BMW Hydrogen.
Hydrogen Storage Workshop.

Cryo-compressed Hydrogen Storage.

Tobias Brunner
February 15th, 2011, Washington D.C.

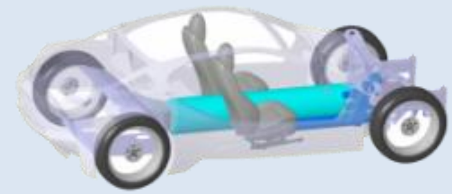
BMW Group

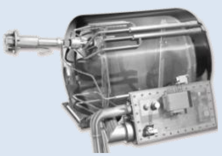
BMW Hydrogen Technology Strategy.
Advancement of key components.

Hydrogen 7 small series → **Advanced key components** → **Next vehicle & infrastructure**

Technology leap storage & drive train

Advancement Storage & Drive train





LH_2 Storage

- Capacity ✓
- Safety ✓
- Boil-off loss ✗
- Pressure supply ✗
- Complexity ✗
- Infrastructure ✗

V12 PFI engine

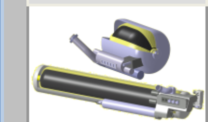
- Power density ✓
- Dynamics ✓
- Durability & cost ✓
- Efficiency ✗

H_2-Storage

CGH_2

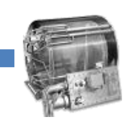
Source: Dynetek

CcH_2



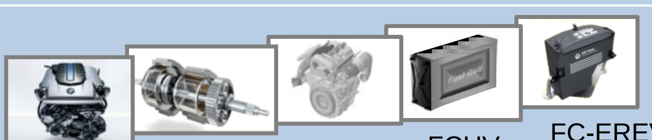
Source: BMW

LH_2



Source: BMW

H_2 Drive train



H_2ICE, H_2HEV, EREV, FCHV, FC-EREV

Electrification

Efficient long-range mobility:

- Zero Emission
- Focus on vehicles with high energy demand.
- Range > 500 km (6-8 kg H_2)
- Fast refueling (< 4 min / 6 kg)
- Optimized safety oriented vehicle package & component integration
- Loss-free operation for all relevant use cases
- Compatibility to upcoming infrastructure standard

today

H_2-Infrastructure.
Hydrogen distribution.

Role of LH_2 distribution in the longer term.

3500 kg LH_2 / trailer: 3 times a week

1500 kg H_2 / day

500 kg GH_2 / trailer: 3 times a day

H_2-Infrastructure forecast:

- „Cost-effectiveness, station footprint and safety issues will decide on delivery method und station layout“.

⇩

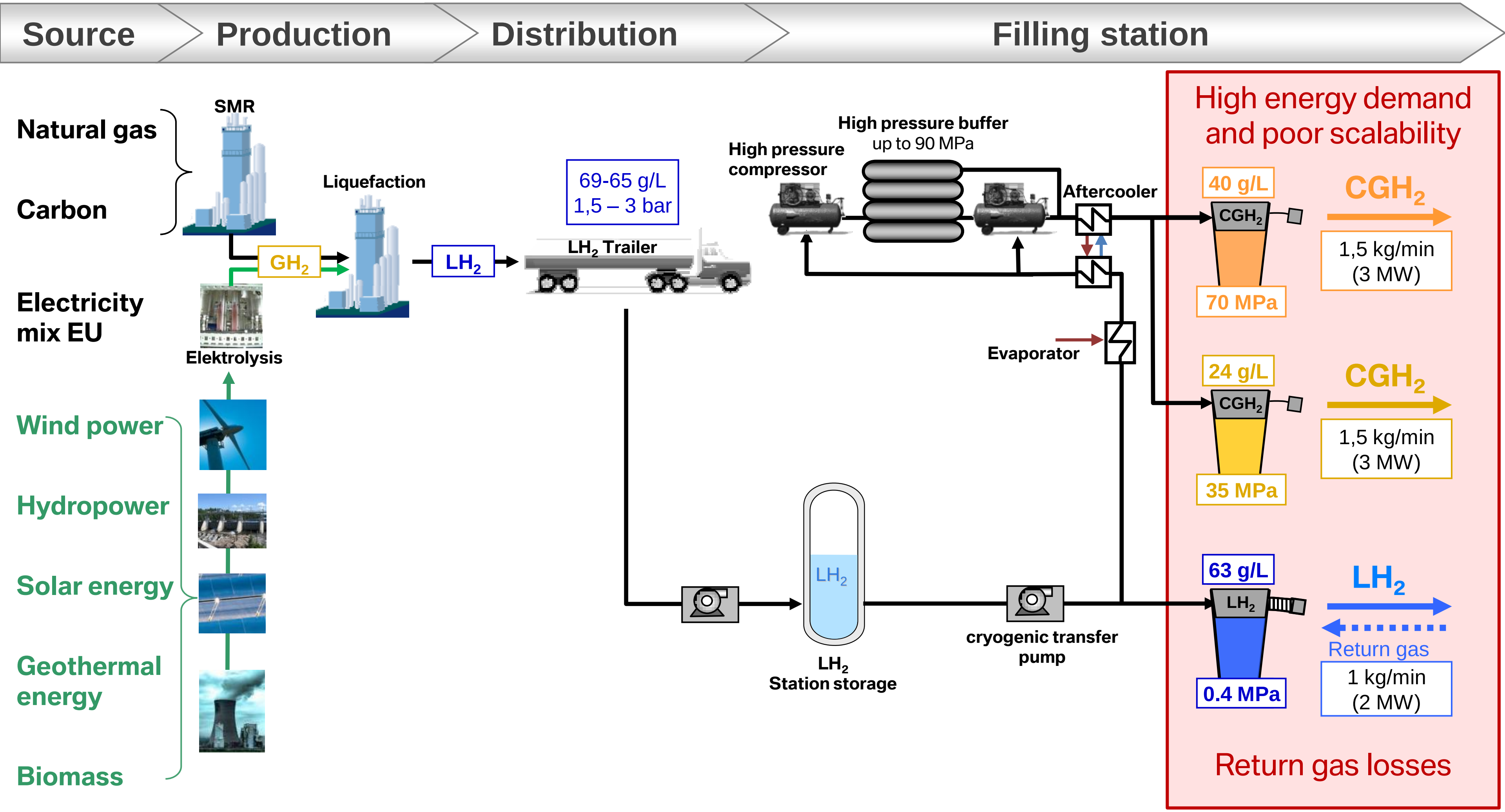
- Liquid hydrogen distribution along highways and in remote areas.
- Gaseous hydrogen distribution via pipelines in only in the long term and only in selected locations.
- Compressed gas trailers and onsite electrolysis in ramp-up phase, only.

