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# Liquid Hydrogen storage for (on-road) mobile applications

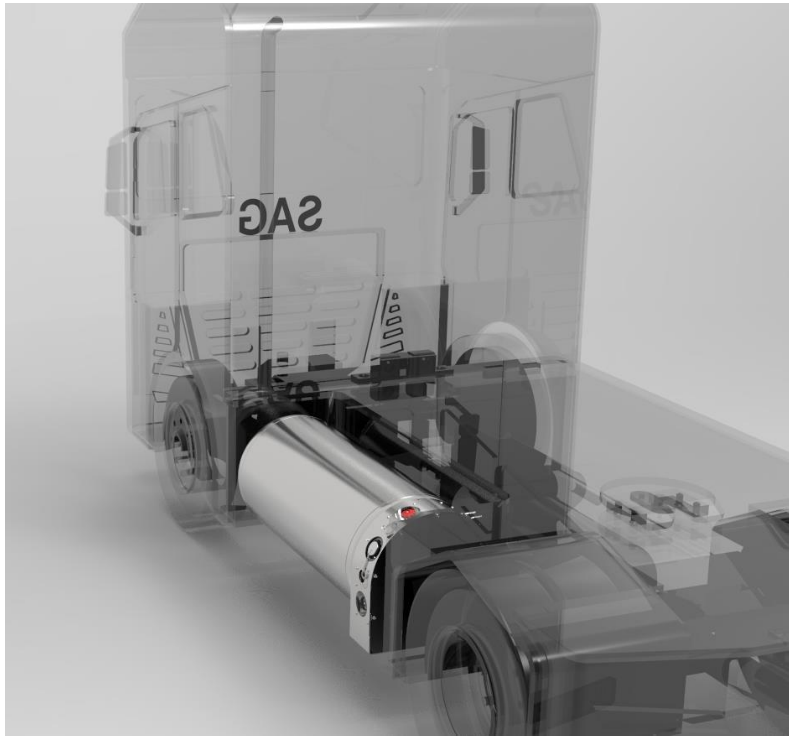
European Cryogenic Days, March 28th 2023

Thomas Stepan – Salzburger Aluminium Group

Contact: thomas.stepan@sag.at

# Agenda

- Short Introduction SAG
- Why liquid hydrogen tanks?
- Zero emission drivetrain technologies
- Initial design goals
- Main components of LH2 storage system
- SAG $LH_2$ tank: technical specifications
- Specific requirements of LH2 storage for mobile applications
  - Volumetric storage density
  - Dormancy time
  - Static and dynamic loads on the road (including crash)
- Current state of development and next steps

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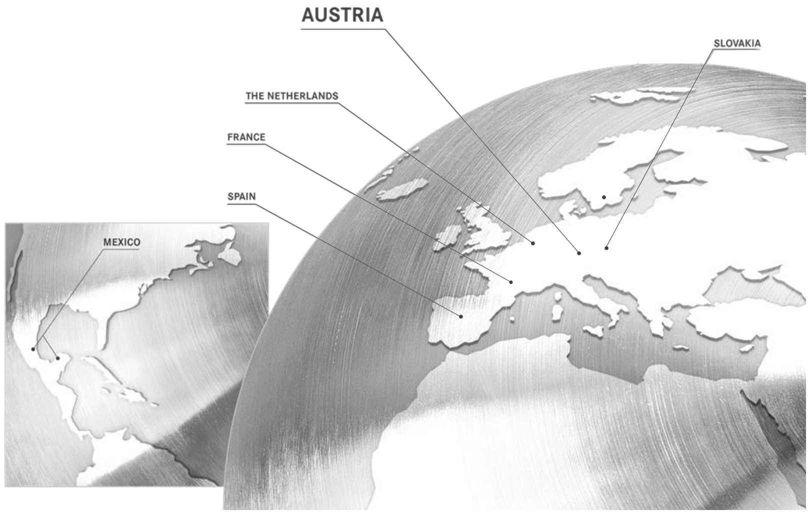
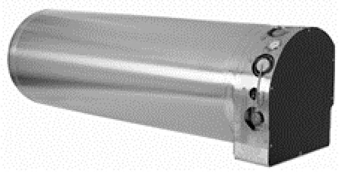
# Salzburger Aluminium Group

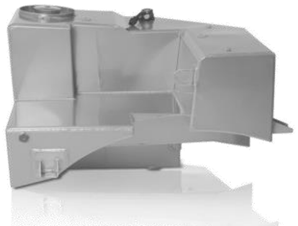



| | |
|---|---|
| **Industry** | Commercial Vehicle \| Automotive \| Railway |
| **Turnover 2021** | 200 Mio€ |
| **Employees** | 1.000 FTEs |
| **Locations** | Austria, France, Netherlands, Slovakia, Spain, Mexico |

