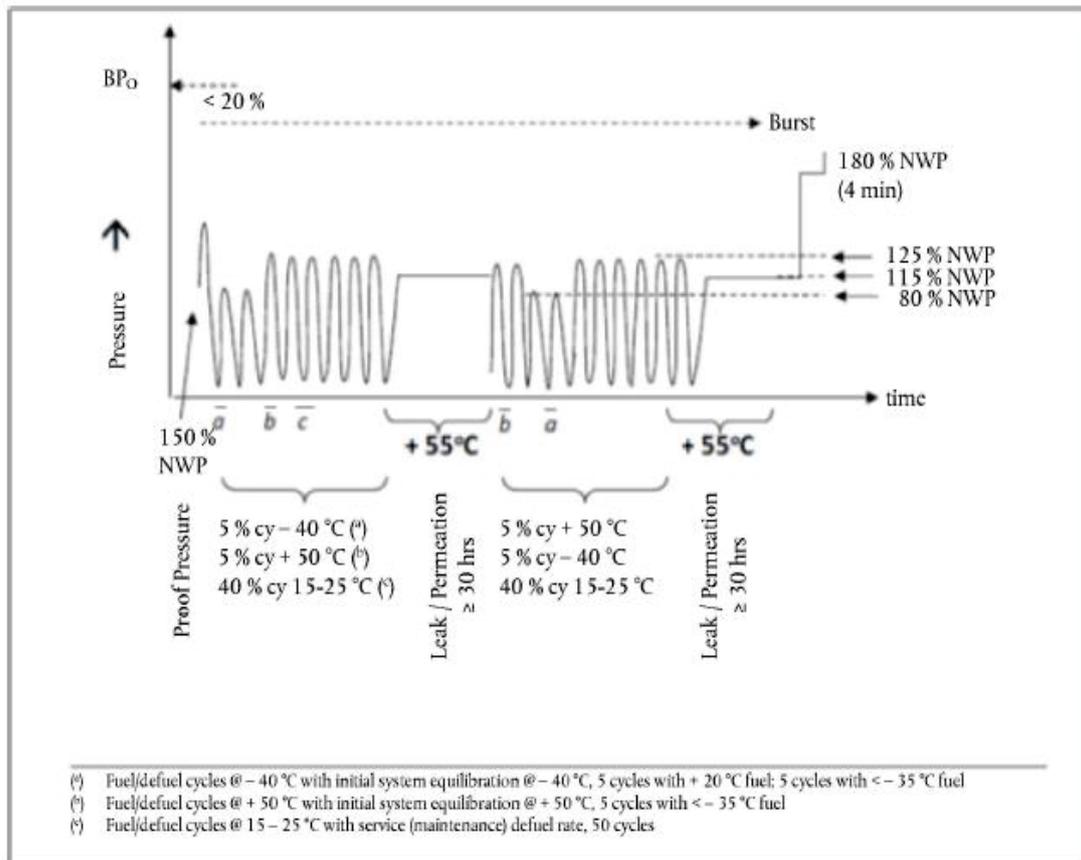
Figure 3   Illustration of the test sequence for on-road performance, from UNECE R134.

The service terminating performance test does verify the behaviour during fire and does not have a real impact on the scope of this project as it does not relate to the lifespan.

For the baseline cyclic testing the number of cycles has been motivated by [ECE/TRANS/180/Add.13/Amend.1]:

The requirement of paragraph 5.1.1.2. (baseline initial pressure cycle life) is 22 000 cycles. The 22 000 full-fill cycles correspond to well over 7 million vehicles kilometres travelled in lifetime service (at 350-500 km travelled per full-fuelling). Since the expected lifetime service is far less than 1 million km, the requirement for 22 000 pressure cycles was judged to provide substantial margin above extreme worst-case vehicle service.

Also note that manufacturers are expected to monitor the reliability, durability and residual strength of representative production units throughout service life.

5.1.3 Recent changes in revised regulations

The revision of GTR 13 (Global Technical Regulation 13) from 2013 to GTR 13.2 (or phase 2 or amendment 1) adopted in 2023, introduced some key changes related to the safety and reliability of hydrogen fuel systems in vehicles. Some relevant for life extension:

One of the adopted suggestions was to allow carbon composite tanks to have an increased lifespan from 15 to 25 years based on the existing qualification without any modification to the qualification testing. This was motivated by studies made in Japan, US and Germany that no vehicle will be able to be driven to such extreme number of filling cycles during the tanks calendar lifetime as originally assumed in first version of GTR 13. These studies were accompanied by several tests on type 4 CNG tanks that had been in service. The tanks were burst tested, introduced to damages and cycled beyond their end of life and thereafter burst tested. The conclusion from these studies supported that the lifetime could be extended as no degradation could be proven.
These changes were approved by the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29) in June 2023. In GTR 13.2, it is up to the manufacturer to decide the lifespan, but there is still a maximum lifespan of 25 years. The European counterpart, UNECE R134, also adopted this change in June 2024. The suggestion to extend the life was made several years earlier but the formal decision was postponed, motivated by the lack of real-life supportive data.

The baseline burst pressure, BP_0, was also decreased, from 225% to 200% in the GTR 13.2 revision. This change has not been adopted in UNECE R134 yet but is scheduled to go into legal force in September 2026. This decrease was primarily motivated by the final step in the test sequence where the tank should sustain 180% NWP for 4 minutes and then not burst until 20% below BP_0 (above 80% BP_0). By meeting this criterion, it was argued and supported by experiments that the 225% demand was unnecessarily high for the desired safety throughout the tank's lifetime. The conclusion was that the initial pressure level could be dropped to 200% while still fulfilling the requirements of burst at the end-of-life tests. Note that this is only valid for carbon composite tanks. For glass fibre reinforced tanks, the requirements are different due to different material behaviour and the initial burst pressure, BP_0, remains unchanged at 350% even after the decrease from 225% to 200% in GTR 13.2. This is supported by the rationale in ECE/TRANS/180/Add.13/Amend1e.
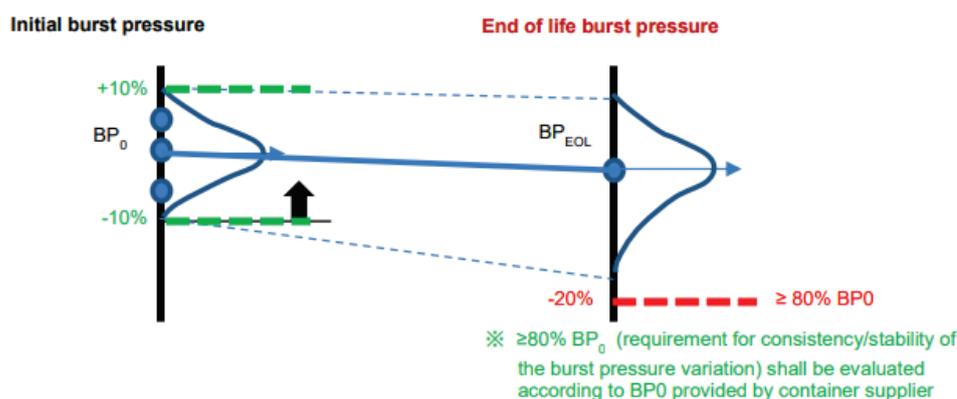
Figure 4   Visualization of the impact of residual strength at end-of-life. Illustration from: ECE-TRANS-180-Add.13-Amend1e.

No work evaluating the possible combined influence on the structural integrity over time when changing both parameters (lifetime and BP_0) at the same time has been found.