⇩

Liquid delivery and station storage will play an important role in future infrastructure.

H_2-Infrastructure.
Today's LH_2-based filling station layout.

Filling station with LH_2-supply and warm compression.

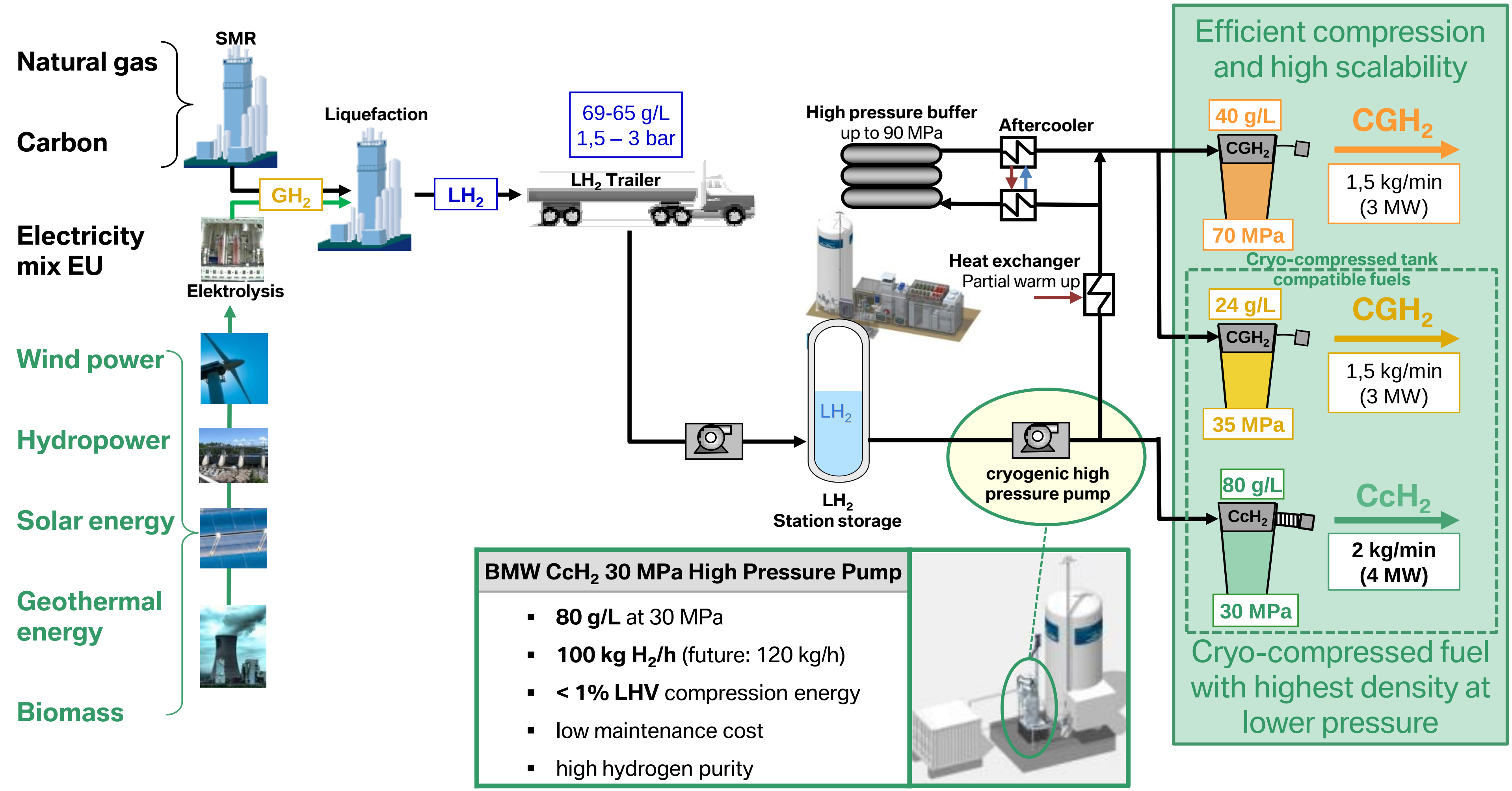


H_2-Infrastructure.

Future filling station layout.

Filling station with LH_2-supply and cryogenic high-pressure pump.