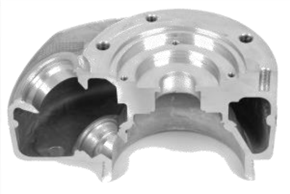

Fuel tanks


Cryo tanks (LNG and H2)


Air pressure tanks


Special tanks


Hydraulic tanks


Rheocasting

# Why liquid hydrogen storage tanks?

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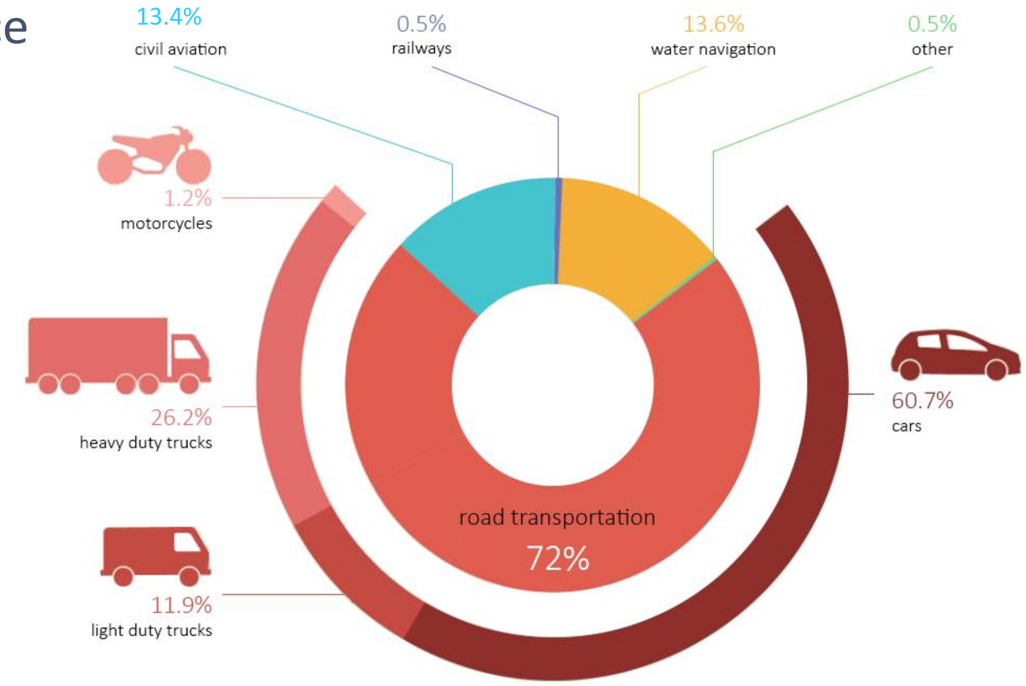
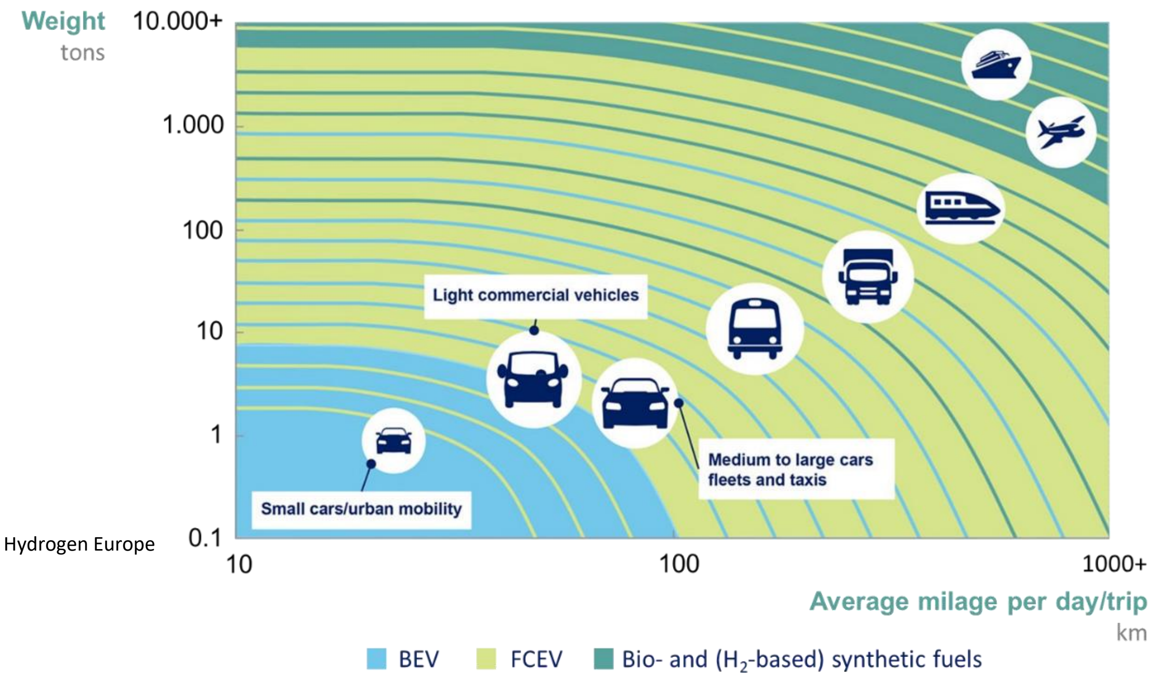
- Transport is the only sector to increase its emissions since 1990 and accounts for 30 % of total EU CO2 emissions where **72 % comes from road traffic and transport**
- **HDT contribute 26 %** to road traffic CO2 emissions
- EU Regulations for new heavy-duty vehicles
  - **15 % reduction compared to 2019 until 2025**
  - **30 % reduction until 2030:** Every second vehicle sold needs to be zero emission
- European Green deal
  - **90 % reduction until 2050**