5.1.4 Efforts and political decisions addressing second life

In EU, there is a Circular Economy Action Plan as a part of the European Green Deal, aimed at making Europe climate-neutral by 2050. It focuses heavily on sustainable resource use, waste reduction, and fostering a circular economy where products, materials, and resources are reused, repaired, refurbished, and recycled as much as

possible. Although not directly addressing hydrogen components, the intention in this plan aligns with the scope of second life. During this project no political initiatives for a second life usage for hydrogen tanks and components has been found. The initiatives are simply restricted to recycling and primarily of the carbon fibre material or the steel material itself. The gap between this plan and the explicit decisions that needs to be made are therefore still to be filled.

In comparison, batteries, as being one of the competitors for energy storage, second life is a well spread concept since many years. It has been part of the legislation at a European level with specific demands that the manufacturers enable the reuse of batteries outside of the original application. In the Battery Regulation (Regulation (EU) 2023/1542) adopted in July 2023, it is explicitly encouraged to make second-life applications possible batteries. The regulation more specifically address:

- Provide battery performance and durability information
- Label batteries for easier reuse/recycling
- Ensure design allows for removal and replacement where feasible

There are also International Standards addressing second life for batteries:

- IEC 62933 (energy storage systems): Covers safety and performance, also supporting second-life applications.
- UL 1974 (North America): Provides requirements for evaluating and repurposing used batteries.

5.2 Technical considerations

The safety of type 4 tanks has been proven in the aerospace industry with no known stress rupture failure for over 25 years (ISO 17533, 2015). This suggests that as long as we produce tanks in high quality processes, the composite degradation behaviour is possible to predict. By increasing amounts of data from existing applications, future assessments of the life expectancy of materials should be even more well founded.

5.2.1 Review of composite durability

Use of polymeric composite materials opens opportunities for developing new lightweight components (such as tanks) with the potential to reduce the overall climate

impact of road vehicles. The components will, during their lifetime, be subjected to combinations of mechanical and hygro-thermal load scenarios. Reliable methods for understanding and predicting the properties of the composites throughout their lifetime are therefore critical.

Exposure to the environment

Despite decades of research on the subject, ageing of composites is still a challenging topic, and not fully understood. Aging can lead to reversible or irreversible property changes due to several degradation processes, acting alone or synergistically, in a complex combination of physical and chemical phenomena that may operate at different time scales. An example of reversible degradation is the softening of the polymer matrix at elevated temperatures, leading to reduced stiffness and strength of the composite. Primarily, the properties that are negatively affected are transverse stiffness and strength, shear stiffness and strength as well as transverse compressive properties. To some extent this also applies for compressive loading in the fibre direction since that strength depends on the shear strength of the matrix. In the glassy state (below Tg) these properties decrease approximately linearly with an increase in temperature, White & Hahn (1992) and de Kok & Meijer (1999). At the onset of Tg and above, the properties drop drastically. The tensile properties in the fibre direction are relatively unaffected, both for temperature and due to humidity, see Selzer & Friedrich (1997). Degradation by oxidation (an irreversible process) is generally considered to be the most serious problem when using polymers at elevated temperatures.

Thermal cycling, hot/wet, dry/wet and freeze/thaw cycling, exposure to liquids (including water, fuels, acids, alkalis, solvents etc), and weathering conditions (such as absorption of UV radiation) can all have significance depending on the level and time of exposure in each case, affecting the involved material components (fibre, matrix and interface) differently. The incurred degradation strongly depends on the chemical composition of the materials involved. For instance, glass fibres are known to chemically degrade when water attacks the Si-O bond, Schutte (1994). Aramid fibres are sensitive to moisture and UV radiation. According to Maxwell et al. (2005) substantial strength losses have been observed with these fibres under natural weathering conditions. Carbon fibre is typically considered more stable and is therefore better suited as load bearing constituent in harsh environments. Moisture absorption in composites occur when they are in direct contact

with water including humid air. Water enters via a combination of diffusion and capillary actions. The lowest moisture content at saturation is obtained under humid air conditions, and the highest content is obtained when composites are fully immersed in water. On the other hand, the diffusion rate in humid air is higher and thus allows saturation to be reached faster, Korkees (2023). The presence of moisture at the fibre-matrix interface can modify interfacial adhesion and thereby degrade the mechanical performance of the composite. Polymer matrices plasticize, swell, and may chemically degrade via hydrolysis. If the matrix becomes cracked, additional water uptake is observed as it fills the newly developed empty spaces.

A reasonably high Tg ensuring that the structural integrity is less affected by a temperature increase during operation is desirable. Material manufacturers often specify the maximum operating temperature. However, there is no accepted method for determining this temperature for any given environment, rather it is usually based on experience and historical data. In general, however, it can be said that maximum long-term use should not exceed "wet Tg" including a suitable safety margin of 20-40 °C depending on the expected mechanical loads at that temperature.

Fatigue

Fatigue, which is the progressive damage of the material when subjected to repeated cyclic loading, is a key behaviour to understand for a proper sizing of composite components. During cyclic loading, even at load levels well below the elastic limit, microscopic damage occurs in the material due to the complex combinations of thermo-mechanical and environmental loads, defects and stress concentrations caused by the heterogeneous micro-meso structure. This micro-damage accumulates throughout the material and can grow steadily into larger distinct cracks on the meso-macro level or be more diffused, e.g. as many fibre-matrix debonds, partially developed matrix cracks or as local delaminations between plies. In tensile loading, which is most relevant for tank design, intralaminar cracking in plies usually substantially precedes the final failure of the laminate, which is caused by fibre failure in the critical load-bearing ply or large-scale delaminations between plies, see, e.g., Ben Kahla et al. (2020). These cracks are caused by in-plane transverse tensile and shear stresses in the ply, Quaresimin et al. (2014). During service, the number of cracks increases depending on loading conditions and may

lead to significant degradation of the laminate thermo-elastic constants, see Varna (2013) and Kashtalyan & Soutis (2007).

To simplify the analysis of fatigue damage, constant stress ratios (R-values), frequencies and comparable waveforms are typically being used. The fatigue life of composites is highly dependent on the stress ratio, and this influences the shape of the S-N curve, Alam et al. (2019). Unlike the fatigue analysis of metallic materials, where a linear Goodman diagram is broadly used to identify fatigue limits, the fatigue limit of composites may not be determined using a simple linear approach. Instead, an effective method of evaluating S-N curves for constant amplitude fatigue loading at different R-values is through a constant fatigue life (CFL) diagram, Alam et al. (2019). The CFL diagrams describe the fatigue behaviour by plotting the alternating stress amplitude against the mean stress, and these diagrams become asymmetric due to differences in the tensile and compressive strengths. Kawai & Koizumi (2007) showed that the shape of CFL diagrams progressively changes from a straight line to a nonlinear curve as a given constant value of fatigue life increases, see Figure 5. They presented a methodology for constructing these diagrams and used it to predict the S-N curves for different R-values with reasonable accuracy, see Figure 5.
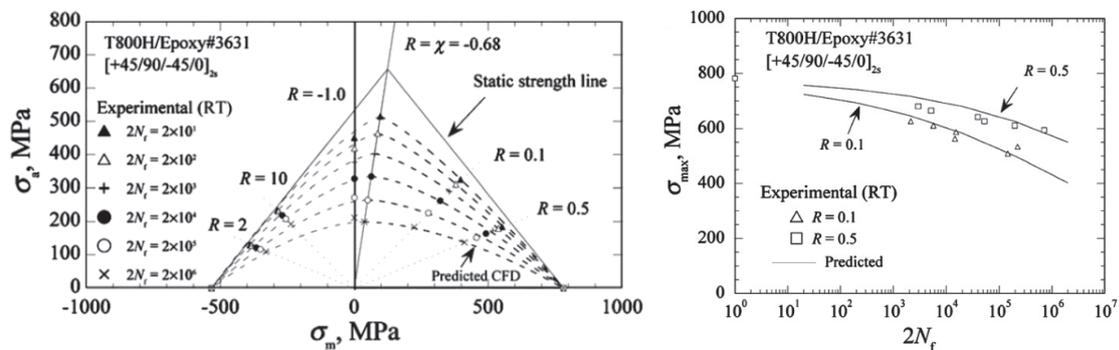

Figure 5   CFL diagram for a [45/90/-45/0]2s carbon fibre epoxy laminate (left) and predicted S-N curves compared to experimental data for T-T fatigue loading with R-values 0.1 and 0.5 (right), from Kawai & Koizumi (2007).

