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EVS30 Symposium

Techno-economic evaluation of hydrogen refueling stations with trucked-in gaseous or liquid hydrogen

Stuttgart, Germany, October 9 - 11, 2017

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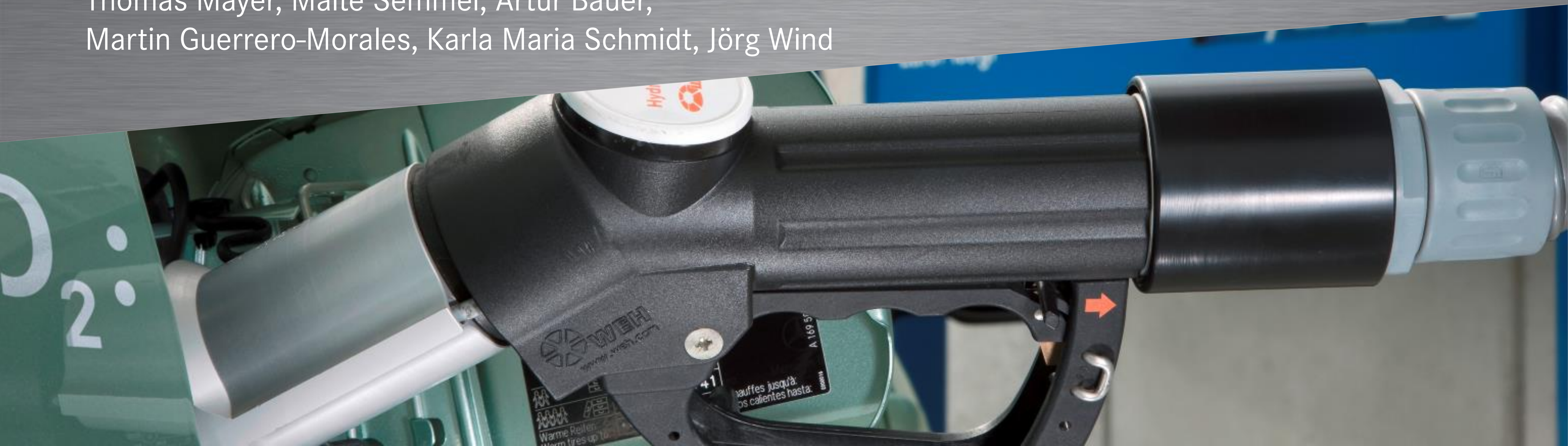


Introduction

Hydrogen pathways and existing Refueling Station models

- Several hydrogen supply concepts like centralized production with pipeline, truck transportation or onsite-production feasible
- Existing research studies investigate either only parts of a refueling station or only a complete compressed gaseous hydrogen (CGH_2) refueling station.

Our research

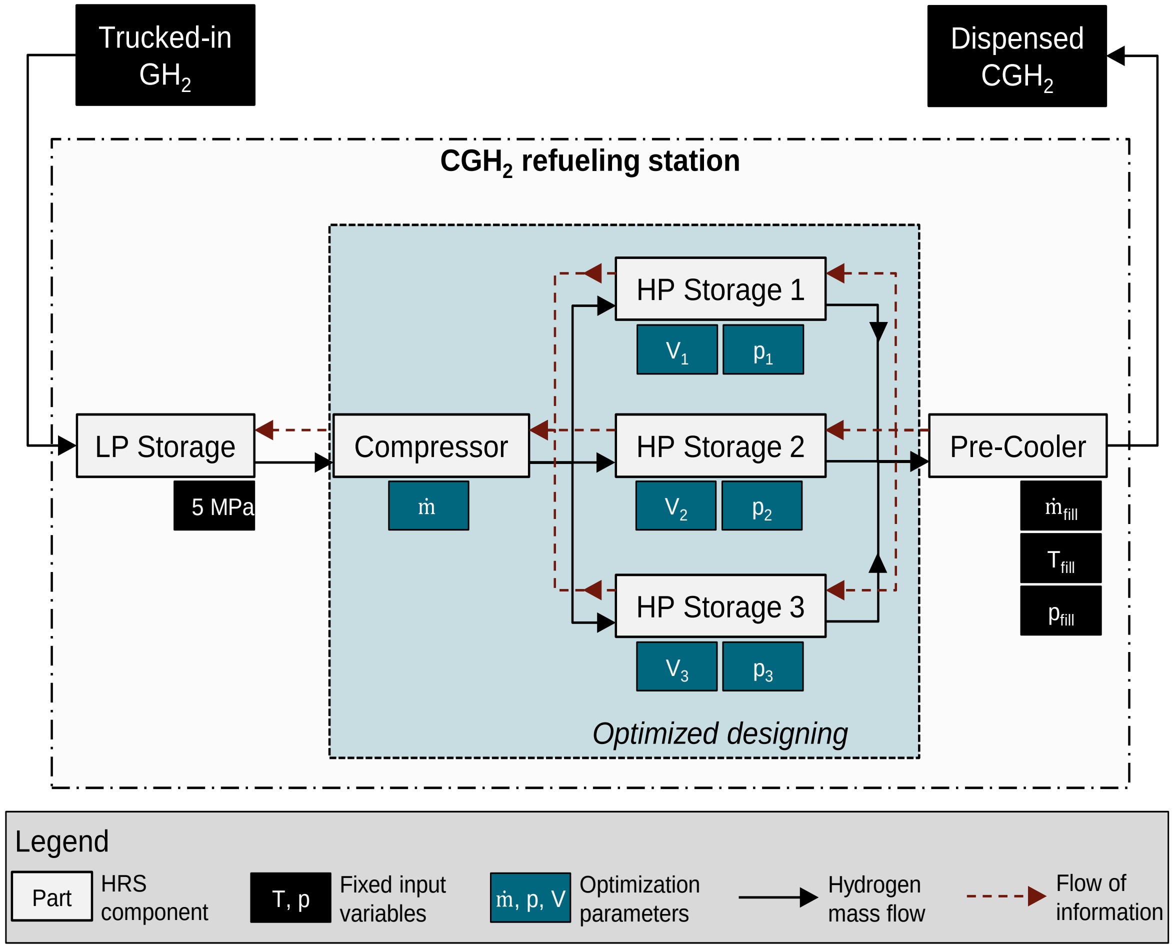
- Both concepts (CGH_2 and LH_2) are analyzed
- Technical (incl. thermophysical) and economical simulation
- Total cost optimized sizing of compressor/pump - high pressure storage system
- Energy consumption and specific costs depending on
  - Ambient temperature
  - Utilization
  - Station size (number of dispensers)

