COSMHYC XL
Public deliverable

- Refuelling / compression requirements (2019)
- Techno-economic results (2023)

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Main result from the techno-economic work package (WP2)

Clean Hydrogen Partnership
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The project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research.

Large-scale FC transport applications and their requirements

(Selected results; status: August 2019)

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WP 2 Selection of most relevant applications for project

In 2019, the project consortium selected applications that are special interest for this project (see table) Other applications are less relevant and not in focus e.g. material handling vehicles, passenger cars, ships, etc.

Application	Justification
Rigid truck (e.g. for distribution)	First prototypes and small fleets are currently introduced in Europe [Asko 2016], [Coop 2017], [Van der Laak 2018]
Semi-trailer tractor (e.g. for long-distance transport)	First prototypes are being developed. Strong interest and awareness of hydrogen for this application in Europe e.g. due to US company Nikola which claims market introduction of FC vehicle in 2023.
City buses	Continuously European efforts to commercialize FC city buses; larger fleets are continuously being deployed, ordered and planned. [EE 2016], [CHIC 2016]
Regional trains	Demonstrations and commercial roll-out of FC regional trains has started in recent years; large fleets are announced to be delivered. One in three non-catenary trains could be hydrogen powered in 2030 [RB 2019b].

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WP 2 Identification requirements and parameters

The most relevant parameters/requirements for hydrogen compression include:

- Allowable downtime and frequency of downtime of compressor
- Ambient temperature
- Available heat sources and sinks at HRS site
- Average and/or peak dispensing capacity
- HRS demand profile and resulting operation dynamics
- HRS/compressor energy consumption/efficiency and grid connection
- HRS/compressor noise emissions
- HRS/compressor reliability
- Hydrogen purity
- Output pressure
- Plannability, repeatability, suggestibility of hydrogen demand profile
- Possible floor space limitations, footprint
- Source pressure / suction pressure

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WP 2 Relevant vehicles

FC truck models relevant in 2019, distribution (top) and long-distance trucking (bottom):

Vehicle	Tank size	Nominal pressure	Range per tank
ESO MAN (34t)	34.5 kg (31 kg net)	35 MPa	400 km
Scania (27t)	33 kg	n/a	500 km
DAF CF FAN (28t)	30 kg	35 MPa	400 km
Hyundai (34t)	33 kg	35 MPa	400 km

Vehicle	Tank size	Nominal pressure	Range per tank
Clean Logistics	~ 45 kg	35 MPa	400 to 500 km (future increase)
HV systems			1,200 km
Toyota / Kenworth		70 MPa	480 km
Nikola Tre	60 kg [AllThingsEV 2019]	70 MPa (estimate)	500 to 1,200 km

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WP 2 Identified requirements for refuelling applications (2019)

Relevant requirements (FC rigid trucks)

Parameter	Value	Comment
Output pressure compressor	50 MPa	Based on current vehicle designs; future upgrade to 70 or up to 100 MPa might become necessary
Suction pressure compressor	≤ 5 MPa	Depends on H_2 supply which is a site-specific choice
Daily compression capacity	Approx. 1.000+	1.000 kg/day sufficient for approx. 40 trucks; smaller fleets possible (out of project scope)
Hourly compression capacity	Up to 20% of daily capacity	Estimated based on Figure 11 and a refuelling + handling time of approx. 15 minutes and 2 dispensers occupied; depends on HRS HP storage size
Operating dynamics and dispensing profile	Dynamic operation	Dynamic operation to serve peak demand hours; longer idle periods on Sundays and holidays
Required hydrogen purity	ISO-14687	
Efficiency	Relevant	Impact on OPEX; high efficiency might also be relevant for corporate social responsibility
Reliability	Very relevant	Short periods (hours) of unavailability might be acceptable during introduction/prototype phase but not for commercial roll-out
Power requirements /grid connection	Relevant	Site specific limitations might apply
Noise emissions	Relevant	Site specific limitations might apply
Floor space	Relevant	Smaller footprint enables higher flexibility when it comes to selecting the site for the HRS
Compatible to HRS capacity upgrade	Very relevant	Growing fleet sizes as more models and vehicle classes become available
Adaptable to higher pressures	Very relevant	Higher vehicle storage pressure e.g. 50 or 70 MPa will likely be introduced in combination with higher flow rates to reduce refuelling duration
Compatible to higher refuelling flow rates	Very relevant	
FC fleet composition	Inhomogeneous	Trucks from different manufacturers, different model years and even different vehicle classes (cars, long distance trucks, material handling vehicles,…) might be served from one station.