Source → Production → Distribution → Filling station



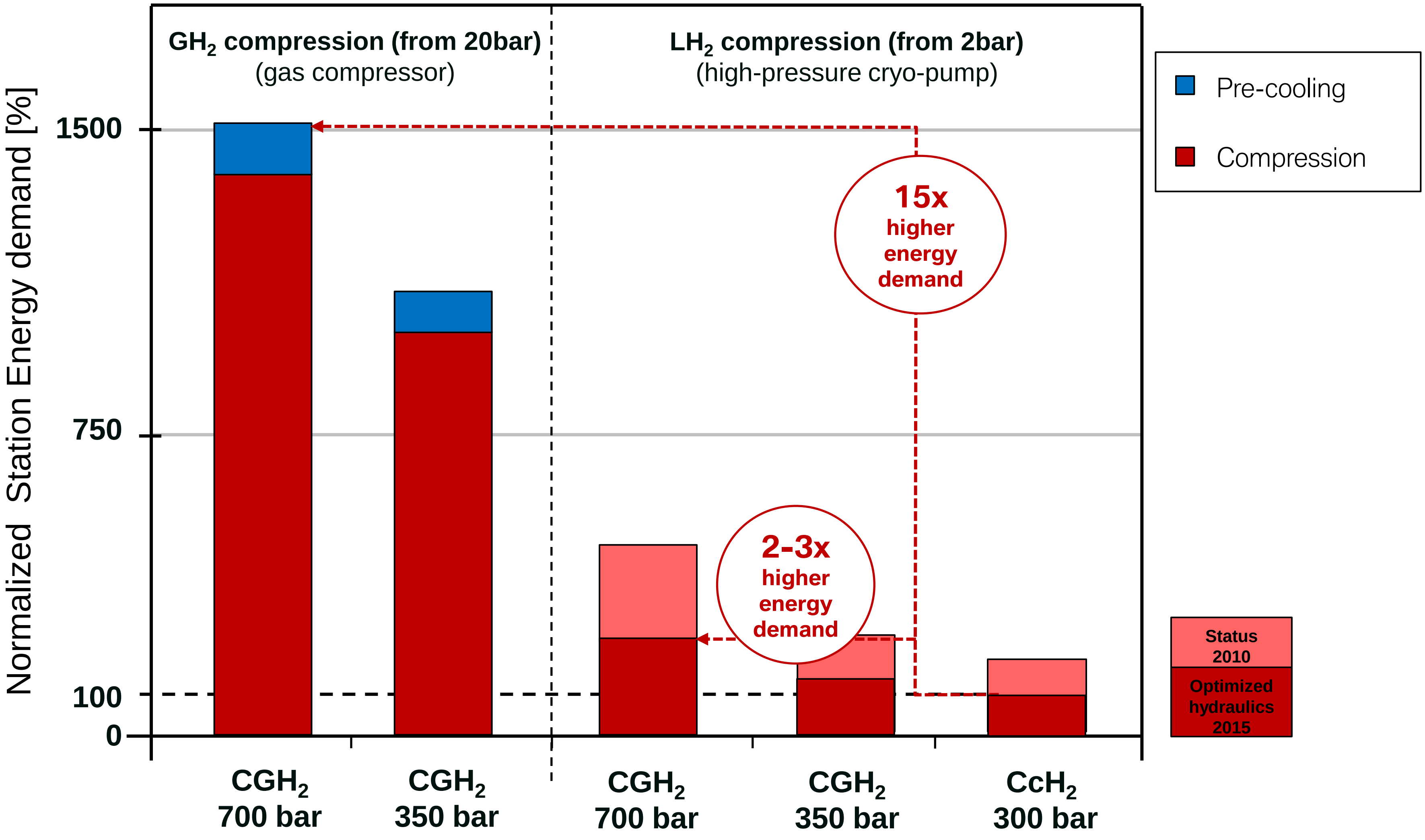
H_2-Infrastructure.
Cryogenic high pressure pump.

Refueling density 80 g/L at 300 bar.

BMW Linde CcH_2 pump prototype

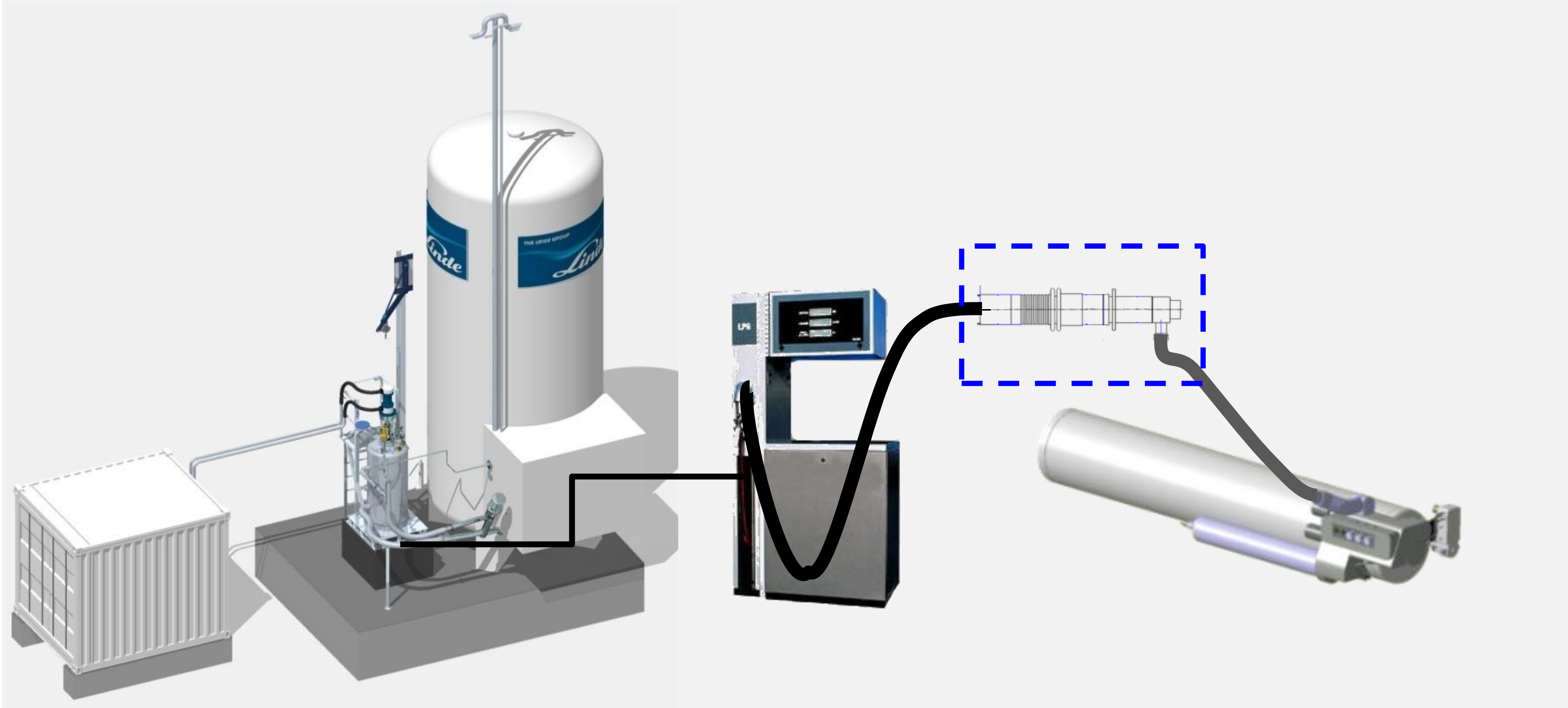
- **80 g/L** at 300 bar
- **100 kg H_2/h**
- **< 1% LHV** compression energy
- Start of operation: Feb. 2010
- **H_2 delivered** (02/2011)**: ~ 30,000 kg** (> 6000 refuelings with subscale and full size tank systems)

H_2-Infrastructure.
Energy demand for compression and cooling.