Technical Configuration of a Hydrogen Fueling Station

Status quo of hydrogen filling stations:

- Pressure of hydrogen: 350 bar (Bus) and 700 bar (Passenger cars)
- Pre-cooling down to -33° to -40° Celsius (Passenger cars)
- Standardized refueling process (SAE TIR J2601, ISO/TS 20100) using infrared data interface for communication vehicle <> filling station (SAE J2799)
- Station pressure ramp depending on ambient temperature (SAE TIR J2601) → Influences refueling time
- Refueling time ca. 3 min. (below 10°C), ca. 4 minutes (20°C), ca. 5 min. (at 30°C)
- Standardized hydrogen filling connector (SAE* J2600, ISO/FDIS 17268)

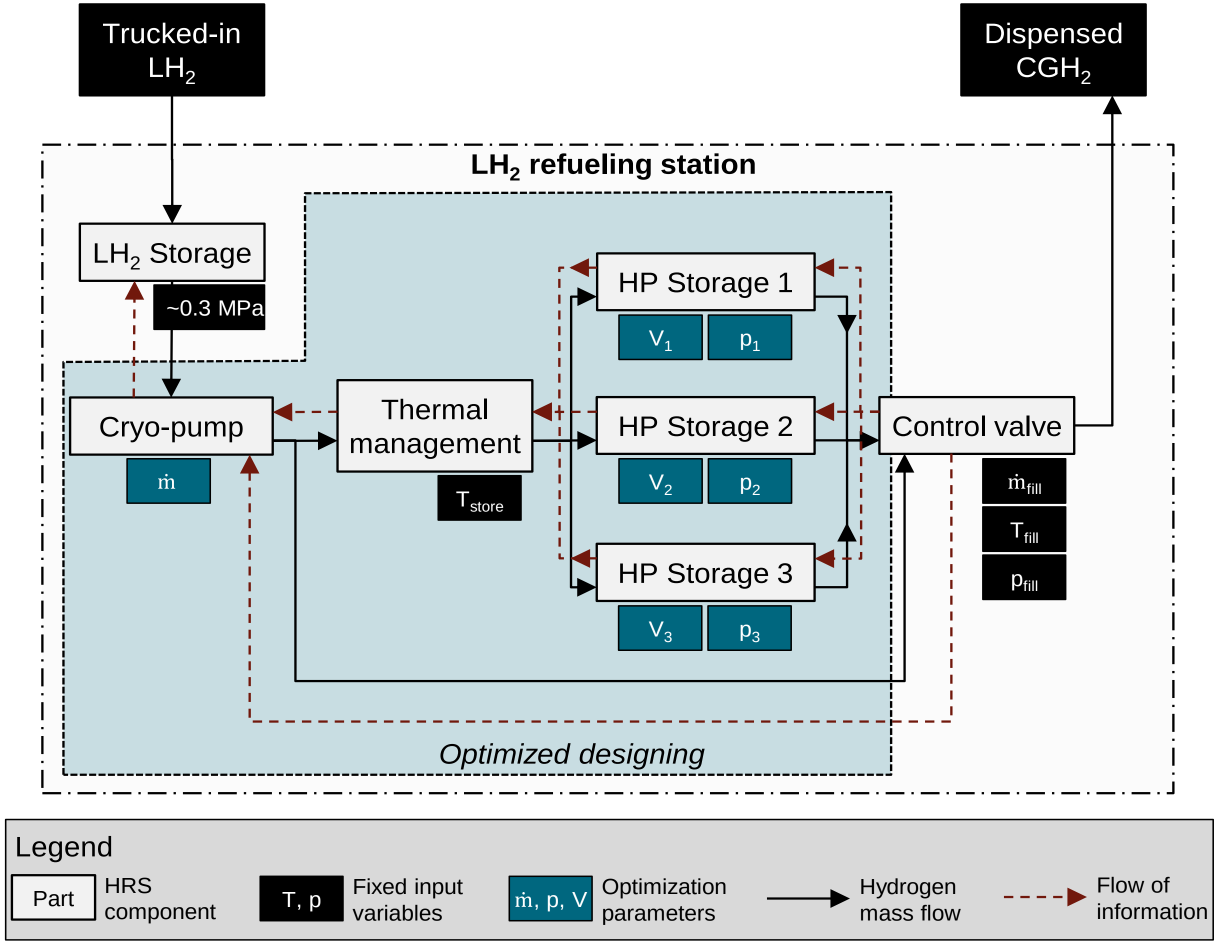
Refueling Station with gaseous trucked-in hydrogen



Schematic of a hydrogen refueling station with trucked-in gaseous hydrogen.