Relevant requirements (FC semi-trailer tractors)

Parameter	Value	Comment
Output pressure compressor	50 or 100 MPa	Short-term demonstration projects rather 50 MPa, medium- to long-term 50 or 100 MPa
Suction pressure compressor	≤ 5 MPa	Depends on H_2 supply which is a site-specific choice
Daily compression capacity	Approx. 1.000+	
Hourly compression capacity	~ 15% of daily capacity	Assuming that 80% of daily capacity is dispensed within 6 hours
Operating dynamics and dispensing profile	Dynamic operation	Dynamic operation to serve peak demand hours; longer idle periods on Sundays and holidays
Required hydrogen purity	ISO-14687	
Efficiency	Relevant	Impact on OPEX; high efficiency might also be relevant for corporate social responsibility
Reliability	Very relevant	Short periods (hours) of unavailability might be acceptable during introduction/prototype phase but not for commercial roll-out
Power requirements /grid connection	Relevant	Site specific limitations might apply
Noise emissions	Relevant	Site specific limitations might apply
Floor space	Relevant	Smaller footprint enables higher flexibility when it comes to selecting the site for the HRS
Compatible to HRS capacity upgrade	Very relevant	Growing fleet sizes as more models and vehicle classes become available
Adaptable to higher pressures	Very relevant	Higher vehicle storage pressure e.g. 50 or 70 MPa will likely be introduced in combination with higher flow rates to reduce refuelling duration
Compatible to higher refuelling flow rates	Very relevant	
FC fleet composition	Inhomogeneous	Trucks from different manufacturers, different model years and even different vehicle classes (cars, long distance trucks,,…) might be served from one station.

Relevant requirements (FC city buses)

Parameter	Value	Comment
Output pressure compressor	50 MPa	Based on current vehicle designs
Suction pressure compressor	≤ 5 MPa	Depends on H_2 supply which is a site-specific and/or political/regulatory choice
Daily compression capacity	1.000 to 6.000 kg/day	
Hourly compression capacity	15 to 25%, max. up to 50% of daily capacity	Refuelling window usually between 4 to 8 hours; "Worst-case" 2 hours
Operating dynamics and dispensing profile	Depends on strategy	
Required hydrogen purity	ISO-14687	
Efficiency	Very relevant	Impact on OPEX; a high efficiency is an advantage or less of a disadvantage compared to alternative technologies
Reliability	Very relevant	Availabilities of 99.8% for bus HRS have already been achieved
Power requirements /grid connection	Relevant	Site specific limitations
Noise emissions	Relevant	Site specific limitations
Floor space	Relevant	Space limitation often exist
Upgradable to higher capacity	Very relevant	Multiple smaller batches of FC buses over several years
Adaptable to higher pressures	Less relevant	35 MPa technology already provides sufficient range
Compatible to higher refuelling flow rates	Relevant	New technology might become available; attractive to operator → shorter refuelling time
Fleet composition	Rather homogeneous	Limited variations e.g. bus type (12m, 18m articulated), models (manufacturers) and technology generations at one depot possible; however plannable

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Techno-economic analysis

(Selected results, status: July 2023)

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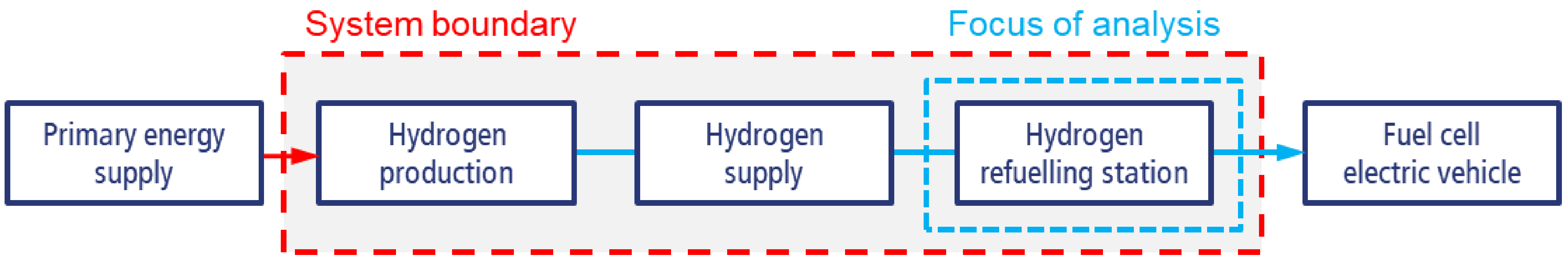
WP 2 Techno-economic evaluation – general remarks