5.2.2 Review of hydrogens influence of the material properties

Hydrogen embrittlement is a known degradation phenomenon that occur in certain metals such as high strength steels and titanium. Hydrogen diffuses into the metal lattice, especially under high pressure, and is responsible for subcritical crack growth in the material. With subsequent loss in mechanical properties such as ductility, toughness and strength, this may then lead to catastrophic failure of the tank. Polymers and polymer composites are generally not susceptible to hydrogen embrittlement in the same way that metals are. Polymers are made up of long chains of covalently bonded molecules and lack the crystalline atomic lattice structure that metals have. However, large amounts of hydrogen are often soluble in polymer materials and may therefore cause damage such as blistering or swelling, San Marchi & Somerday (2012). This may occur in high-pressure applications due to depressurisation of a system or rapid temperature changes as hydrogen expands in the free volume and at interfaces within polymers and composites.

5.2.3 Review of the repair of components

A composite structure in-service experiences inevitably damage that comes from mechanical loading and/or environmental conditions. Damage in laminated composites happens in many forms (delaminations, matrix cracking, fibre breakage etc). Damage degrades the mechanical properties, compromises the performance and functionality, and reduces the service life. A way to sustain in operation for a costly and complex composite structure without the need of replacement, is via repair. The purpose of the repair is to restore the structure to its original strength and stiffness, satisfy damage tolerance limits, restore the functional requirements, and have negligible weight penalty at an acceptable fabrication cost. Efficient, reliable and cost-effective repairs are essential not only for the maintenance of the structures but also in relation to the end-of life options for composite materials. Repair can facilitate the extend of life of a composite part and it´s repurpose, instead of being disposed in a landfill. The repair action taken on a damaged composite structure is highly dependent on the damage level. Repair can be classified as, Barroeta Robles et al. (2022):

- Non-structural: Applied to minor scratches, gouges, nicks and to subtle debonds or delaminations (provided that a leak has not happened in a pressure vessel). This repair practise is performed by injection/infusion of low viscosity resin into the

damaged area. It remains limited to non-critical structural applications because it does not replace the damaged or broken fibres with new intact fibres, Pierce & Falzon B (2017), Perera et al. (2024) and Hautier et. al. (2010).

- Structural: Applied in the case of extended damage in the composite with severe or complete loss of material performance.

The most common methods for structural repair of composite structures are adhesive bonding or mechanical fastening of a composite patch to assure the load transfer between the undamaged components, Budhe et al. (2018) and Composite repair (1999). Mechanical fastening is not a technique to be used in repair of hydrogen storage vessels and will not be further analysed here. In bonded repairs, the patch is formed directly over the damaged area from layers of neat material (e.g. prepreg) with or without interleaved layers of adhesive, which is vacuum bagged in place and cured (co-bonded). Alternatively, the patch can be laminated and cured in a separate operation and bonded afterwards on the damaged area with an adhesive (secondary bonding operation), Baker (2006). In bolted repairs, holes are drilled around the undamaged parent structure and a pre-cured patch, typically called a doubler, is installed in place with the use of some type of mechanical fastener. The basic repair configurations namely external patch repair, scarf repair, and stepped-lap repair are based on the four fundamental joint configurations which are graphically represented in Figure 6.
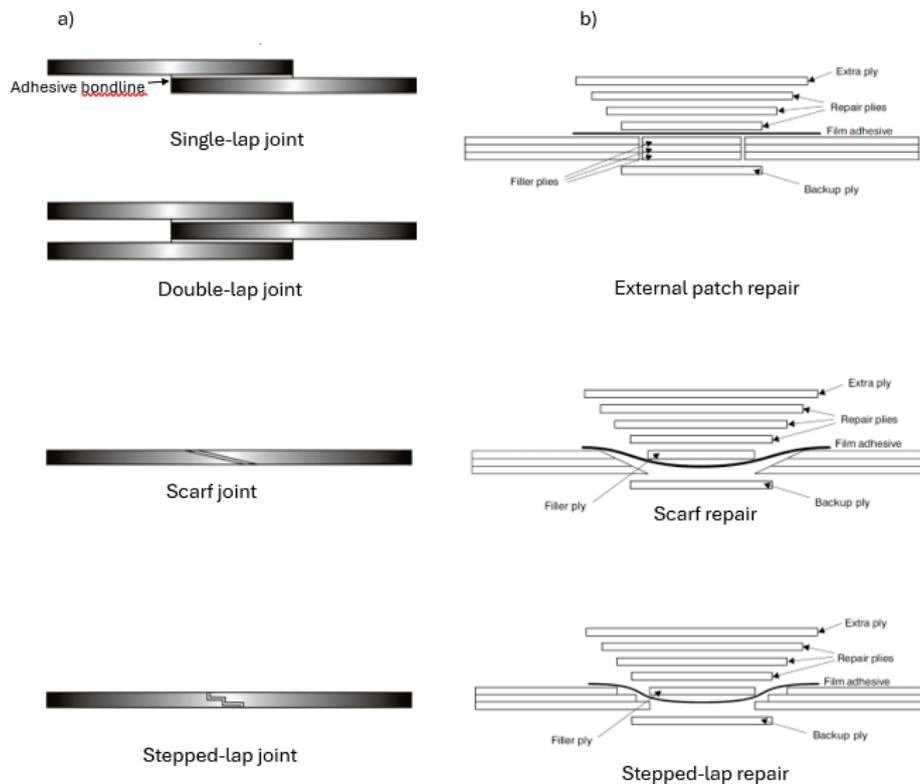
Figure 6　　　*Fundamental joining configurations (a) and repair configurations in adhesive bonding and (b) 2D representation, from Composite repair (1999).*

The repair action depends greatly upon the component and its function, the extent of the damage and safety requirements, as well as the cost of the repair. The primary challenge of composite repair is to ensure that it can function properly for long-term service. The repair must be designed and executed very carefully. The operating environment (loading and environmental conditions), safety restrictions and the repair cost are of particular importance. Adhesively bonded repairs have been employed rigorously in various industrial sectors for a full and safe recovery of damaged structures. External patch repairs (Figure 6) are relatively easy to execute and are typically employed when full-strength recovery of the structure is not required. Due to their geometry, they are characterized by load transfer eccentricities at the overlap edges, leading to repair flexure and composite/joint damage Soutis et al. (1999) and Campilho et al. (2009). Flush repairs are more difficult to execute due to their geometry, which reflects on higher costs. They are usually applied to restore the undamaged strength of the component, and they preserve the structure's smoothness. The patch lamination in scarf repairs is designed to match that of the parent laminate. Their high efficiency is caused by the elimination of

the significant joint eccentricities of external patch repairs, Jean-Baptiste et al. (2023). Stepped-lap repairs are an alternative to scarf repairs, easier to execute and with very similar behaviour after careful design. Adhesively bonded repairs in general present fewer sources of stress concentrations, minimise the weight penalty, behave well under fatigue loads and allow joining different materials.