H_2-Infrastructure.
Cryo-compressed refueling process.

Single-flow fast refueling with new CcH_2 nozzle.

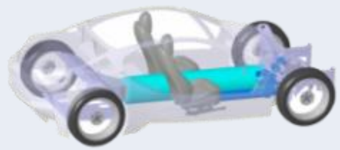


- ⇨ Direct single-flow refueling to 300 bar via cryo-pump (⇒ varying fill density)
- ⇨ 100 -120 kg/h continuous fill rate (⇒ 3 - 3.5 minutes for 6 kg)
- ⇨ New quick connector nozzle concept (available in September 2011)
- ⇨ No need for communication between vehicle and dispenser

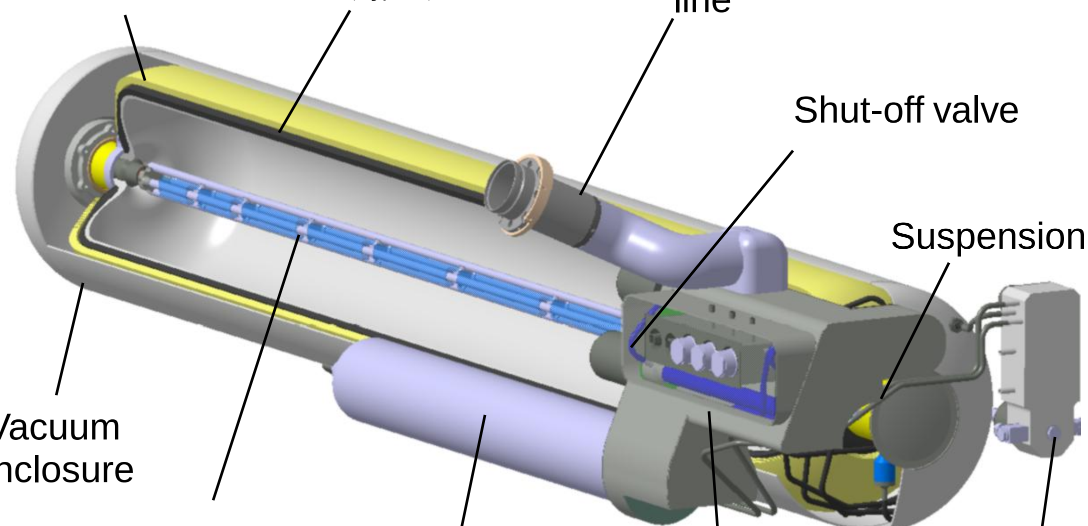
BMW Cryo-compressed Hydrogen Storage.
System layout – BMW prototype 2011.

Modular Super-insulated Pressure Vessel (Type III)

Max. usable capacity	CcH_2: 8 kg (265 kWh) CGH_2: 2.7 kg (90 kWh)
Operating pressure	≤ 350 bar
Vent pressure	≥ 350 bar
Refueling pressure	CcH_2: 300 bar CGH_2: 350 bar
Refueling time	< 5 min
System volume	~ 235 L
System weight (incl. H_2)	~ 145 kg
H_2-Loss (Leakage| max. loss rate | infr. driver)	<< 3 g/day | 3 – 7 g/h (CcH_2) | no significant losses