The COSMHYC XL prototype and project insights:
Basis for estimating costs, energy consumption and performance of a future commercial product

Main assumptions for the techno-economic evaluation:

- Series production of 50 units/year (metal hydride and mechanical compressor)
- Comparison to pre-project compression technology
(techno-economic parameters for piston and diaphragm compressors available before the start of the project)
- While covering the overall H_2 fuel supply-chain, focus is on HRS, especially on compressors



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WP 2 Techno-economic evaluation – general remarks HRS

The following parameters have been considered for the estimation of HRS costs

70 MPa hydrogen fuel
2 MPa suction pressure

70 MPa hydrogen fuel
0.5 MPa suction pressure

The main design parameters of the **70 MPa HRS** include:

- Nominal dispensing capacity: 1.44 t/day
- Station utilization: 70% (1,000 kg/day = 1,440 * 70%)
- Peak dispensing capacity: 240 kg/h
- Maximum number of hours at peak dispensing: 3 h
- Hydrogen transfer to vehicle:
  - First half of refuelling: via pressure difference from medium pressure storages
  - Second half of refuelling: booster compression into the vehicle tank
- Dispensers: 1
- Pre-cooling of hydrogen: Yes
- Hydrogen supply pressure: 2 MPa; 0.5 MPa

35 MPa hydrogen fuel
2 MPa suction pressure

The main design parameters of the **35 MPa HRS** include:

- Nominal dispensing capacity: 1.44 t/day
- Station utilization: 70% (1,000 kg/day = 1,440 * 70%)
- Peak dispensing capacity: 2x 120 kg/h
- Maximum number of hours at peak dispensing: 3 h
- Hydrogen transfer to vehicle:
  - First half of refuelling: via pressure difference from 30 MPa storages
  - Second half of refuelling: via pressure difference from 45 MPa storages
- Dispensers: 2
- Pre-cooling of hydrogen: Yes (increased refuelling speed is assumed)
- Hydrogen supply pressure: 2 MPa

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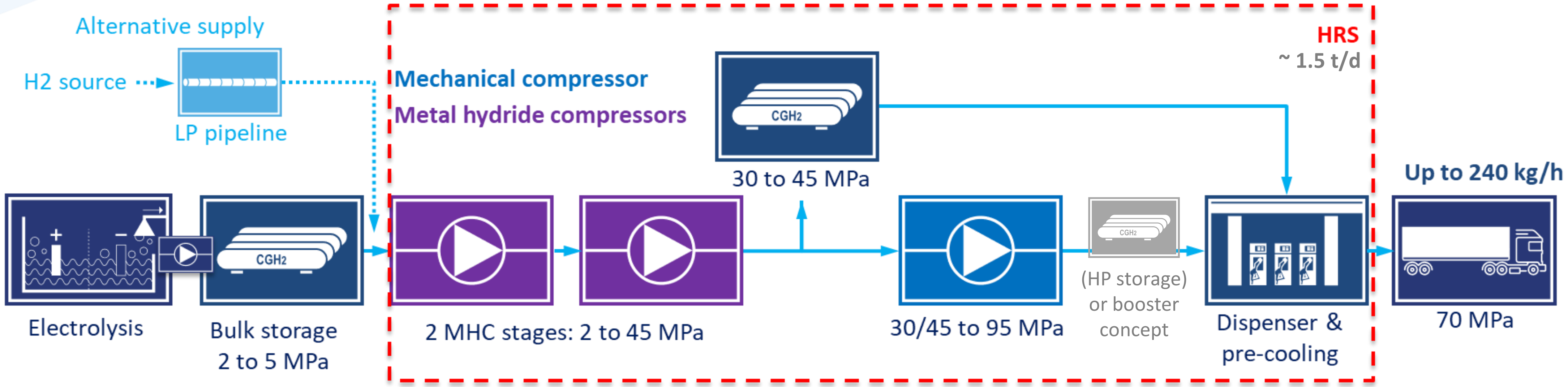
WP 2 Techno-economic evaluation – HRS setup