It must be noted that thermoset and thermoplastic composites display similar damage types, however, the greatest advantage of thermoplastics over thermosets regarding repair is that they can be melted and reformed. For repair to matrix damage (delamination, fibre-matrix debonding, matrix cracking) thermal reforming may be applied which requires volumetric heating. This can be done by a heat source applied to the surface and transferred into the bulk by conduction or by internal heat generation via e.g. induction heating. For extensive damage, thermoplastic composites can be repaired by fusion-bonding, Barroeta Robles et al. (2022) and João et al. (2020). Fusion bonding involves the application of localized heating to the regions to be bonded to form a weld which subsequently is cooled down under the application of pressure. Fusion bonding techniques are classified according on the heat generation mechanisms on the bonding interface, namely thermal, friction, and electromagnetic welding. Examples of welding techniques are resistance welding, induction welding, ultrasonic welding etc based on the internal heat generation mechanisms. Fusion bonding is very attractive for repair of composite laminates; however, important drawbacks are the high pressures required to achieve a good quality bond, probably to the level of consolidation pressure and the lack of developed fusion bonding systems to be used in the field. Additionally, given the range of possible structural forms and types of damage, it is likely that a combination of methods (adhesive and fusion bonding) may be necessary, Smiley et al. (1991). For adhesive bonding, common aerospace epoxy or acrylic based adhesives can be used. However, thermoplastic polymers typically have lower surface energies when compared to thermoset ones, which makes it difficult for adhesives to wet the adherend surface and create a good bond. Special surface treatments are typically required for cleaning and functionalising polymer surfaces such as corona discharge, plasma treatment, acid etching, oxidizing treatment etc. Disadvantages associated with these surface preparation methods include high equipment cost, restrictions on part size and the difficulty associated with the surface treatment of complex geometries. Recent developments in adhesive technology have presented two-part acrylic adhesives to improve adhesion in low energy surfaces, Shi et al. (2025).

Repairs have been extensively studied experimentally and numerically to improve the design for better performance, ease of manufacturing and cost reduction. Nowadays, Finite element (FE) models have been developed for stress analysis and have been combined with damage initiation and propagation criteria for damage tolerance assessment to study repair under a variety of static and dynamic loads. Additionally, efforts have been made to incorporate the effect of manufacturing and environmental (hygrothermal) conditions to increase the reliability on repair, especially from a long-term perspective, Budhe et al. (2018). The reliability of an executed repair depends on its quality. Repair defects such as insufficient curing, porosity, insufficient adhesive wetting etc could be detrimental for the repair performance. Experimental tests and NDT methods such as ultrasonics, thermography, laser shearography, acoustic emission (AE), digital image correlation (DIC) have shown great applicability identifying the quality of the repair, Wang (2020). However, the interest has shifted towards the incorporation of systems based on Structural Health Monitoring (SHM) that aim to combine advanced sensing technology with intelligent algorithms to diagnose the 'health' condition of structures in real time or whenever necessary. There is a variety of approaches that can be used to monitor the health of composite structures, and an increasing number of commercial systems are now available e.g. piezoelectric sensors or optical fibre sensors.

Life expectancy and repair

Composite hydrogen storage vessels represent a promising solution for the storage and transportation of hydrogen fuel, offering significant advantages in terms of performance, durability, and environmental impact. Hydrogen Fuel Cell Vehicles (HFCV) use storage vessels type III and IV to store hydrogen efficiently as gas compressed in a range of 350-700 bar. Considering these vessels are developed to be operational from 10 to 20 years, this means that they could potentially outlive the lifespan of the vehicle and could be potentially reused in another one. It is important to mention that repairing Type III and IV pressure vessels, which are made of composite materials with a metal or plastic liner, respectively, presents unique challenges:

- Material Complexity: The vessels use advanced composite materials that require specialized repair techniques. The plastic/metal liner and composite

layers must be carefully handled to avoid compromising the integrity of the vessel.

- Pressure Sensitivity: These vessels are designed to withstand high pressures, making repairs more critical. Any flaw in the repair can lead to catastrophic failure under pressure.
- Manufacturing issues: Ensuring proper adhesion between the repair materials and the existing composite structure is challenging. Repairs will require specialized techniques and materials to ensure the vessel can safely withstand the high pressures.
- Inspection and Testing: Thorough inspection and testing will be required post-repair to ensure the vessel can safely handle the intended pressure. This involves advanced non-destructive testing methods and reliable health monitoring systems integration.

One notable development is the enhancement of leak detection systems with the utilisation of advanced sensors. It is expected that soon, research efforts will be shifted toward the optimization of sensor-substrate bonding and further enhancement in flexibility/stretchability to ensure more durability and expand the circle of applications on different composite structures. These advanced sensing technologies will be integrated into the realization of intelligent composite processing and enhance Type IV COPV safety and performance monitoring design for end-of-life considerations, Frias et al. (2010).

Regulatory Compliance

Repairs must comply with stringent industry standards and regulations to ensure the vessel remains safe for use (information can be found in e.g. Bremer & Berg (2012) and other directives). These factors make repairing Type III and IV pressure vessels a highly specialized task requiring expertise and precision. In many cases, it might be more practical to replace a damaged pressure vessel rather than attempting a repair. To the authors knowledge, there are not documented repair techniques for hydrogen pressure vessels of type III and IV with the purpose of prolonging their use in case of damage. For example, the study of Weiszflog & Abbas (2022) aimed in extending the knowledge base regarding the life cycle environmental impacts of different hydrogen storage system alternatives for fuel cell electric vehicles in collaboration with Volvo Group. In the study,

however, maintenance and repair activities were entirely excluded from the use phase for all hydrogen storage systems. In discussion with Volvo experts, it was determined that a hydrogen storage system and its components are designed not to require any maintenance or repair during their lifetime. As per manufacturer specifications, the hydrogen storage system would undergo routine visual inspections. However, the impacts from these inspections were deemed negligible. Additionally, all the potential repair activities resulting from abnormal operating events, such as accidents, were excluded. However, although repair is not on the forth in high pressure hydrogen storage technology, it should not be neglected. For example, it is worth exploring the possibility of repairing non-structural damage in the composite part (delamination, fibre-matrix debonding, matrix cracking) via the classical methods such as resin injection for thermosets and thermal reforming in thermoplastics considering various damage extends and locations in the pressure vessel. One can argue that this technique is cost effective and even if the vessel cannot return to its original operation capabilities, repurpose in less demanding applications can become a possibility. Full recovery from repairing a structural damage in a hydrogen pressure vessel seems quite an outreach however, repair of the individual components should be explored, again for repurposing reasons.

5.2.4 Reuse of components

Reuse is defined as "repeated use of a product or component for its intended purpose without significant modification", Ref. Ellen Macarthur Foundation (2021). In this context, reuse action means that the used pressure vessel, or components of it, are reused and reinstalled in another vehicle. Storage vessels of Type III and IV typically have an overwrap of carbon fibre composite which is an energy-intense material. Incineration and landfilling as an End-of-Life (EoL) treatment method, creates huge resource waste and pollution. Circular Economy (CE) is an approach to optimize resources and minimize material waste, such as repair, reuse, recycle and eco-design. For metal pressure vessels, the existing CE actions are recycling and reuse, and recycling is dominating while only very few get reused. For the Type IV pressure vessels, the existing CE actions are mainly from the side of Eco-design and specifically the reduction of the complexity of the material, ease of disassembly as well as integration of recycled carbon fibre and recyclable resins.