European Environment Agency

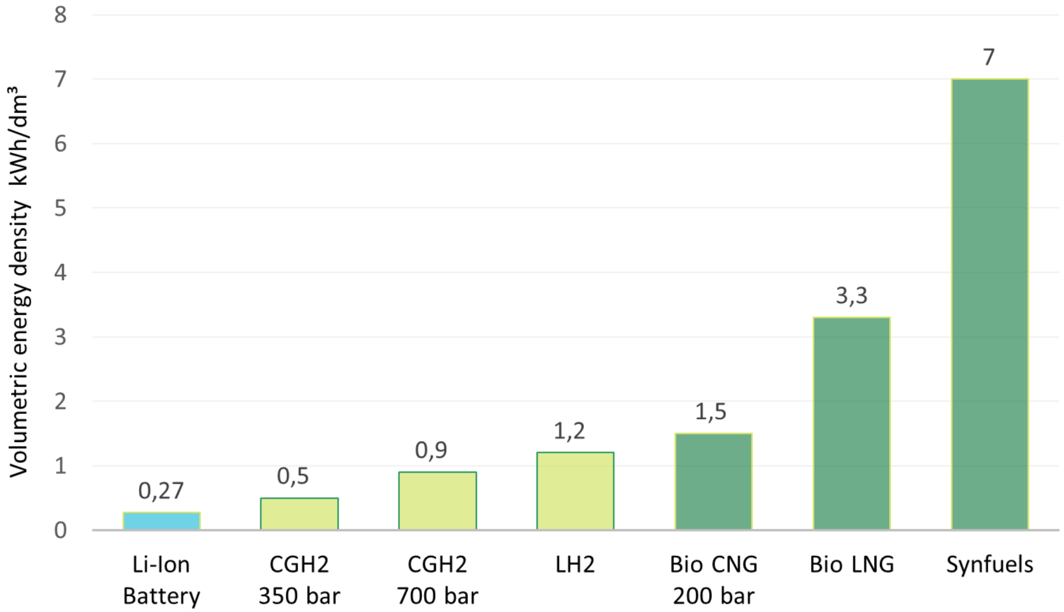
# Zero Emission drivetrain technologies

Future propulsion segmentation of zero emission transport




Hydrogen Europe

Volumetric energy density of zero emission energy storage systems



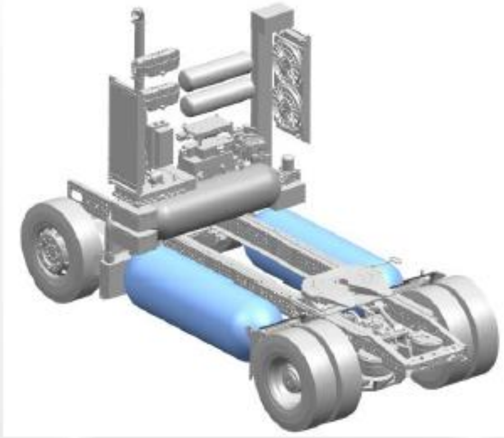
# Requirements for LH2 storage system

## Initial Design goals:

Development of a fully certified tank system for a fuel cell driven commercial vehicle to be used in the heavy-duty transportation segment in the European market