- For compression, a 5-stage compressor (isentropic compression) with cooling after each stage applied.
- High-pressure storage system consists of 3 storage tanks - with different capacities and maximum pressures "cascade storage system"
- Heat exchanger (aluminum block)with a high thermal capacity is hold at -50°C.
- Standby-losses caused by heat input into aluminum block and dispensing line are included in the model.

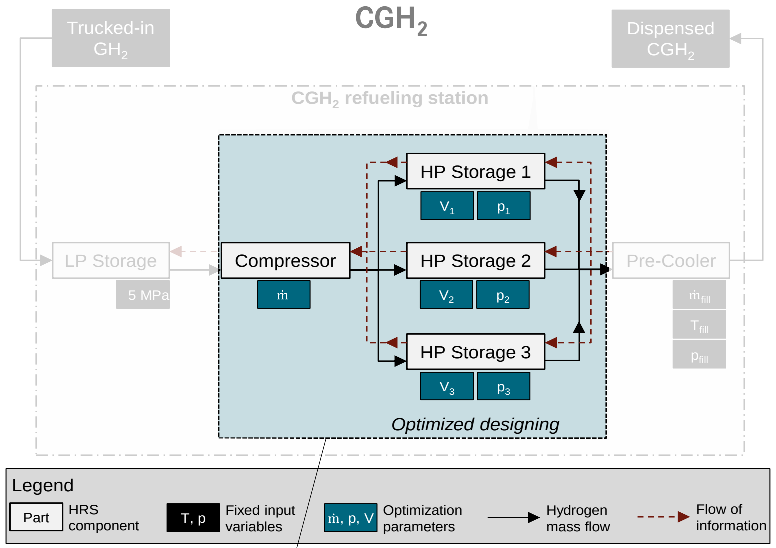
Refueling Station with liquid trucked-in hydrogen



Schematic of a hydrogen refueling station with trucked-in liquid hydrogen

- Stored liquid hydrogen is assumed to be in thermodynamic equilibrium and thus boiling at a temperature of about -253°C.
- "Boil-off" hydrogen is let out of the storage and used in a fuel cell to generate electricity.
- The liquid hydrogen pump compresses the liquid hydrogen to pressures up to 90 MPa (isentropic)
- Air heat exchanger warms up hydrogen to -40°C

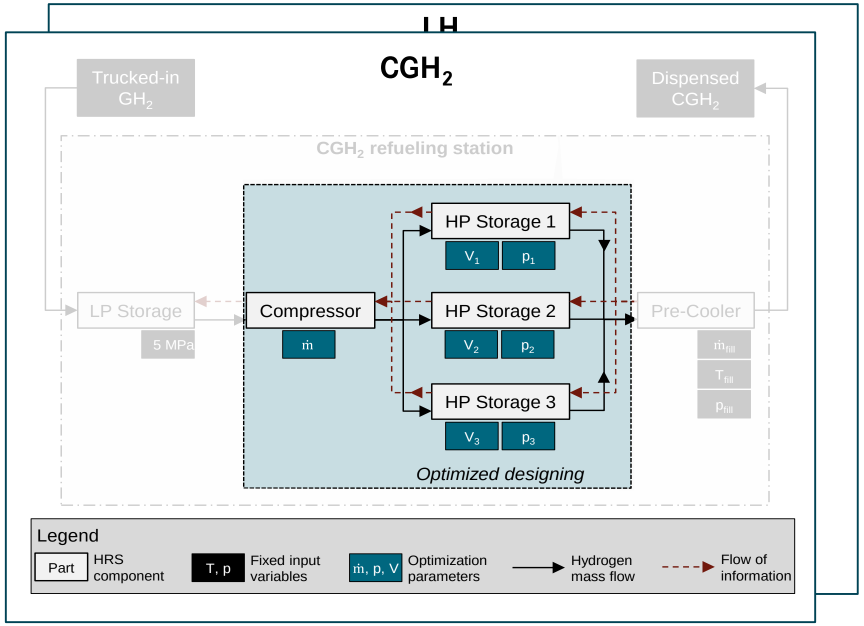
Design optimization - Methodology



Main drivers for hydrogen refueling station costs:
Investment costs: Compressor (CGH_2) or pump (LH_2) and cascade storage system
Operational costs: electricity consumption of compressor/pump.

- One refueling process with 5.6 kg considered (due to simulation time)
- System with 1 dispenser considered (as representative for other station sizes)
- The electricity consumption for one refueling is projected to hydrogen amount refuelled over HRS lifetime (4.6 kg per refueling).
- Optimization is conducted at ambient temperature of 10°C (Highest performance requirements)
- At higher temperatures, refueling process itself takes longer (SAE TIR J2601)
- Lower temperatures than 10°C, high-pressure storage capacity requirements are lower as hydrogen density (at same pressure) is smaller than at 10°C.