There are opportunities to make the pressure vessels in mobility applications more circular because of their long lifetime, valuable materials, and merging recycling technology innovations. The average lifetime of the pressure vessel is from 10 to 20 years (Mohd Shahneel Saharudin et al. (2025), Liu (2024), CompositesWorld (2024)) which means it could potentially outlive the lifespan of the vehicle and be reused into another vehicle. Therefore, pressure vessels have a potential to be reused. Additionally, the high residual value of the composite material such as carbon fibre also provides financial motivations for reusing. However, for the reusing action, several barriers exist, Ref. Liu (2024), that could be identified as:

- Strict inspection requirements, meaning that only a limited volume of used pressure vessels is reusable.
- Inadequate EoL volume of pressure vessels. In Sweden, the domestic supply of used gas vehicles and pressure vessels is still limited so it is difficult for customers to find matching pressure vessels. Additionally, the pressure vessel producers are not willing to disclose the production data as well as estimations of the lifespan.
- For metal components the cost of the virgin metal material is affordable while the transaction cost of the used pressure vessels adds extra costs.
- Safety concern of the used pressure vessels decreases the acceptance of reusing actions.
- Vehicle dismantlers lack the market demand information.
- Downcycling of the carbon fibre as an action where the carbon fibre is taken from the used pressure vessel and then being utilised in manufacturing of new pressure vessels is a technology challenge. Also, using this "recycled" carbon fibre may risk the original design and production of pressure vessels.

Opportunities include upcoming regulations such as the End-of-Life Vehicle (ELV) Directive (2023/0284 (COD) (2023)), which promotes circularity by banning landfills, requiring a minimum level of recyclable and recycled materials, covering more vehicles, and applying the Extended Producer Responsibility (EPR). The ELV Directive states that for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year. Within the same time limit, the reuse and recycling shall be increased to a minimum of 85 % by an average weight per vehicle and year (Article 7) (Directive 2000/53/EC (2000). Considering that pressure vessels are one of the crucial components of gas vehicles by mass, pressure vessels which are

designed reusable, recyclable, or recoverable are likely to be favoured by the vehicle manufacturers to fulfil the requirements. Considering that FRP pressure vessels are not currently easily and massively recycled and recovered (De Fazio et al. (2023), Qureshi (2022)), it is expected that vehicle manufacturers will reconsider their choices on pressure vessels and put pressure on the vessel producers to design more recyclable pressure vessels and consider incorporating recycled materials as well.

The EPR regulates that the vehicle producers are responsible for covering the financial and/or physical responsibility in collecting and disposing of the EoL vehicles, Naturvårdsverket (2025), and that vehicle manufacturers need to exchange information with their downstream actors, which could facilitate more circular economy actions. They also must ensure that the car scrappers and equivalent actors in the Member States of the European Union have access to the disassembly instructions. Additionally, by European law (2003/138/EC), a coding standard is required to be used for the components to facilitate identification. All the required information is identified as helpful and needed for promoting circularity.

Reuse actions, primarily applied to metal pressure vessels, can be discovered even though they are not common. The critical actors who are directly involved in the reuse actions of pressure vessels in the mobility application include pressure vessel producers, workshops and dismantlers. Even though certain actors like public authorities, vehicle producers, and spare part trading websites are not directly involved in CE actions, they are the main source of the information. Inspection is the unavoidable prerequisite to deciding the reusability of the used pressure vessels, and the inspection guidelines provided by public authority are the most critical tool and the only information needed for dismantlers to decide the reusability. Although the expected lifespan of the pressure vessel and the requirement of disclosing the manufacturing date of the pressure vessel creates a potential market for reuse the strict inspection requirements also limit the volume and availability of reusable pressure vessels. Additionally, social and corporative norms influence the reuse action. The biggest social norm regarding the used pressure vessels is safety concerns. Both the supply and demand side are concerned with the safety risks. Therefore, there is a tendency to choose a new pressure vessel instead of the used spare part. Regarding metal pressure vessels, the most common CE strategy is recycling while reusing is very limited. The currently low volume of the End-of-Life FCEVs makes both the demand and supply side very limited. Because of this, most of the dismantling facilities have not recognized the market demand for the used pressure vessels and prefer

hand them over for recycling or disposal. This decision is also important considering the extra work, cost, and safety risks involved in the reuse action. Regarding the Type III and IV pressure vessels, the most common circular action is from the eco-design point of view and specifically reducing the complexity of materials, designing the product in an easy dissemble way, and purchasing recycled and recyclable materials. Therefore, the circular actions such as recycling or the potential for reusing are limited, and more efforts are given on design, material selection and manufacturing.

5.3 Considerations for second life

There is seemingly an easy task to reuse a tank initially made for 70 MPa (700 bar) in a mobile application in a stationary application at typically 20 MPa (200 bar). However, when making a more detailed investigation of the regulatory requirements there are several difficulties that are blocking such initiative. The main difficulty is that each application for these pressure vessels typically have initial requirements for its respective type-approval that is not transferable to the other desired applications.

One strategy would be to simply use the toughest demands from each test and thereby qualify the tank for more than one approval. However, when comparing the demands, they have different approaches of testing and multiple requirements for the same test of e.g. temperatures, time and ambient conditions.

The new strategy would be to simply repeat the tests on the same individual tank. Unfortunately, the standards require the tanks, as a last step to gather information, either to be pressurized until burst or simply to be punctured for safety reasons.

The conclusion is then; the qualification process would need to be made for each approval. No real opportunities for coordination gains have been found in this study. It might therefore not be economically feasible having such approach. It is a costly exercise that would likely not gain a commercial value from a customer perspective. This, based by the increase of the initial investment combined with the fact that the actual benefit would be too far ahead, 15-25 years, or more in the future. So, the gain, apart from the environmental, would possibly be made in the future by the customer that could reuse the tanks. This makes it into a long-term business case outside of the scope of this study, but still relevant to further economic investigation.

5.3.1 Comparison of hydrogen and CNG for re-purposing

For vehicle mounted tanks, there are two standards of pressure levels, 35 and 70 MPa. These tanks are typically qualified by the GTR 13 or the UNECE R134 regulations. Each regulation is applicable for both pressure levels and shares the fundamentally same qualifications in terms of the test methods. As the qualification is made within the same standard, this gives an obvious opportunity for re-purposing with a minimum of adjustments in the requirements. There is also support for an extended technical life as the loads and stresses on the tank would dramatically decrease by the 50% drop in working pressure. With an argumentation based on the fatigue life in 5.2.1 the expected life increase would be of several magnitudes, possibly to more than 100 times the theoretical regulatory service life based on type testing. Such life increase, only based on the fatigue life, should be considered strictly theoretical, but it implies that there is a potential to evaluate in parallel with other life-limiting factors. Other considerations such as leakage rates would also be able to be determined. As hydrogen is a smaller molecule compared to the CNG molecules, this will reduce the leak rate if re-used as a CNG tank. Therefore, a second life extension of a hydrogen vehicle tank should be possible with minimum efforts for reuse in a CNG-vehicle application.