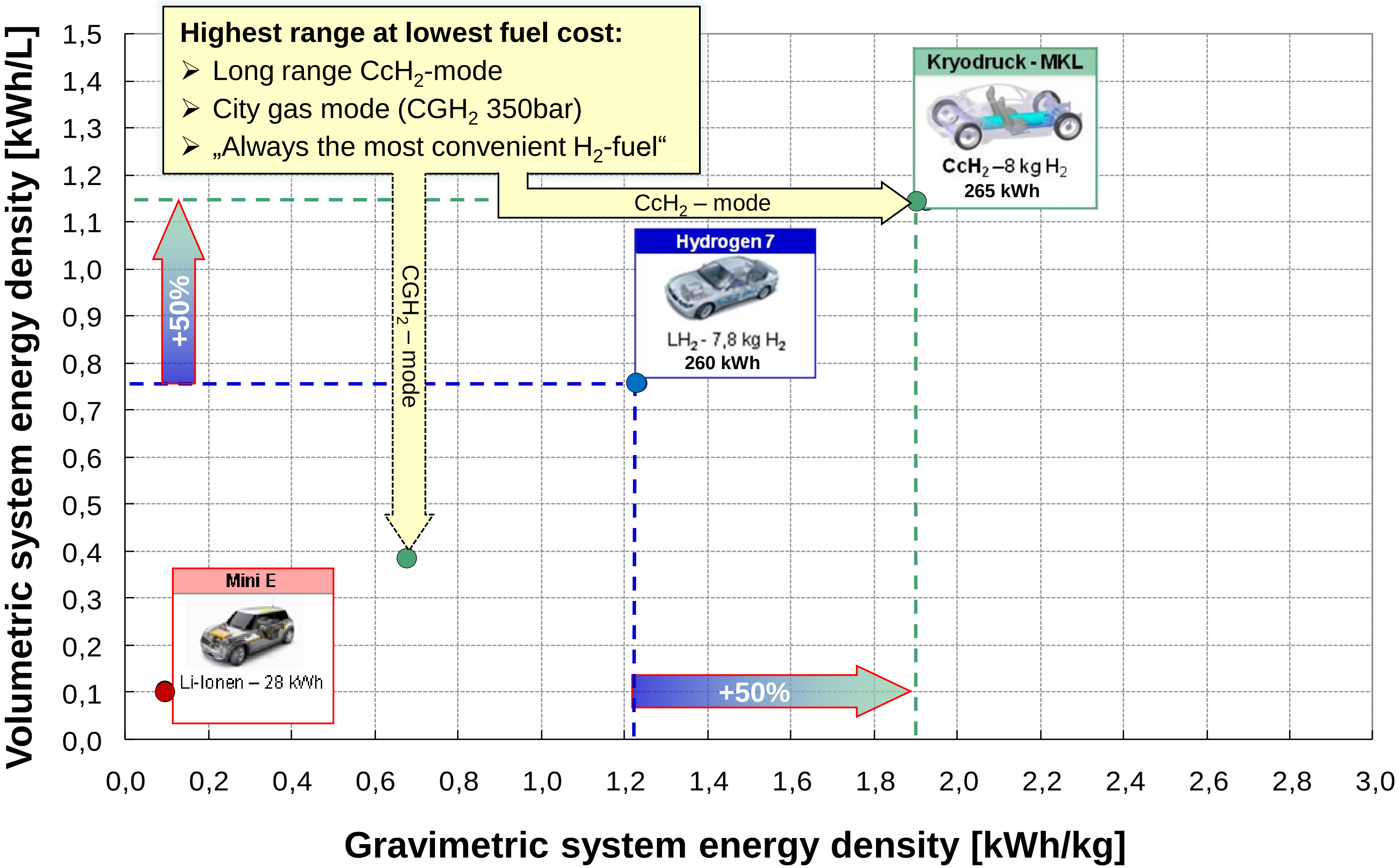


+ Active tank pressure control
+ Load carrying vehicle body integration
+ Engine/fuel cell waste heat recovery
+ Compatible with 350bar CGH_2 refueling



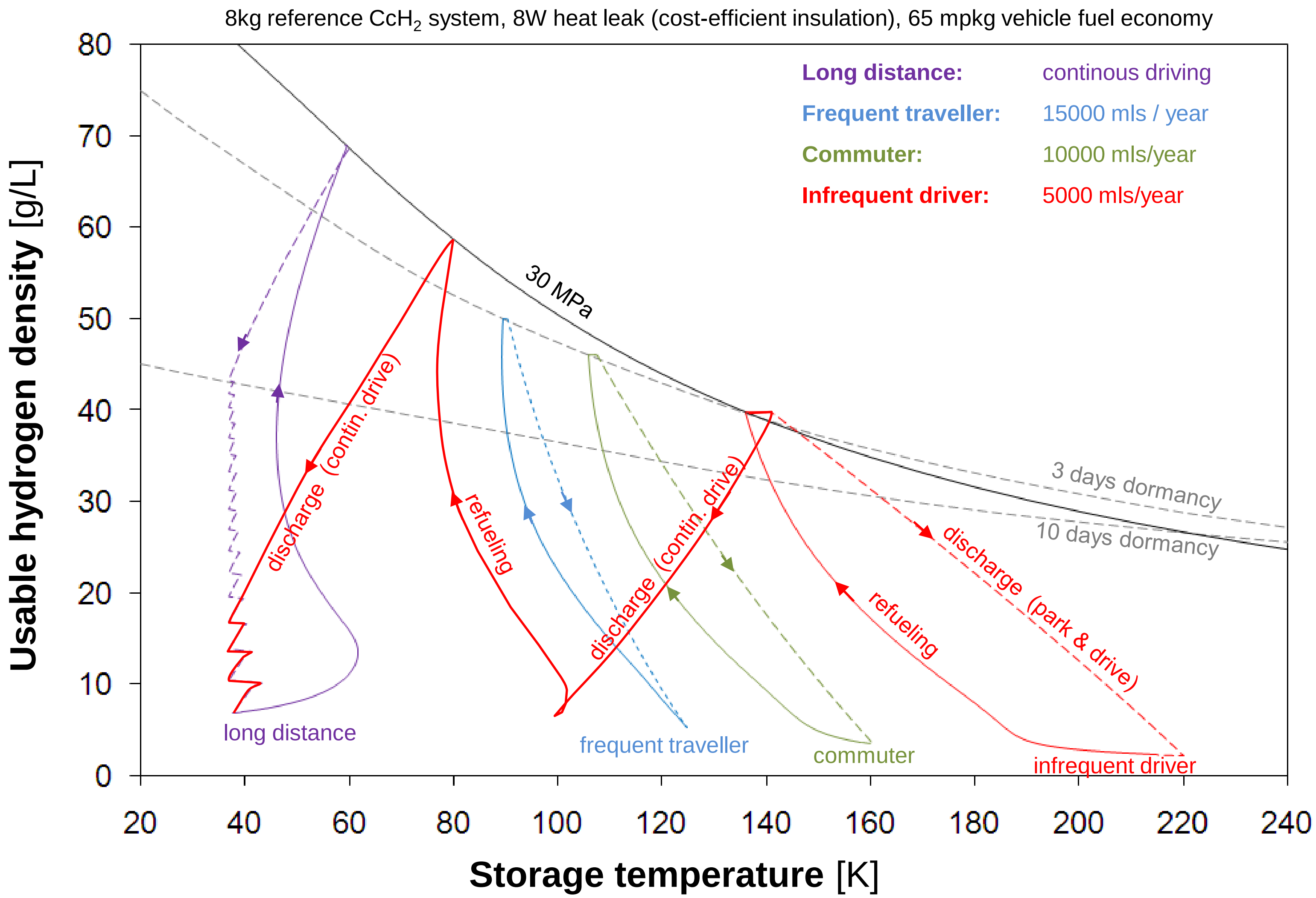
BMW Cryo-compressed Hydrogen Storage.
Operation modes.

Dual mode H_2 storage system: CcH_2 30 Mpa and CGH_2 35 MPa.