Design opimization - Results



Boundary conditions

- High pressure storages
  - Capacity: 5 kg until 50 kg (step size 5 kg)
  - Maximum pressure 20 MPa until 90 MPa (step size 10 MPa)
- Compressor/pump throughput: Min. 56 kg/h (5.6 kg/Veh. * 10 Veh./h)

Constraint

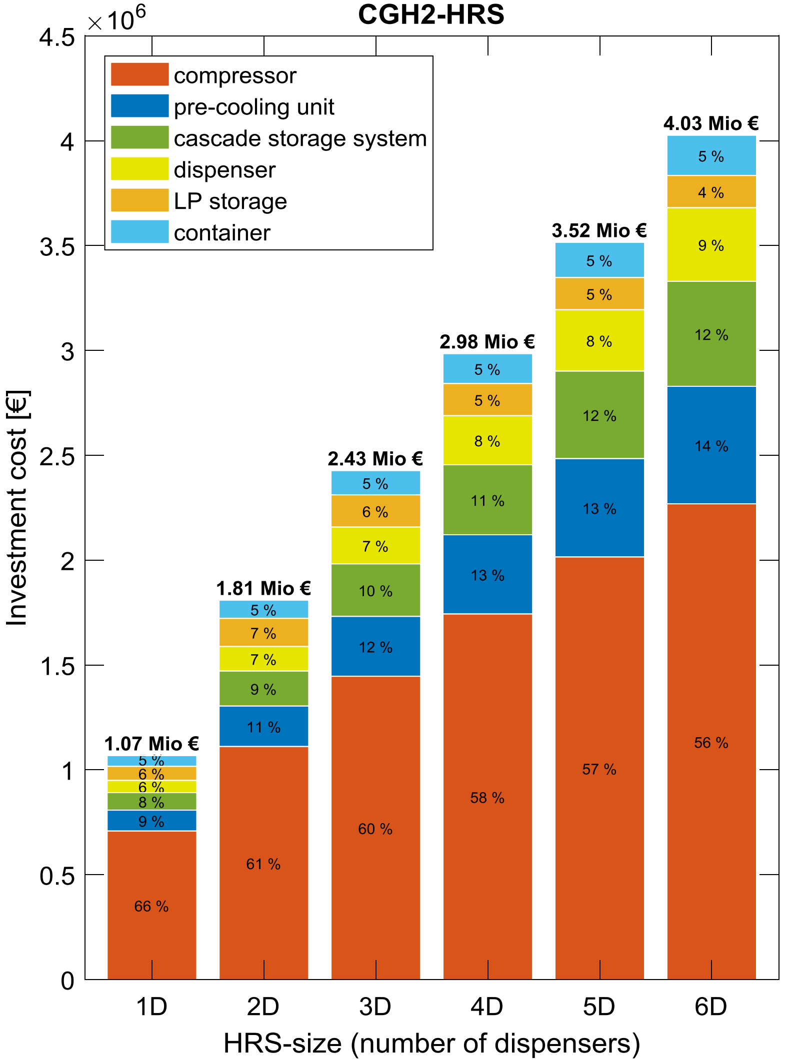
- End pressure in the last storage of the system min. 87.5 MPa (highest possible station pressure accord. to SAE TIR J2601)

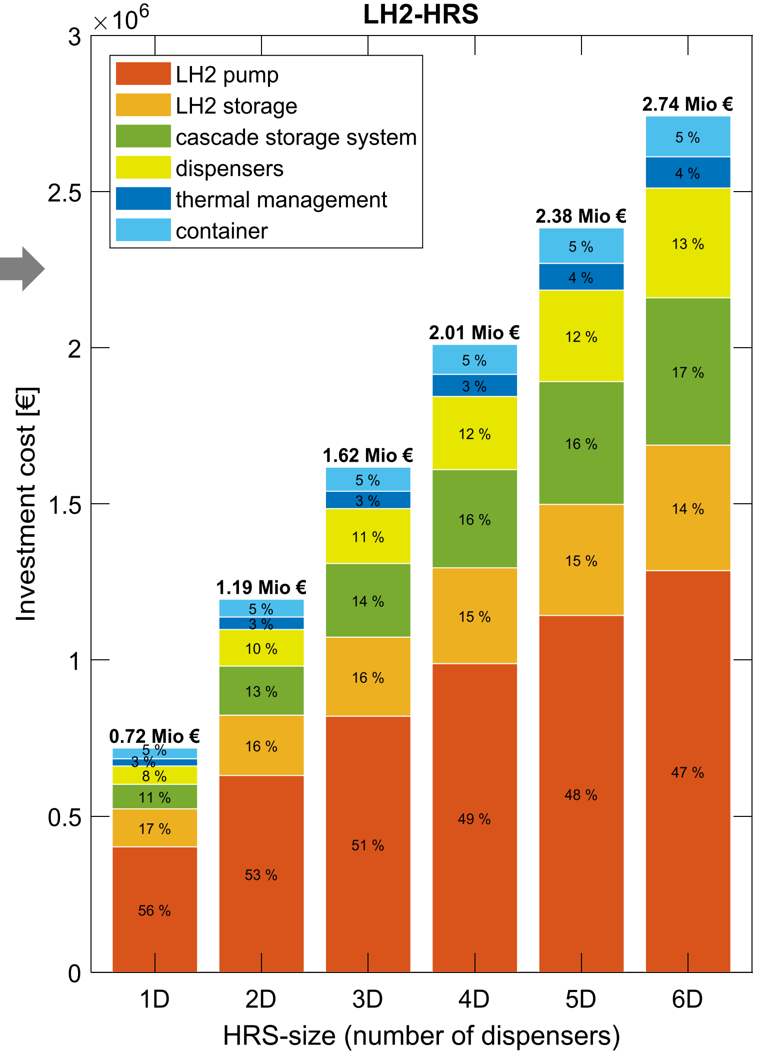
Results

HRS	Max. throughput compressor /pump	High-pressure storages		
		Number	Max. pressure (MPa)	Max. capacity (kg)
CGH_2	56 kg/h	1	50	20
		2	90	10
		3	90	20
LH_2	56 kg/h	1	50	15
		2	90	15
		3	90	15

→ Compressor/Pump throughput: 56 kg/h → Cheapest way to minimize compressor/pump throughput and (despite additional costs for high-pressure storages and compression)