5.3.2 Utilization of type approvals in between different tank applications

As mentioned in the introduction to section 5.3, there is typically no homologation between standards for pressure vessels dedicated to different applications. Although certain safety factors are the same and several tests share similarities, the results are typically not transferable. During this project, we have found one exception that might indicate that such work is made within the regulations and standard committees. In the latest revision of the ISO standard 17533:2025 "Gaseous hydrogen — Cylinders and tubes for stationary storage" there is a possibility for utilization of test results from standards from other applications. The approach is to use existing and approved design standards for transportable cylinders or tubes and to determine how to adapt them for use in stationary storage service. In Appendix A, "Pressure cycling calculation using design standards for transportable applications" results can be reused from the qualification of a few other specific standards. These standards for transportable tanks are typically based

on the TPED-requirements that are somewhat different to the PED-requirements in terms of pressure designations. Therefore ISO 17533:2025 states a method for re-calculating differences in the maximum allowable working pressure, MAWP and test pressure, TP. The standard also suggests a method for recalculating full-pressure cycles to shallow pressure cycles (i.e. 80-100% NWP). This as the usage of a stationary tank more likely will consist of a smaller number of full-fill cycles compared to the transportable tank usage. This method is based on the overall number of cycles for the approval in the TPED-standards and states a method for translating to shallow cycles. However, it is also explicitly mentioned that the method only applies for type, 1, 2 and 3 tanks. For type 4 tanks (composite) it is mentioned that: "The design life of composite cylinders is often limited by the reference standard. The shortest of the pressure cycle life and design life shall apply". So, for lifetime assessment of the tanks, ISO 17533 gives only limited support outside of the main standard for life assessment. Alternatively, the manufacturer can verify the performance by testing the expected number and type of pressure cycles. However, this method of transferring in between approvals between PED and TPED only applies for solely new tanks. The concept is therefore not directly applicable for second life usage.

5.3.3 Vehicle tanks used for stationary applications

During this project efforts have been made to find an actual example of where vehicle tanks have been reused in stationary applications. No such examples have been found, neither during interviews nor elsewhere (even though the expectation was that it should be technically feasible). One contributing factor may be that the regulatory lifetime of originally 15 years for the tanks is keeping tanks unavailable. One can also argue that there were not a lot of vehicles for the first years, thus also limiting the available number of tanks. As the number of tanks are expected to increase coming years there might be a financial opportunity promoting such initiatives.

5.4 International benchmarking

5.4.1 Method

The international benchmarking was based on interviews and digital meetings with actors working with solutions potentially relevant to this pre-study. All project partners were asked to propose informants. In addition, a review of literature and on-going projects with public co-funding was made to identify further informants. One factor making the international benchmarking a bit challenging was that several informants were not willing to disclose details about their solutions without having an NDA signed. As such an agreement would have made the sharing of information impossible, this approach was not used.

5.4.2 Results

Quantum Fuel Systems based in California, United States, made a presentation of their commercially available solution to check the structural health of their Type IV tanks. Basically, they fit several acoustic sensors on each tank and register the acoustic events when filling the tank to 150% of the nominal working pressure. If the event profile has changed since previous measurement, it could indicate a structural problem with the load bearing carbon fibre layers. This procedure is carried out during inspections every 5 years, which are required by the US Department of Transport.

Thanks to their Model Acoustic Emission testing, the factor of safety has been reduced from 2.25 to 2.00, which means that less carbon fibre is used, which in turn means lower cost and environmental impact. A five year longer calendar period of use is also accepted by the regulators in the United States.

Forvia, is a large tier one supplier to the automotive industry (a merge of Faurecia and Hella, which previously was owned by Stellantis). The company has a whole portfolio of hydrogen solutions including fuel cells and tank systems for compressed and liquid hydrogen. Approximately 300 of their engineers work with hydrogen solutions. Tanks are made in France, China and South Korea. The carbon fibres come from two different suppliers.

According to Forvia, the tanks last longer than the trucks. Possible reuse of tanks after a crash is being investigated. Second life in a different application is problematic as the homologation requirements differ and a rehomologation is expensive. Multiple homologations are seldom made.

OP Mobility, previously named Plastic Omnium, is headquartered in France and has a global footprint for hydrogen tank production. Two meetings were carried out with OP Mobility, one focusing on recycling and one on structural health monitoring. The R134 regulation is the rule but there are special requirements in China and South Korea. OP Mobility makes two sizes of Type IV tanks; 175 L and 415 L. Carbon fibres represent approximately 81% of all GHG emissions during manufacturing. Different streams of material are considered for recycling, residuals via scrap from production and quality control tests, to end of life tanks. Several methods to recycle carbon fibre have been tested, among the mechanical, thermal (pyrolysis), thermochemical (vapothermolysis) and chemical (solvolysis). Chemical recycling allows for the extraction of long carbon fibres, and it appears also to be the preferred approach in OP Mobility's research portfolio. Second life in the same type of application is obviously possible but for the same reasons as stated by Forvia (see above), a second life in another type of application is difficult. There are also questions relating to who is responsible for ensuring the quality of the tank in the second application. With better health monitoring and tracing systems, a second life is facilitated.

An overarching OP Mobility ambition when it comes to health monitoring is to develop a Digital Product Passport for each tank. It would include production and use data. Three detection levels are outlined, deep scratch, shock and laminate failures. All three levels require some sort of electronic device to analyse and register signals. In the handling process before the tank is connected to such a device (during delivery to the customer), a G-meter is used. OP Mobility's main solution when it comes to scratch detection is a net of conductive wire fitted inside the tank's protective layer. For shock detection, several concepts are being investigated, including piezoelectric sensors. The sensors will be permanently mounted on the tank, and they could indicate the location of the shock as well as the severity. Laminate monitoring is the most challenging task with the lowest TRL for OP Mobility. Sensors on the surface as well as embedded inside the composite are being tested. Depending on the solution, the laminate monitoring might also be able to indicate scratches and shocks.

Fast refuelling according to the standard being developed for heavy vehicles will, according to OP Mobility, not imply any problems due to the quicker changes in tank pressure. However, temperature gradients might cause some challenges, and the health monitoring systems outlined above would allow for a measurement of them.

Fraunhofer LBF had a key role in the publicly funded German project HyMon, which was carried out with partners from industry, research institutes and academia for 38 months ending October 2024. Total budget was 2.06 M€, whereof the public funding was 1.46M€. The project was motivated by the difficulties to visually inspect the tanks as damages are not always visible on the surface and the judgement is subjective. Specific weaker tanks were used for the tests to allow for accelerated aging. For cost reasons, tanks for passenger cars were used. Similar to the approach used by Quantum Fuel Systems, it was noted that different damage modes in the composite can be captured and analysed using acoustic emission. The sound profile including the distribution over the frequencies can be used to analyse the type of damage and its location. Over the lifecycle of the tank, many acoustic emissions are generated in the first couple of cycles, followed by a long period with limited emissions. When approximately 20% of the lifetime remain, the acoustic emissions increase gradually again. The project also investigated the use of optical fibres to detect failures. However, this approach did not deliver as the optical fibres relatively quickly changed their characteristics. One innovative part of the project was the development and verification of a new, much more economical sensor to capture the acoustic emissions. It was compared to existing expensive sensors on the market and its performance was satisfactory. It was demonstrated that sensors could be fitted on the surface of the tank and remain there throughout the lifetime. Although the project delivered several promising results, a definition of what constitutes the end of life based on the measured acoustic emissions could not be established.

5.5 Future research

Throughout the project, some key issues for life extension have been identified that will need more efforts.

The traceability is critical for making future considerations. If a tank would be considered for second usage 30 years from now. It is necessary to be able to find relevant

information and likely historical documentation for the individual tank. Today, there are requirements for marking of the tanks but no requirements of recording historical data such as over-pressure events and other life reducing occurrences. Therefore, an obvious interest would be to conduct a study identifying which actual parameters that would be needed for evaluation, for data collection and how to assess the result together with methods for verification of structural health monitoring.

Composite materials are complex and very different from steels. When used for pressure vessels, the number of layers and wall-thicknesses increase, and this is increasing the complexity of the detection methods. There is a potential for development and tuning of upcoming technologies. There are efforts that needs to be made in terms of long-term stability, robustness and price efficiency. A lot of work will be needed within this field. Also, there is a need for more specific end of life criteria based on the results from NDT measurements.