| Item | Specification | Goal/Purpose |
|---|---|---|
| Storage capacity [kg] | To be maximized (see next slides) | ~ 40-45 kg per tank |
| Average Refueling rate [kg/h] | 400 – 500 | Min. refueling time |
| Dormancy time [d] | > 8 (@50 % fill level ) | Min. $H_2$-Boil-Off |
| $H_2$-supply rate [kg/h] | 0.5 – 25 | Determined by FC (ICE) |
| $H_2$-supply rate change [kg/h/s] | 0 – 0.83 | |
| $H_2$-supply temperature [°C] | -40 – 85 | LH2 conditioning for FC (ICE) |
| $H_2$-supply pressure [barg] | 5 - 20 | |
| Ambient conditions | -40 – 50 °C | Unrestricted operation |
| Additional components | • Boil-Off Management | $H_2$-conversion |
| | • Cryo-Connection line | Filling from one side |

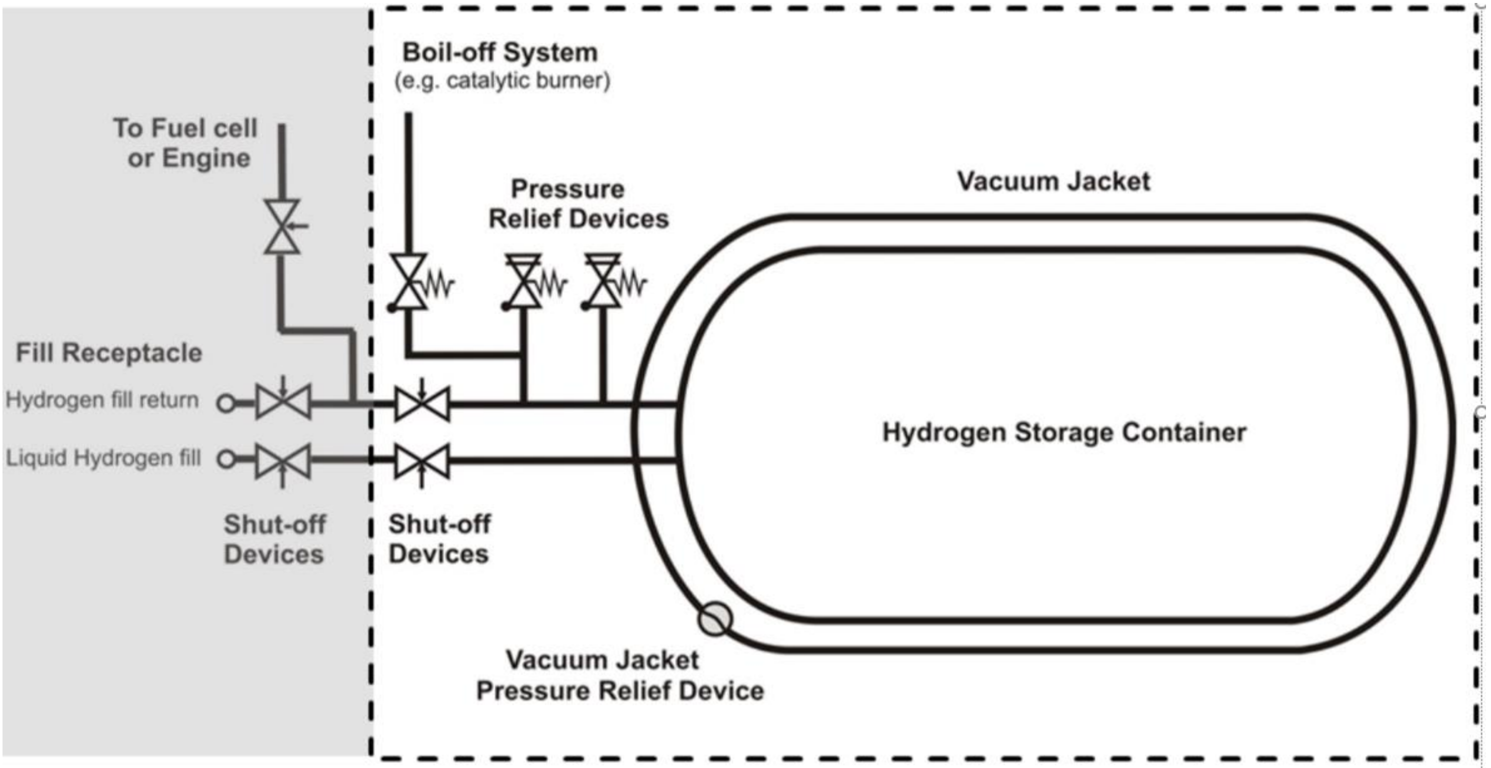
Design space, large variant:



**Dimensions (L&R) in [mm]**
Length: max. 2500
Width: max. 710
Height: max. 710

# Main components of LH2 storage system

## LH2 fuel tank system for on-road transportation according to EU2021/535




From EU2021/535

### Mandatory components

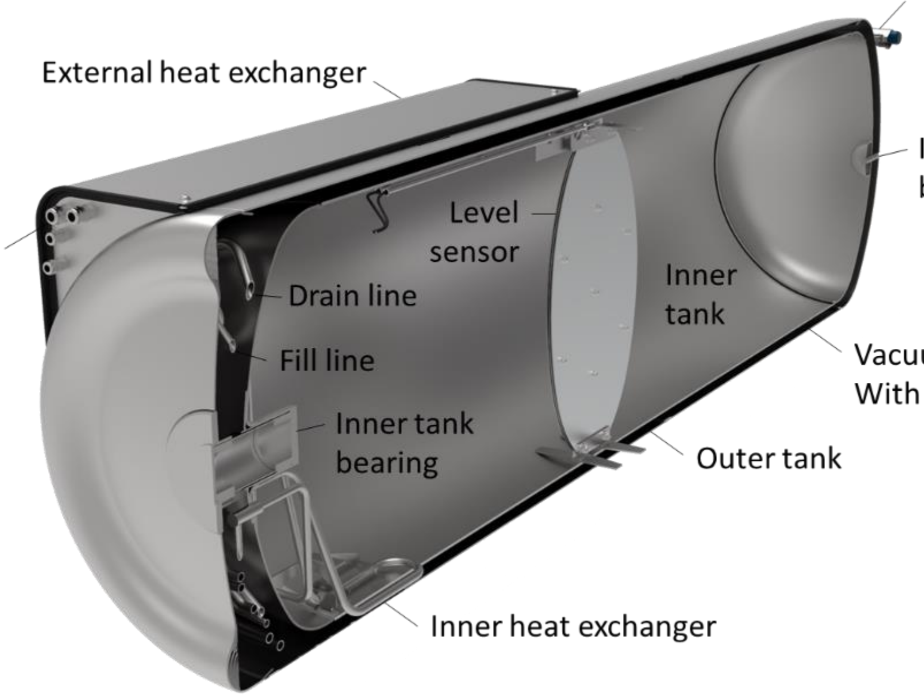
- Storage tank – double walled container
- High Vacuum ($10^{-5}$ – $10^{-6}$ mbar) and multi layer insulation
- Pressure relief device for vacuum jacket (vacuum plug)
- Redundant pressure relief devices (Boil-off and safety)
- Fill receptacle (Interface to fueling station)
- Redundant shut off devices for fill and extraction line
- Boil-off system to minimize hydrogen emissions

### Further main components

- Heat exchanger for LH2 conditioning
- Internal (electric) heat exchanger for evaporation of LH2 (Pressure regulation)
- Fill level sensor
- …

# SAG LH2 Tank

| | |
|---|---|
| Material: | Stainless steel 1.4301, 1.4404 … |
| Outer Diameter | 711 mm |
| Overall Length | 2500 mm |
| Operating Pressure | 5 - 20 barg |
| MAWP | 21 barg |
| Inner tank gross volume | 760 l |
| Weight | 430 kg wo H2 |
| Hold time at 50 % SOC | 4 d |
| Capacity approx. | 42 kg LH2 |