Current HRS Investment Costs

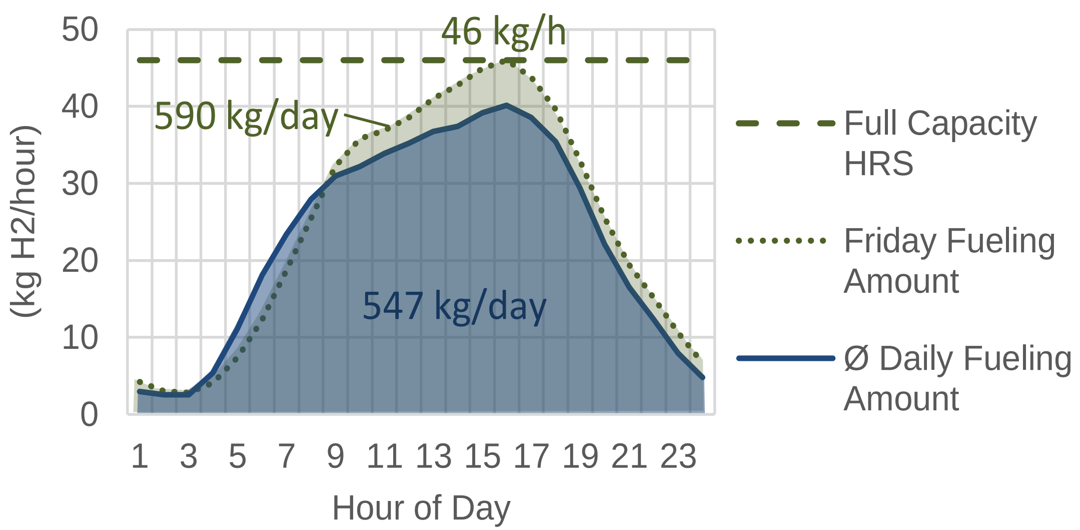




- Current investment costs of CGH_2 refueling stations are higher than for LH_2 refueling stations
  - ➢ Mainly caused by the compressor compared to the technical simpler and cheaper liquid pump.
  - ➢ Further caused by cheap thermal management (LH_2) compared to cost expensive precooling system (CGH_2)

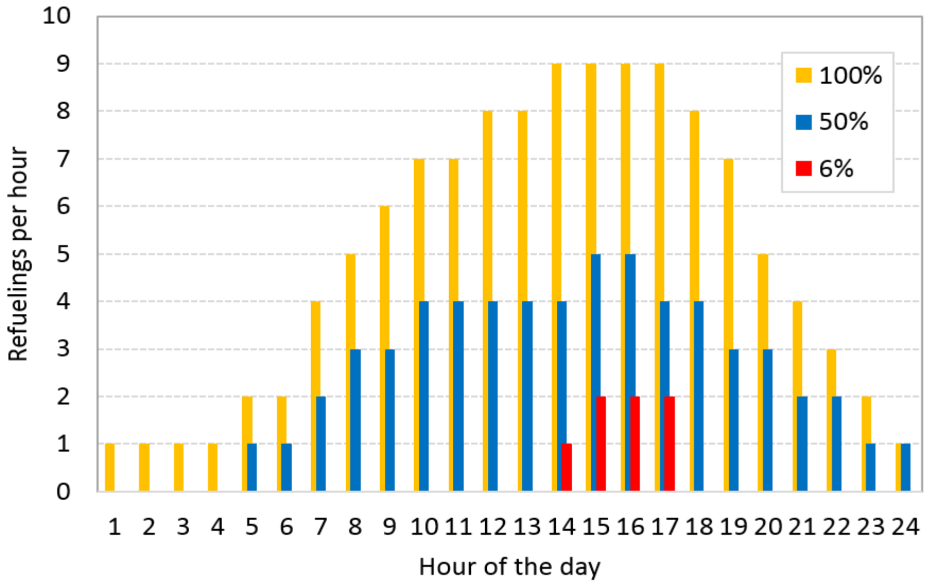
Modell application

Typical Refueling profile (derived from gasoline fuel stations)