When accelerating pressure cycle life tests, water is typically used as the test medium. The drawback is that this method does not allow for accurate assessment of the corresponding hydrogen leakage rate. Instead, leakage testing is addressed separately in the existing standards. In the future, if lifespans increase, there may be a demand for more precise methods of leak quantification. Since hydrogen is expected to become one of the dominant energy carriers, and contributes to the greenhouse effect, this issue will likely grow in importance as the amounts of stored hydrogen increases significantly compared to today. These test methods may be investigated and further adopted to longer lifespans.

As one of the main arguments for 70 MPa systems today are the possibility of fast fuelling. During fast fuelling, the hydrogen is pre-cooled to achieve fast fill rates and compensate for heating within the vehicles system. At such fuelling the material in the tank will be subjected to thermo-mechanical induced stresses. It would be interesting to further investigate the impact of these degrading mechanisms on the load bearing capacity of the structure in terms of cycle life extension. A tank that only has been fast filled might have a shorter lifespan.

5.5.1 Future unforeseen potentials

From a sustainability and safety perspective, the optimized method would be to automatically and continuously lower the contained pressure in a tank to a pre-determined safe level that steadily decreases based on a "decreasing strength"-model approach. In theory, such a model could run for, in this context, an "infinite" time, still being safe to use. The end of life would rather be defined as when the contained energy of the fuel in the tank is insufficient to propel the actual vehicle for its purpose. Although this is a simplified conceptual exercise, there is a fundamental approach that may be applied to some extent with future technologies. This approach would rely on the knowledge of the degrading events and the accuracy of the residual life model. Of course, it is also necessary to keep a margin in the model for the residual strength covering the effects of an unexpected event such as a vehicle crash or similar making it very interesting from the perspective of safety research.

As the energy infrastructure is prone to change fundamentally with the green transition, we might be expecting new approaches of managing the flow of energy throughout the society. Wherever there is a need for storage or load balancing, the alternative of using hydrogen may likely be an option. If so, the financial prerequisites may be changed substantially the upcoming years. And consequently, the demand of storage alternatives may rapidly increase. It is therefore wise to evaluate alternatives and to create an awareness to be prepared for these unforeseen changes. Since legislative processes take considerable time to adapt, proactive efforts should be made now to ensure future flexibility for adaptation.

5.5.2 Intentions from the industry

Given the technical potential addressed in this project, there is a relatively low interest from industry to manufacture tanks certified for multiple applications. The main reason is the need for additional certification tests that will multiply the efforts and cost for approval. It is therefore concluded that there is no financial incentive for such an approach within the foreseeable economic horizon.

There are also some efforts from the industry pushing for lowering the safety margins at type approval, from 225% to 200%. The gains from this decrease would be:

- Less composite material and energy consumed during manufacturing
- Lighter tanks that will contribute to lighter vehicles and thereby less fuel consumption and/or capacity for transporting more goods.
- More hydrogen capacity due to thinner walls (if the outer dimensions are kept).

As this already has been accepted at certain committees and regulations such as the GTR 13.2, it is likely that more standard committees will follow. But, for the near future this has created a gap within the legislations making homologation for second life extension difficult.

In Section 5.3.1, the potential for reusing 70 MPa tanks in 35 MPa applications was discussed. This is currently feasible, as the vehicle industry has for several years pursued higher pressures for light-duty vehicles, while medium- and heavy-duty vehicles have traditionally operated at lower pressure levels. However, in recent years, there has been a growing trend toward adopting 70 MPa systems even for medium- and heavy-duty vehicles. This shift is primarily driven by benefits such as reduced installation volume, faster refuelling times, and lower overall system weight. If 70 MPa becomes the dominant pressure standard, it would likely lead to a decline—or even elimination—of 35 MPa systems in road vehicles. Consequently, the market for 35 MPa tanks in road transport could diminish significantly. That said, some manufacturers such as Hyundai and Toyota continue to develop 35 MPa vehicles, particularly for fleet operations with shorter range requirements, such as buses and garbage trucks. Therefore, while the trend toward higher pressures is evident in some regions and vehicle categories, there is still no universally defined global direction, and both pressure standards may be kept. The benefits and drawbacks are listed in Table 3.

Table 3　　　*Comparison of storage pressure levels for vehicle applications.*

Aspect	35 MPa (350 bar)	70 MPa (700 bar)
Storage density	Lower energy per storage volume	Higher energy per volume
Range per storage volume	Shorter	Longer
System cost	Lower	Higher due to more material and more complex manufacturing
Refuelling system cost	Lower	Higher due to high pressure compressors and maintenance
Weight per system volume	Lower	Higher due to increased wall thicknesses etc
Weight per range	Higher due to lower energy storage density	Lower
Typical applications	Buses, fleet vehicles, boats, drones	Light vehicles (e.g. Toyota Mirai), Heavy vehicles and long-distance trucks.
Energy losses	Lower	Higher due to compression losses to 700 bar
Second life potential	No application found from a legislative perspective	May be used at 35 MPa applications under certain circumstances

During the interviews one conclusion is that the industry is focusing on recycling of the carbon fibre, which is possible but still requires significant research and development to become competitive.

Another conclusion is that hydrogen tank systems for heavy duty applications probably will become "intelligent" within the next few years. A continuous collection of information about how the tank is used and any damages to the tank will allow for better state of health monitoring. This can in turn be used to extend the lifetime of the tank or reduce the safety margins.

5.5.3 Considerations for life extension

To achieve an extension of the normal usage for an existing tank system three different methods have been found:

Pre-decided lifetime based on several assumptions. Commonly used on tanks within the vehicle industry. Lifetime may be defined by calendar life or expressed in pressure cycles, full cycles or shallow cycles.

"Non limited life" used for transportable tanks based on periodical inspections.

Within the project we have found examples where life-extension has been made on vehicle tanks outside of the original scope of the regulations, from 20 years, in steps of 5 years, to a total of 30 years lifetime (Quantum, 2025).

There has also been suggested a fourth method that future life extension could be achieved by real-life monitoring of individual tanks. Perhaps best described by a "digital twin" approach. By doing so, the life can rather be expressed as the decrease in residual strength as a function of the accumulated historical events the tank has been subjected to. This method should preferably be evaluated in combination with periodical inspections.

5.5.4 Considerations for secondary usage

To make secondary usage possible, there are two primary pathways. Either by the intention to use the tank fur multiple uses already in the design and qualification phase, or by a change and homologation of today's legislation. If such initiative would be made, a lot of work is needed, and decisions of what regulation should be compromised in favour of the other. The work needs to be made by experts in different committees. Although there is evidence of such work in the latest revision of ISO 17533:2025, described in section 5.1.1, the effort to join other differentiating applications such as vehicle mounted, and stationary might be an even more complex and time-consuming challenge.
One competing factor that may restrict the potential for second usage is recycling. Although that the overall resource usage would increase by a shorter life, the regulatory less complicated recycling is more appealing from a financial perspective. The disadvantage with current recycling methods is that the valuable carbon fibre is degraded

in the process. This may prohibit the use of recycled fibres for the specific application of high-pressure tanks.

5.5.5 Challenges related to re-certification

Re-certification of used tanks for new applications

As mentioned, studies conducted in this project indicate that the severity levels applied in different qualification procedures are rarely fully transferable. This raises the question: would it be possible to re-certify an existing, previously used tank for a new application if additional testing were conducted to justify its safety?

Intuitively, one might argue that significantly lowering the service pressure would increase safety margins enough to compensate for discrepancies between the original type-approval requirements. However, even if such an approach could be technically supported, it also presents statistical challenges. Used tanks to some extent often have an unknown operational history, which introduces uncertainties. Consequently, risk assessments would need to rely on conservative assumptions to account for these unknowns. In conclusion, the feasibility of secondary use is more likely to be successfully addressed when it is considered from the outset, starting with the original type-approval process.