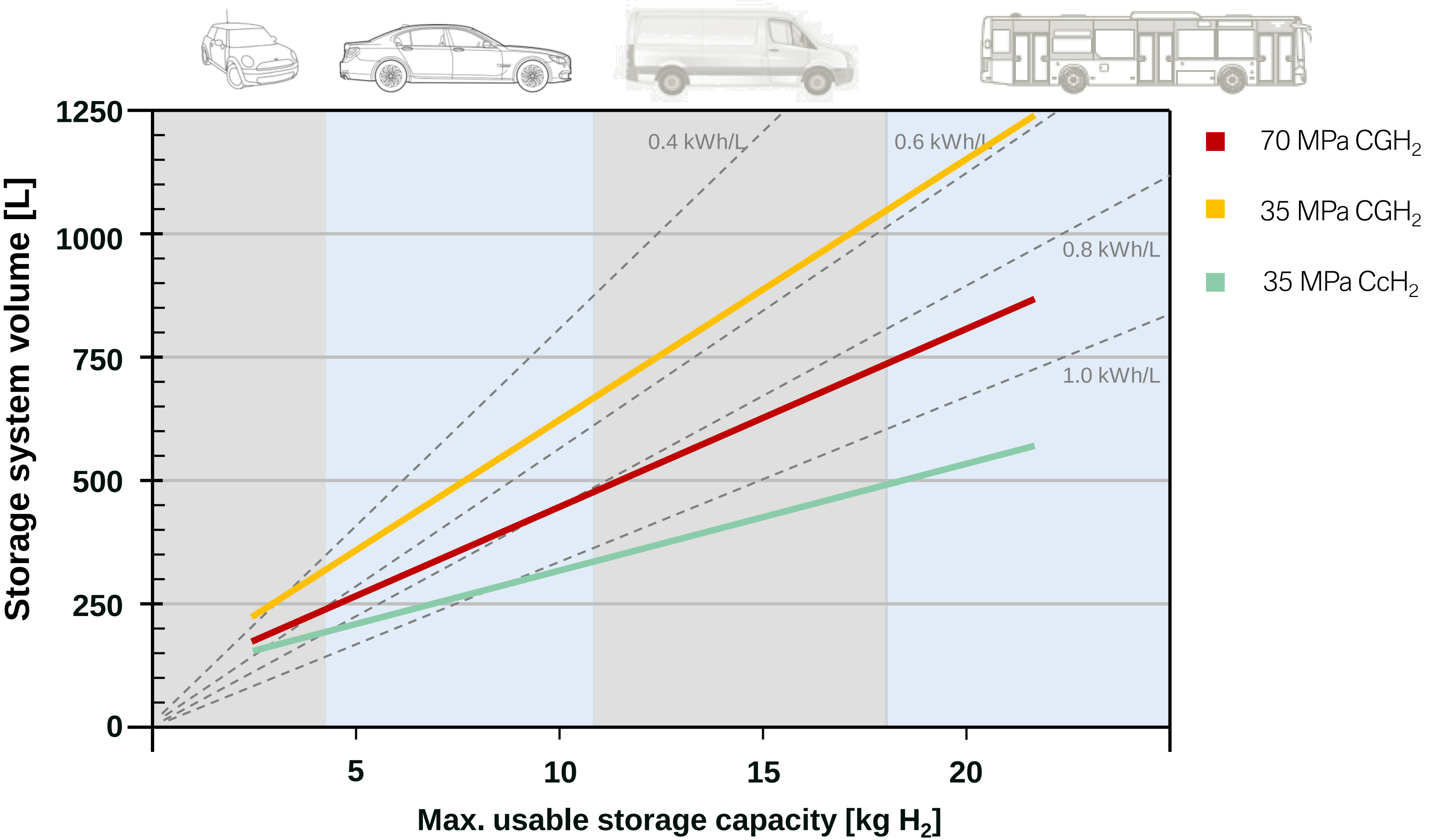
BMW Cryo-compressed Hydrogen Storage.
Use case projections.

Auto-adaptive density minimizes vent loss risk, still leaves max. capacity option.



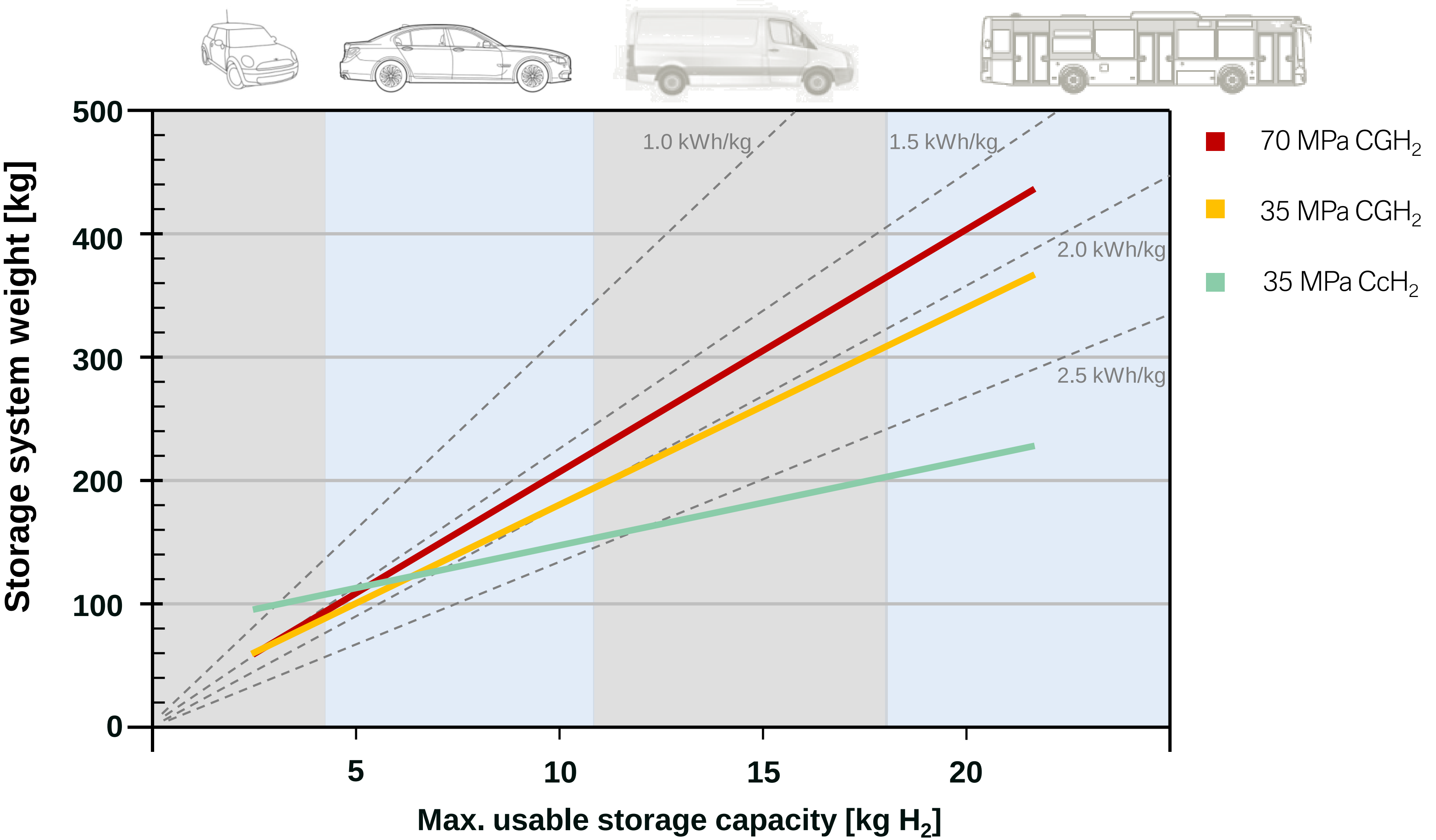
BMW Cryo-compressed Hydrogen Storage.
Storage system volume.