Source: Nexant (2008) applied to Hydrogen Refueling Station with 1 Dispenser

H_2-Refueling profile at different utilizations

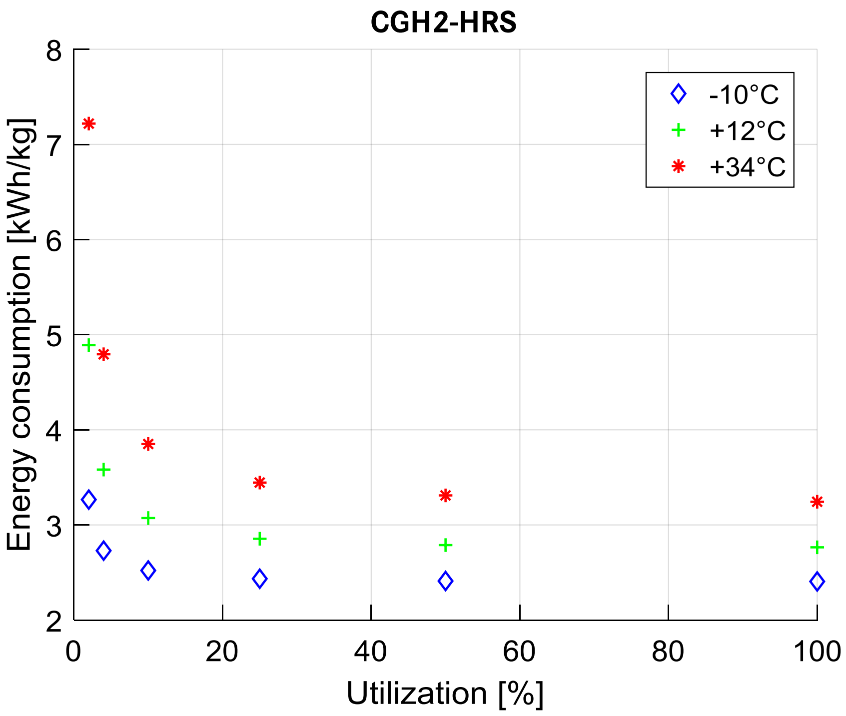


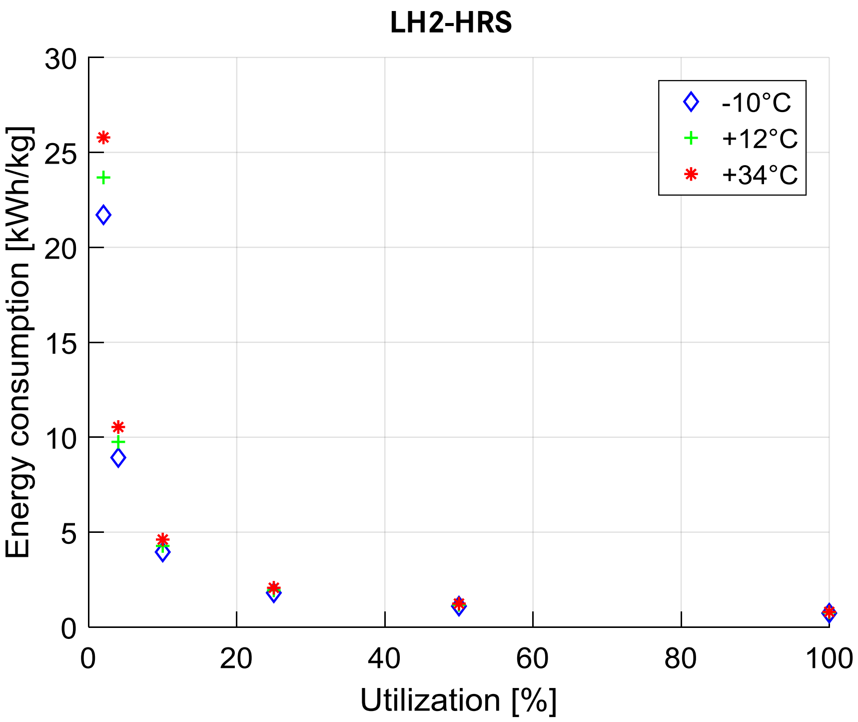
Refueling profile calculation

- The hour with highest share of weekly transactions (Friday, from 3 to 4 p.m.) is defined as full capacity
- 4.6 kg per refueling according to 'H2A Hydrogen Delivery Infrastructure' are assumed (Nexant 2008)
- Refueling Stations with multiple dispensers → Profile shown above is multiplied with number of dispensers

Nexant (2008): H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Nr. DE-FG36-05GO15032.