70 MPa hydrogen fuel
2 MPa suction pressure

Application: 70 MPa refueling of trucks, the upcoming fuel pressure for HDV
(2 MPa minimum suction pressure from bulk storage, intermediate pressure storage 30 to 45 MPa)

- Different operating schemes for the metal hydride and mechanical compressor (Metal hydride compr.: baseload/continuous; mechanical compr.: on demand/refueling)
- MP storage to enable cascaded refuelling and to balance metal hydride and mechanical compressor operation



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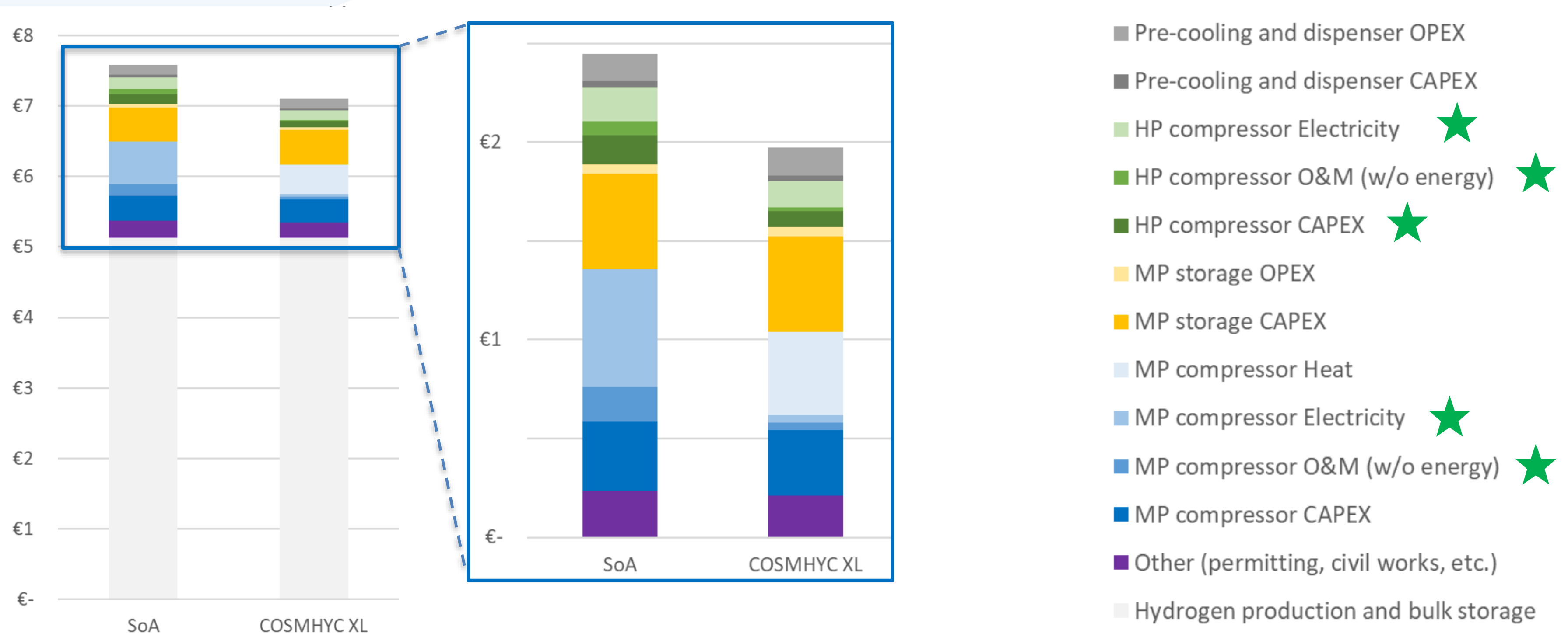
WP 2 Techno-economic evaluation – selected results

70 MPa hydrogen fuel
2 MPa suction pressure

Base case indicates a costs advantage of about 0.5 €/kg compared to pre-project technology data

(base case: **heat @ 0.05 €/kWh**, **electricity @ 0.15 €/kWh**, SoA compression: energy 6 kWh/kg @ 2 MPa input pressure, O&M @ 5% of CAPEX p.a.)