Cryo-compressed storage with highest volumetric density.



BMW Cryo-compressed Hydrogen Storage.
Storage system weight.

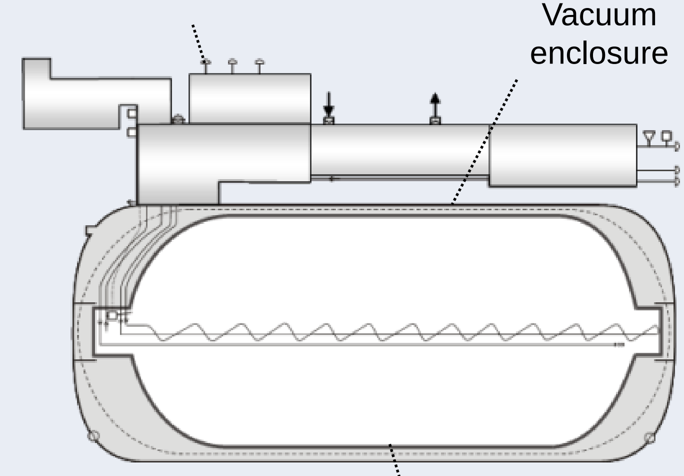
Cryo-compressed storage is competitive for high capacity.

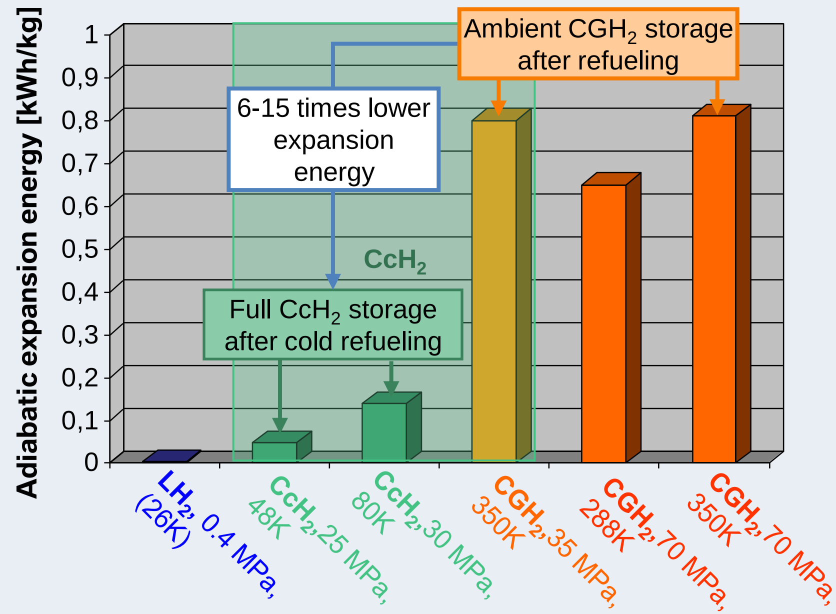


BMW Cryo-compressed Hydrogen Storage.
Safety aspects.

CcH_2 storage eases vessel monitoring and mitigates failure impact.

Vacuum enclosure & safety release control	Low adiabatic expansion energy





Vacuum enclosure design lowers risk of pressure vessel damage (mechanical and chemical intrusion, bonfire damaging and aging) and enables leak monitoring.

Redundant safety devices for safe hydrogen release in case of damage or vacuum failure.

Cryogenic hydrogen contains a fairly low adiabatic expansion energy and thus, can mitigate implications of a sudden pressure vessel failure, in particular during refueling.

BMW Cryo-compressed Hydrogen Storage.
Test Facilities.


Cryogenic Testing.