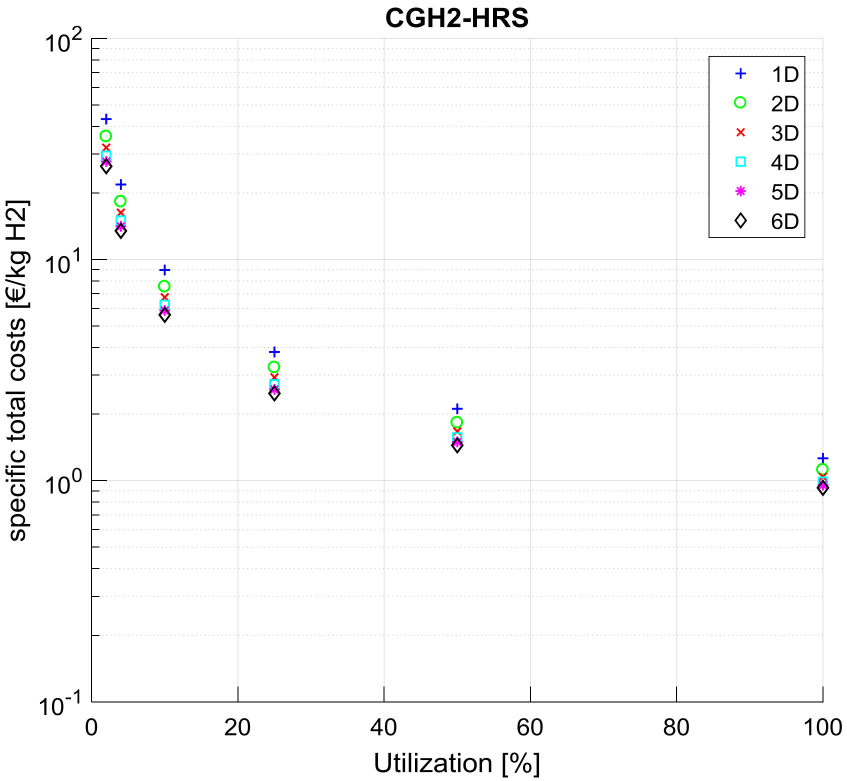
Specific Energy Consumption of HRS

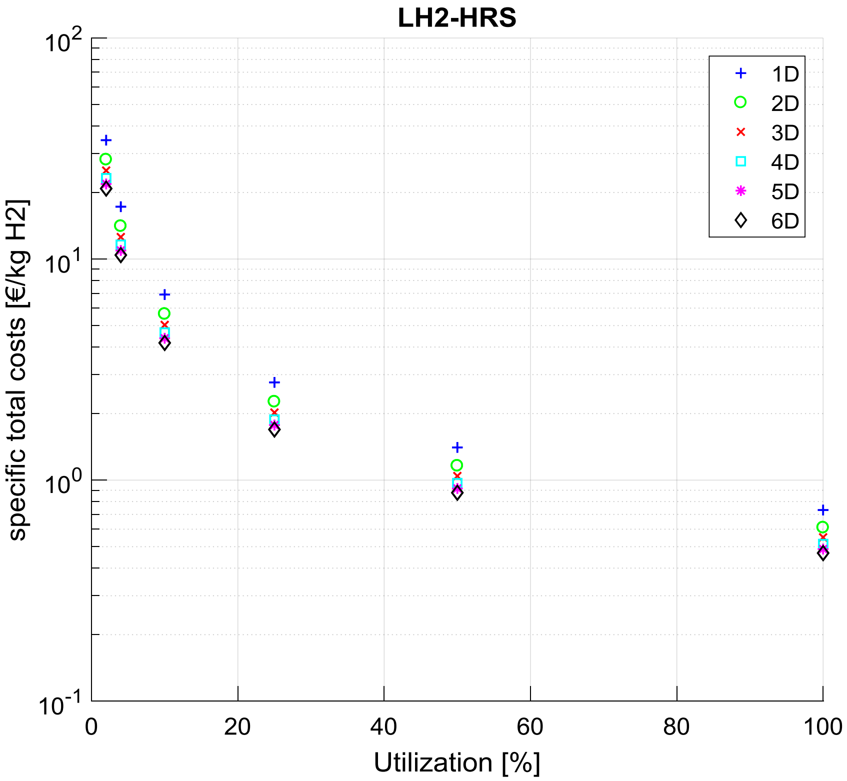




- Impact of ambient temperature on electricity consumption:
  - High at gaseous delivered stations
  - Low at liquid delivered stations (due to the slight relative change of temperature difference between storage (about -253°C) and ambient temperature
- At 100% utilization gaseous delivered stations consume from 2.4 kWh/kg (-10°C) to 3.2 kWh/kg (+34°C)
- In contrast liquid delivered stations consume 0.4 kWh/kg (-10°C until +34°C) at 100 % utilization.

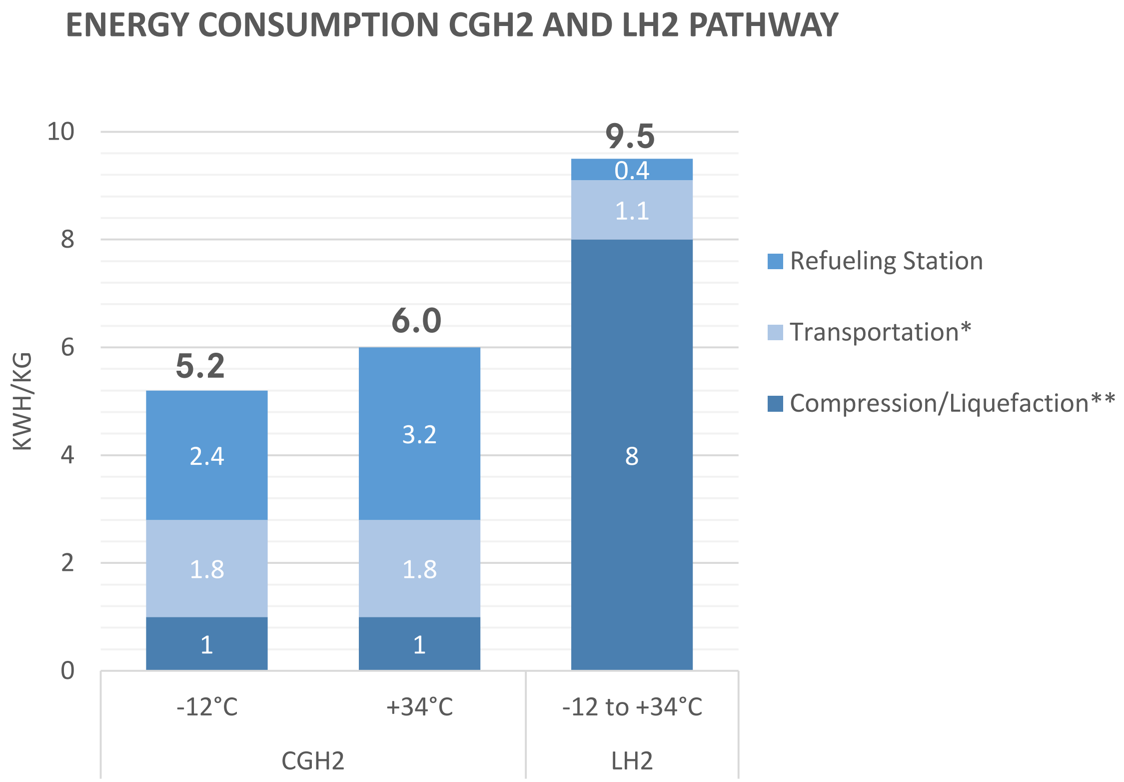
Specific HRS Costs





- The specific hydrogen costs are very sensitive to the station utilization
- The cost range of CGH2 refueling at 100 % utilization is from 0.93 €/kg (6 Disp.) to 1.26 €/kg (1 Disp.)
- In contrast the cost range of the LH2 refueling stations is from 0.47 €/kg (6 Disp.) to 0.73 €/kg (1 Disp.)