# Storage capacity

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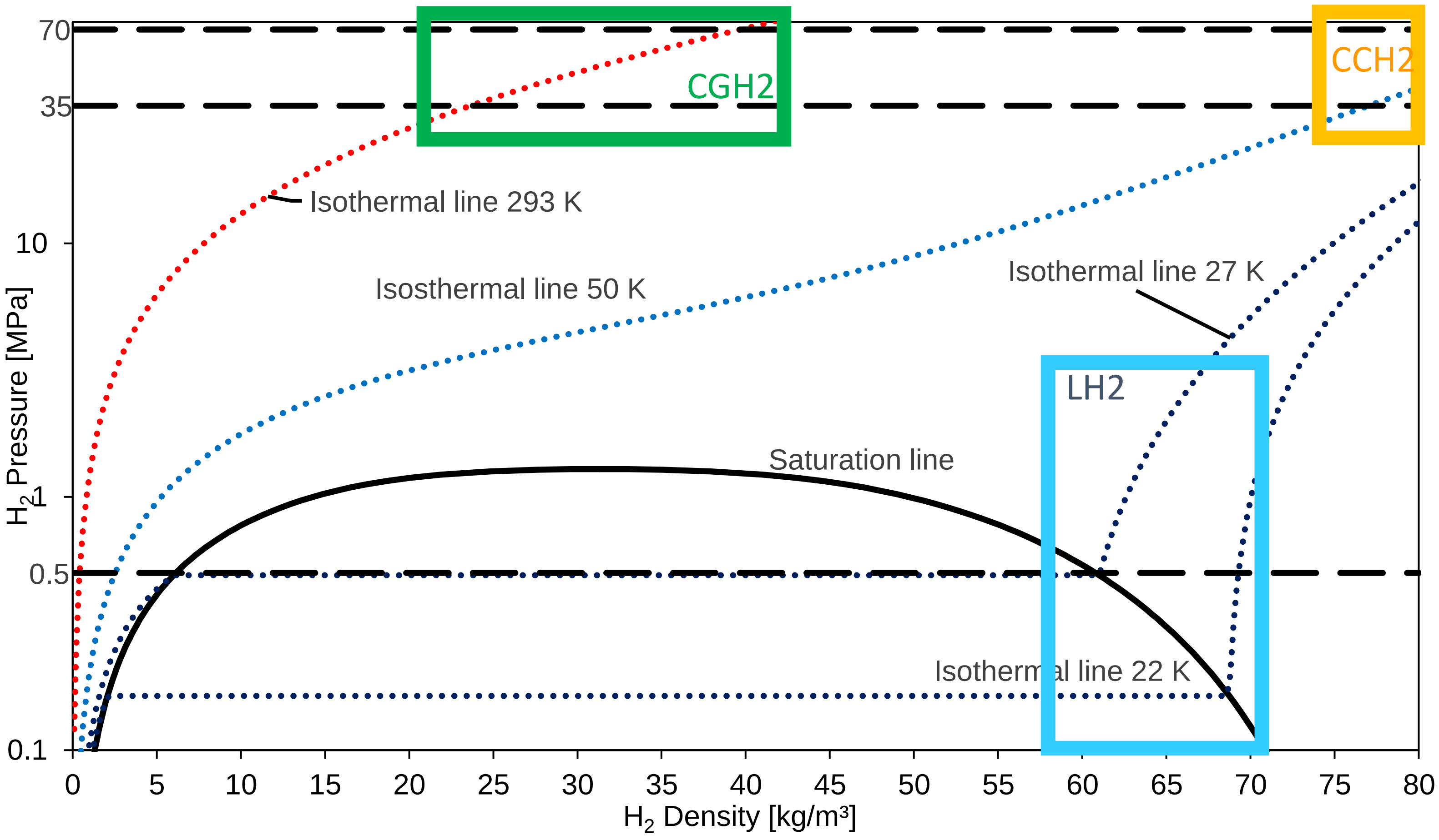
Determined by the combined volumetric storage density of fuel and tank

Fuel:

- Energy density of ~ 2kWh/L feasible for LH2 storage (@ 22-27 K, 60 to 70 kg/m³)
- Energy density of ~ 0.75 and 1.3 kWh/L for compressed gaseous H2 storage (CGH2) at 350 and 700 bar, respectively (cf. 293 K isothermal line, 23 and 40 kg/m³)
- Energy density > 2 kWh/L possible for cryo-compressed hydrogen storage (CCH2) mostly dependent on the achievable temperature in the tank ($H_2$-density > 70 kg/m³)

Storage system:

The current LH2 tank system is able to store approximately 42 kg of usable LH2 mass in an overall volume of 1 m³ -> 1.4 kWh/L (loss of 30%)



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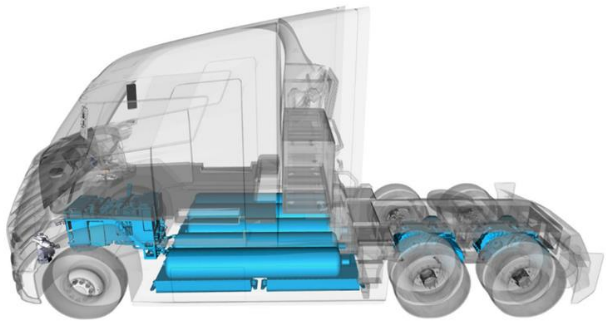
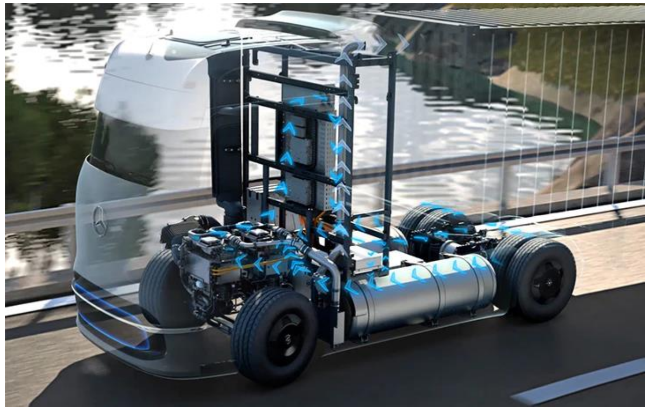
# Hydrogen Storage for FCEV HDT