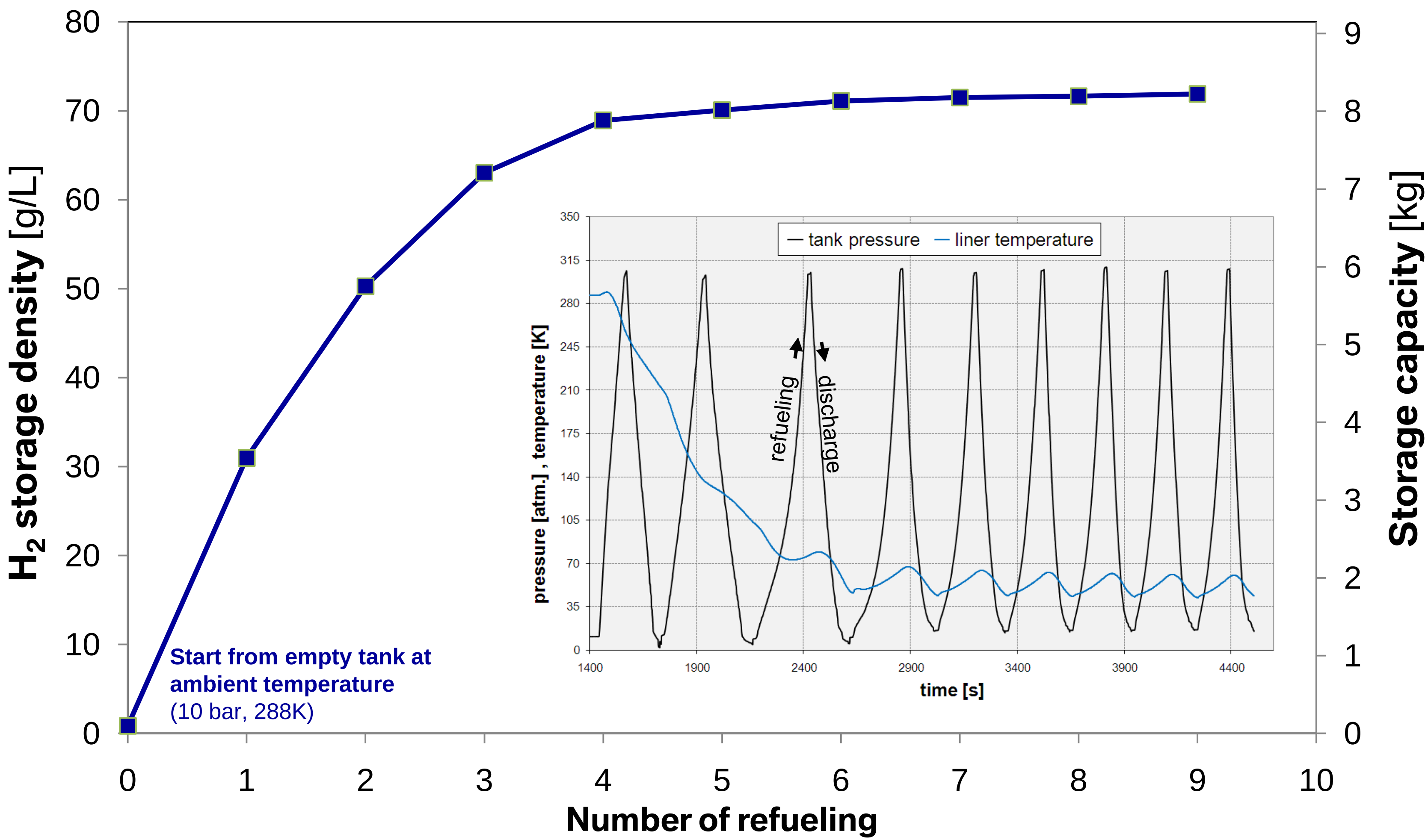

Performance Test Rig


Cycle Test Rig

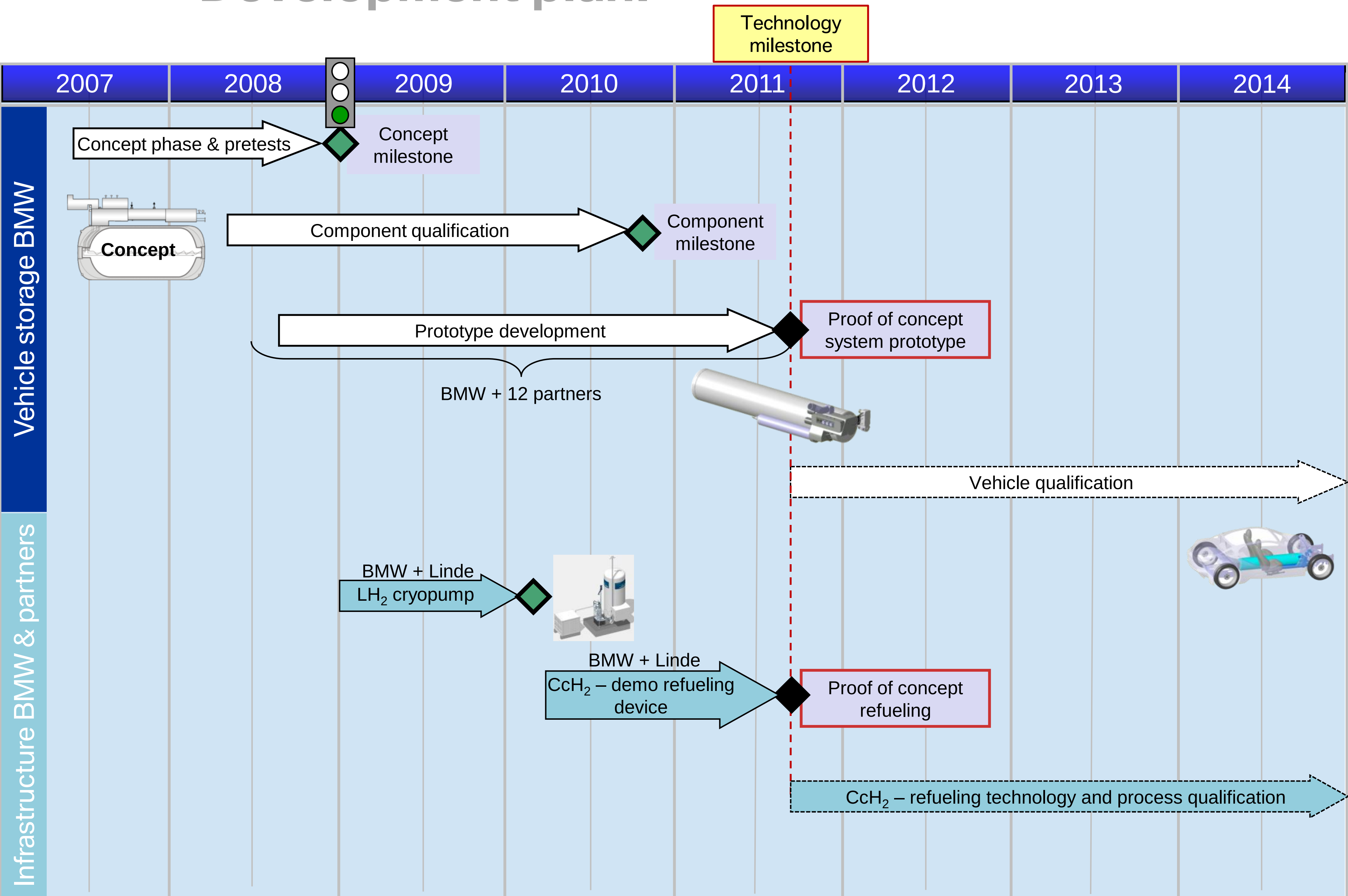

High Pressure Cryopump

BMW Cryo-compressed Hydrogen Storage.
Experimental single-flow refueling results.

Consecutive single-flow CcH_2 refuelings at 100 kg/h, starting from ambient tank.



BMW Cryo-compressed Hydrogen Storage.
Development plan.

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