Current energy consumption of CGH_2- and LH_2-pathway



- Liquefaction of hydrogen needs significantly more energy than compression into a trailer
- Gaseous hydrogen pathway causes currently an energy demand 5.2 and 6 kWh/kg (at theoretically 100% station utilization)
- Ceteris paribus for liquid hydrogen, the energy demand rises up to 9.5 kWh/kg

* Diesel (30l/km) calculated with HHV, truck route calculation see Mayer et. al. (2007): WHTC, ** NREL (2013): Hydrogen Pathways

Conclusions

- Investment costs, energy consumption and specific costs lower at LH_2 delivered Stations
- Large liquid delivered stations with 6 dispensers cause station costs of 0.47 € per kilogram dispensed compared to 0.93 € per kilogram dispensed (CGH_2).
- Cost effectiveness of liquid delivered hydrogen stations due to high density and low temperature of LH_2
- Thermal management of LHRS significantly cheaper because heat from ambience can be taken to warm-up hydrogen
- The gaseous pathway has a significant advantage concerning the total energy consumption
- The economically advantageousness of the entire pathways depends on various factors like electricity costs (production site vs. station site), investment costs etc.

Next steps

Refueling Station Model extension:

- Small Stations with 1 Dispenser and 2.5 / 6 Veh. per hour
- 20 MPa low-pressure storage
- Model year 2030 and 2050
- Boil-off usage by catalytic burner

Calculation of entire fuel chains

- Comparison of gaseous and liquid hydrogen chains
- Comparison to other fuel chains (electricity – BEV, conventional fuels – ICE) etc.

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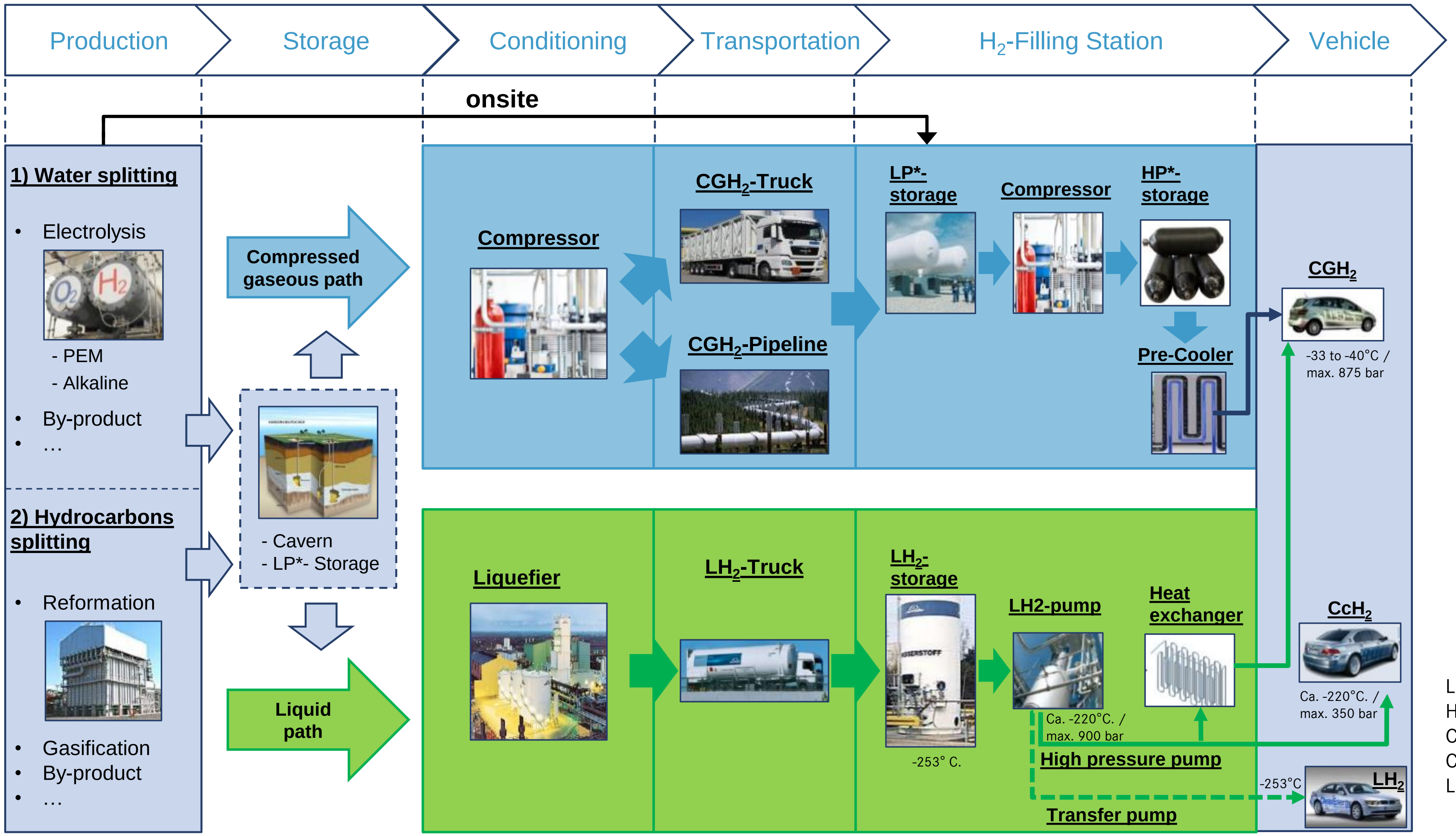
Thank you for your attention!

Hydrogen Pathways: gaseous and liquid



LP: low pressure
HP: high pressure
CGH_2: Compressed Gaseous Hydrogen
CcH_2: Cryo-compressed Hydrogen
LH_2:Liquid Hydrogen