Hyundai



Nikola



Daimler

| | Hyundai Xcient Fuel Cell | Nikola Two | Mercedes-Benz GenH2 |
|---|---|---|---|
| Hydrogen storage | CGH2 350 bar | CGH 700 bar | LH2 |
| Hydrogen capacity / kg | 32 | 60 | 80 |
| Range / km | 400 | 960 | > 1000 |
| Gross weight / t | 19 | 36 | 40 |
| Chassis | 4x2 rigid truck | 6x4 tractor | 4x2 tractor |

# Dormancy Time

Mobile LH2 storage systems feature no active cooling system

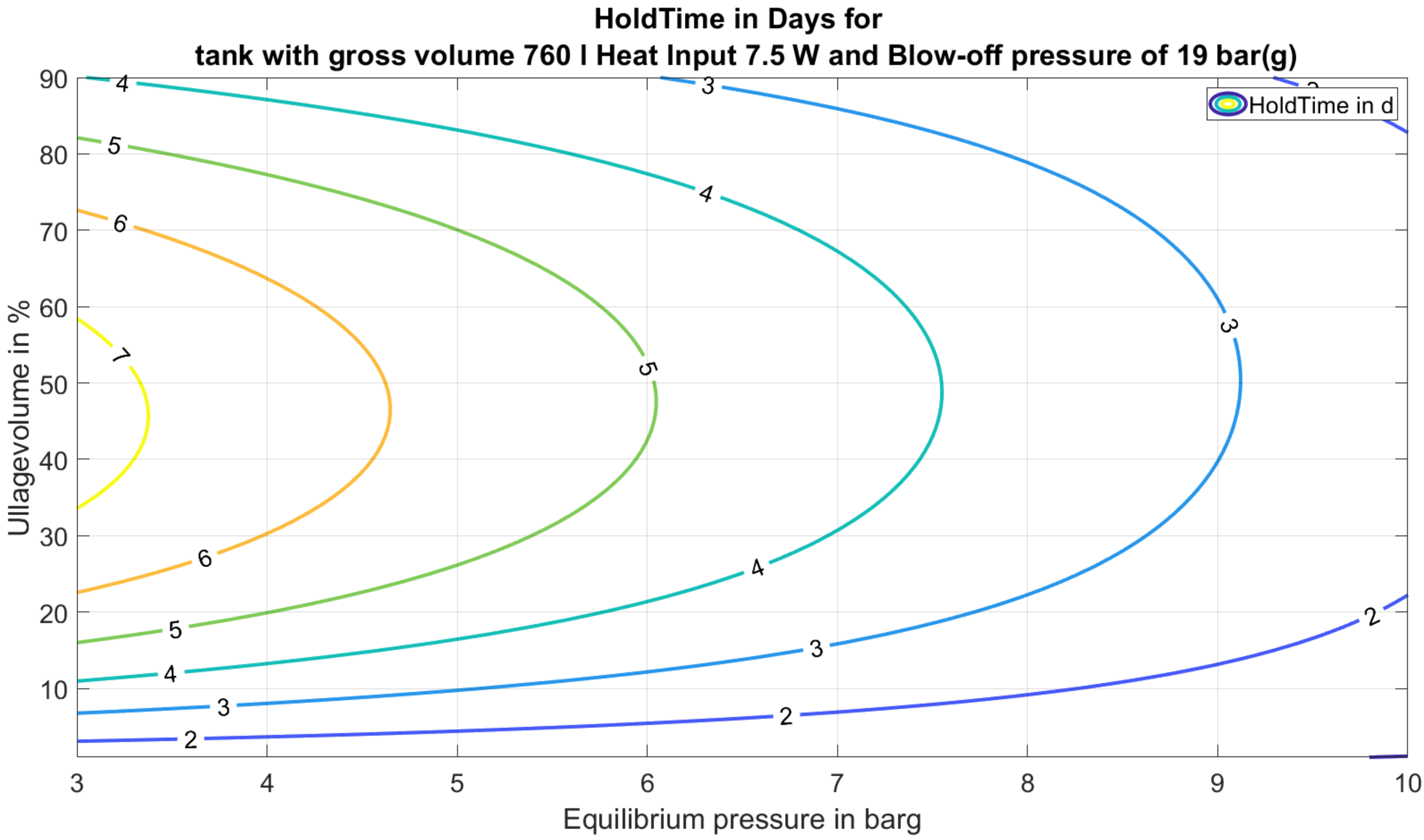
-> Unavoidable heat input into the system which results in pressure increase