Re-certification of used tanks for their initial application

There are several efforts made to extend the regulatory life as described in section 5.1. As these methods are accepted by some authorities, they might get international recognition in the future. As there are new technologies emerging for integrity re-qualification, they need to be evaluated and incorporated into future regulations. There is a substantial work to be made to identify and evaluate these technologies and methods and to interpret them into the regulatory perspective of evaluating pressure vessels. The method by themselves might develop into future standards. Some of the methods may also need to be combined to ensure sustained safety. Additionally, there is a potential to reuse tanks from vehicles that have been decommissioned in other vehicles. When doing so, the same type-approval

may apply to the tank itself, but there are also requirements related to the type-approval of the entire vehicle system that must be met.

6. Dissemination and end seminar

This pre-study contributes to the following overall FFI goals:
- Better knowledge about hydrogen systems as a part of making society's road transport fossil-free, safe, equal, and efficient.
- Through partnership, and collaboration, contribute to developing competence and innovation within the hydrogen system.

This pre-study contributes to the following goals of the sub-program Circularity:
- Advancing the development of innovative solutions to address the challenges associated with the circularity of H2 tanks, by expanding our understanding and knowledge base.
- Facilitating the design of H2 tank circularity by gathering and analyzing international experience and best practice, offering global insights.
- Promoting the establishment of a collaborative partnership among stakeholders across the value chain, aimed at enhancing the lifecycle management of hydrogen tanks through collective expertise and shared objectives.

This study has been conducted in collaboration with actors from the Swedish industry and academia. Project meetings were held regularly where the ongoing status and findings was communicated and discussed within the group. There have been insights and better understanding for the topic itself and an introduction to the perspective from several actors relevant in the bigger overall perspective. Relevant authorities were unfortunately not able to attend the end seminar, and therefore not represented in the final discussions. As this report serves as a pre-study, there is a hope that it will raise the interest in the topic above the critical level at which participation and discussions are prioritized to promote and motivate expanded studies.

On May 13th 2025 the end seminar was held at RISE in Borås. The invitation was public and participants from the project, representatives from authorities, academia and the industry were invited. During this event, that was held physically and digitally, participants from the project presented their contributions and guest lecturers from OP Mobility and Fraunhofer presented some of their efforts in the field. The seminar ended with an open discussion with all participants where opportunities and challenges were discussed and how to formulate and collaborate in future research. There was also an

exhibition where a Toyota Mirai was available for test driving together with a Volvo truck presented to the audience by Volvo engineers.

Figure 7   Exhibition during end seminar in Borås. Toyota Mirai and Volvo truck.

Seminar agenda:

10:00   Gathering
10:30   Project introduction, RISE Andreas Anderson
10:45   Background from the industry, Volvo, Monica Johansson & Toyota, Fredrik
*   Wigelius*
11:15   Intro to composite and damage mechanisms, RISE Erik Marklund
11:30   Existing and potential solutions for hydrogen tank lifetime extension and second
*   life*
*   - International benchmarking, LSP Hans Pohl*
11:45   Intro to Hydrogen Truck and car on Site
12:00   Truck Exhibition and Lunch
13:30   Legislative perspective and rationale, RISE Andreas Anderson
14:00   Invited presenters from hydrogen tank producers and research - Health
*   monitoring and recycling*
*   OP Mobility*
*   Fraunhofer*
15:00   Questions and panel discussions
*   Summary of the day with discussions and future thoughts*
16:00   End

As the this was the final event within the project the result from the discussions at the seminar regarding first life extension and second life has been included into this report.

During the seminar, it was concluded that several of the presented methods for life assessment are at an early stage of their development. Although they may produce relevant and reliable results, there is still a lot of work to be made before it being commercialized, and cost optimized. For some technologies, the reliability for several years of operation also needs to be ensured.

For life extension, efficient pressure cycling is also required. This typically involves pressurization using water for long-duration tests. However, this introduces a challenge: it becomes difficult to determine whether the actual leak rate for hydrogen is affected during the test. Hydrogen leakage behaves very differently from water, making it impossible to accurately evaluate real-world leakage using such tests alone. Performing the test with hydrogen instead would be significantly more time-consuming and costly, highlighting the need for alternative test methods.

Another challenge lies in defining a well-founded end-of-life criterion. While damages can be detected and quantified, there are still difficulties in translating these findings into reliable assessments of the remaining serviceability.

The interviews that were made gave additional knowledge to the project. Unfortunately, some interviews with global actors could not proceed. A few companies required the interviewer to sign an NDA, which was not compatible with the public nature of this report. As a result, these specific interviews could not be fully conducted.

Throughout this study, we have not found any real focus from external parties on the tank valves, TPRD, when it comes to life extension or second life. The focus has rather been on the carbon composite material. As it was suggested in the initial project description, the result was proportionally reduced after making this conclusion. From discussions within the group, the reasoning for life extension or second life extension the argumentation will follow the same reasoning as for the tanks, as they are type approved as a system. This presumes that the release pressure of the over-pressure valves is reconsidered if the tank is to be used in another application. The specific application and possible degradation of the tank then also needs to be considered.

There are also some critical primary aspects for being able to evaluate safety for individual tanks. Two examples:

> It is crucial that a tank can be individually defined by its marking to track historical events and to be able to be make decisions for either first life extension or second-life extension. As an example, it is explicitly mentioned in ISO 17533:2025 that a "pressure vessel without labels or stamps containing mandatory information, or with labels or stamps containing mandatory information that is illegible in any way, should be removed from service". The database for these tanks also needs to be accessible in the future.

> It is desirable to monitor the history of the tanks and record data such as number of filling cycles, over-pressure cycles and similar parameters. For future decisions, such data would be extremely valuable, enabling assessments of the tanks based on their individual history.

During the project, several challenges have been identified. Some of these may not need to be addressed for another 20+ years, but by then, access to this information will be critical. This project has introduced these key parameters and contributed to a better understanding of them. We hope that the parties who have shared the results of this study will gain an advantage in their future efforts related to life extension and second-life applications.

7. Conclusions

The expectation, at the project start, of finding existing second life examples of vehicle mounted tanks being used for less severe applications proved to be wrong. No such real-life examples of second life applications have been found. During the final stage of the project there were findings of standards that address something similar to, but not real second life. One month before the finalization of the report, a revision of an ISO standard gave a possibility to use qualifications for approving a tank for applications other than the intended application. This standard is quite strict, and only specific standards may be used for qualifying transportable tanks for stationary use without being tested by the stationary requirements. The standard is also stating that only new tanks can be used in a different application. No re-purposing is yet known to be allowed. However, this can be interpreted as efforts are actually being made to transfer in between regulations.

It was concluded that there have been recent revisions in governing regulations for first life extension. This work has primarily been made within the GTR 13.2 regulation and other legislations, such as the UNECE R134, have later adopted these changes to be homologised. The change in maximum lifetime has been increased from 15 to 25 years based on collected historical data and additional testing of tanks at their end of life. There are also changes made in the approval pressures by decreasing the levels but, still with sustained safety. This change was adopted into GTR 13.2 but is expected to be approved into UNECE R134 in 2026. This indicates that the legislative authorities are striving towards a homogeneous qualification and that there is an ongoing work with the regulations that may result in changes in the near future.

The methods for re-qualifying tanks for extended regulatory life, some identified in this study, may become increasingly relevant in future revisions of the legislations.

For future traceability there is also a need for data storage. This might be implemented as a digital passport for each individual tank.

It was also concluded that the technical life of the tanks significantly exceeds their regulatory life, as supported by multiple studies. The environmental benefits of extending service life, compared to producing new tanks, are evident. The project concludes that there are no major obstacles to revising and further developing current legislative methods for determining when a tank should be retired from service.

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