Dormancy time is defined as the timespan until the first opening of the boil-off valve occurs (usually during parking)

Minimizing the heat input into the system is the most important constraint for the design of the tank system

Dormancy time further influenced by:

- Storage volume (Surface to volume ratio)
- Fill level (max. at ~ 50 % LH2 level)
- Starting and Boil-Off Pressure (max. pressure difference)



# Mechanical loads on the road

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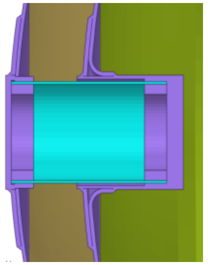
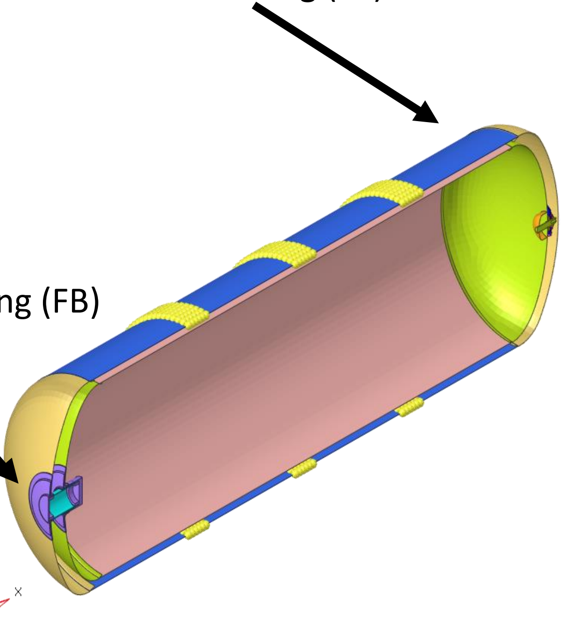
**The design of the bearings connecting inner (cold) and outer tank (warm) must account for:**

- **Compensation of thermal expansion, shrinkage (loose bearing)**

**Shaker test bench**

- **Static load cases:**
  - 8 g in x-direction
  - 8 g in y-direction
  - 10 g in z-direction
- **Dynamic load cases:**
  - Various driving profiles (highway, rough road etc.) evaluated on a multi axis test bench
  - For defined crash scenarios no $H_2$-leakage except through the safety line is allowed, however the bearings don´t have to withstand crash loads (parking damage is critical)
- **Low heat input:**
  - – As low as possible, maximize length and minimize cross section of the bearings
  - – Use material with very low heat conduction, in our case glass fiber composite
- **The design must not feature natural frequencies below 20 or better 30 Hz, because these frequencies are usually excited by the road**





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# Current state of development

First generation of LH2 tanks already in operation on the road (GenH2-Truck)

- Fuel capacity is approximately 42 kg/tank (~ 1.4 kWh/L)
- Fast refueling (> 400 kg/h) is working, however the interface to the refueling station has to be optimized with regards to usability and lifetime requirements (also functionality under cold conditions)
- The heat exchanger is capable to supply 0-25 kg/h of conditioned hydrogen to the fuel cell (driving dynamics can be met)
- Dormancy time must be further increased, currently only ~ 4d

Second generation of LH2 tanks is currently being tested and manufactured (first on-road tests planned for summer 2023)

Refueling process in Wörth (Daimler Truck)


SAG LH2 on the truck on the IAA Transportation 2022

# Next steps and further projects

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Development of third generation LH2-storage system (2023 and following)

- Increase of dormancy time
  - Further improvement of vacuum level, in particular with regards to lifetime (getter material, evacuation process etc.)
  - Decreasing min. operating pressure (minimizing pressure loss along the hydrogen extraction path)
- Redesign of the hydrogen heat exchanger to allow for higher mass flows (scalable design up to 70 kg/h)
- Development of a concept to circumvent the low-pressure supply limitation of LH2, for example with a cryogenic pump (use for HPDI ICE)