Parameters with cost advantage

SoA: State-of-the-art; prior to the project

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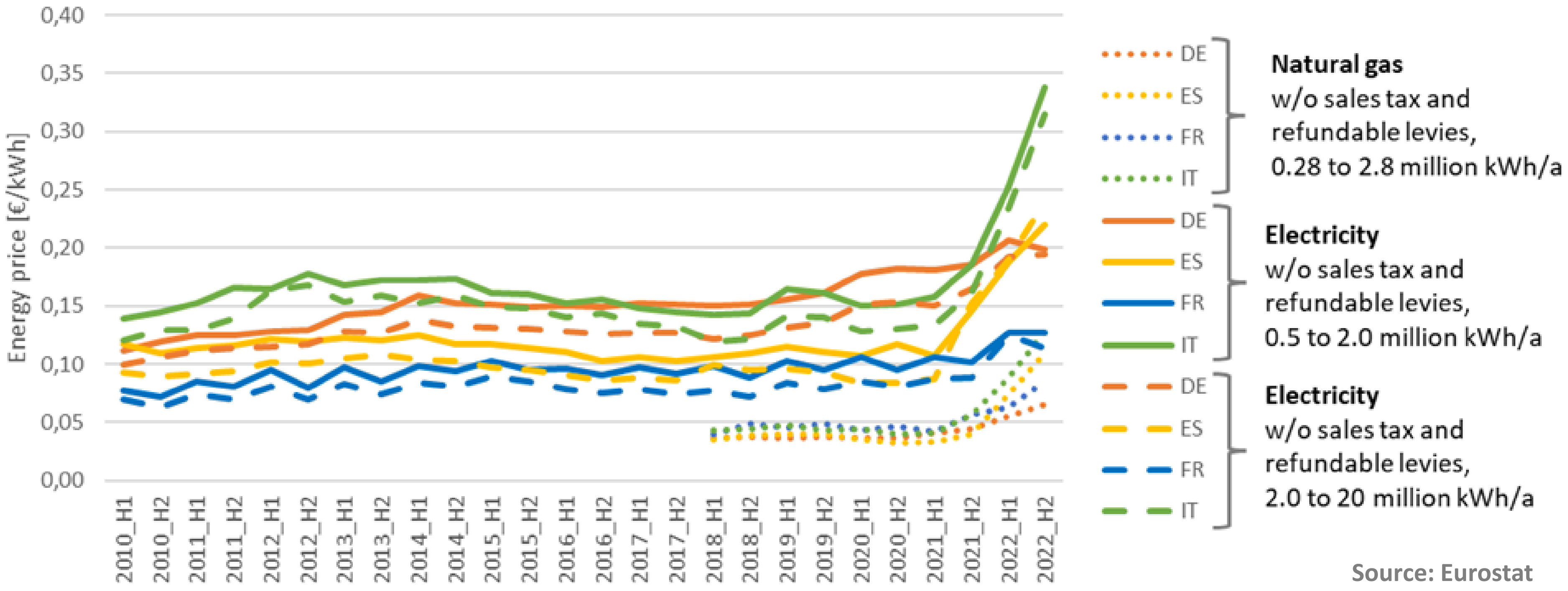
WP 2 Techno-economic evaluation – impact energy prices (1)

70 MPa hydrogen fuel
2 MPa suction pressure

Prices for electricity and heat vary strongly across Europe

(Impact: taxes and levies, energy source, country, applied technology, time of day/year, and others)



Source: Eurostat

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WP 2 Techno-economic evaluation – impact energy prices (2)

70 MPa hydrogen fuel
2 MPa suction pressure

The combination of heat and electricity price/costs is of importance

Conditions with low heat or high electricity prices especially advantageous; however rather average cost levels also economic feasible

		Electricity costs [€/kWh]						
		-	0.05	0.10	0.15	0.20	0.25	0.30
Heat costs [€/kWh]	-	0.3	0.5	0.7	0.9	1.1	1.3	1.5
	0.02	0.2	0.4	0.6	0.8	1.0	1.2	1.4
	0.04	0.0	0.2	0.4	0.6 Base case	0.8	1.0	1.2
	0.06	- 0.1	0.1	0.3	0.5	0.7	0.9	1.1
	0.08	- 0.3	- 0.1	0.1	0.3	0.5	0.7	0.9
	0.10	- 0.4	- 0.2	- 0.0	0.2	0.4	0.6	0.8
	0.12	- 0.5	- 0.3	- 0.1	0.1	0.3	0.5	0.7

Resulting advantage [€/kg] for the COSMHYC XL concept for various energy price combinations

Remark: Standard compression technology has also evolved during the project duration; thus, results might be different when compared to latest/upcoming compression product for which, however, no cost data is publicly available.

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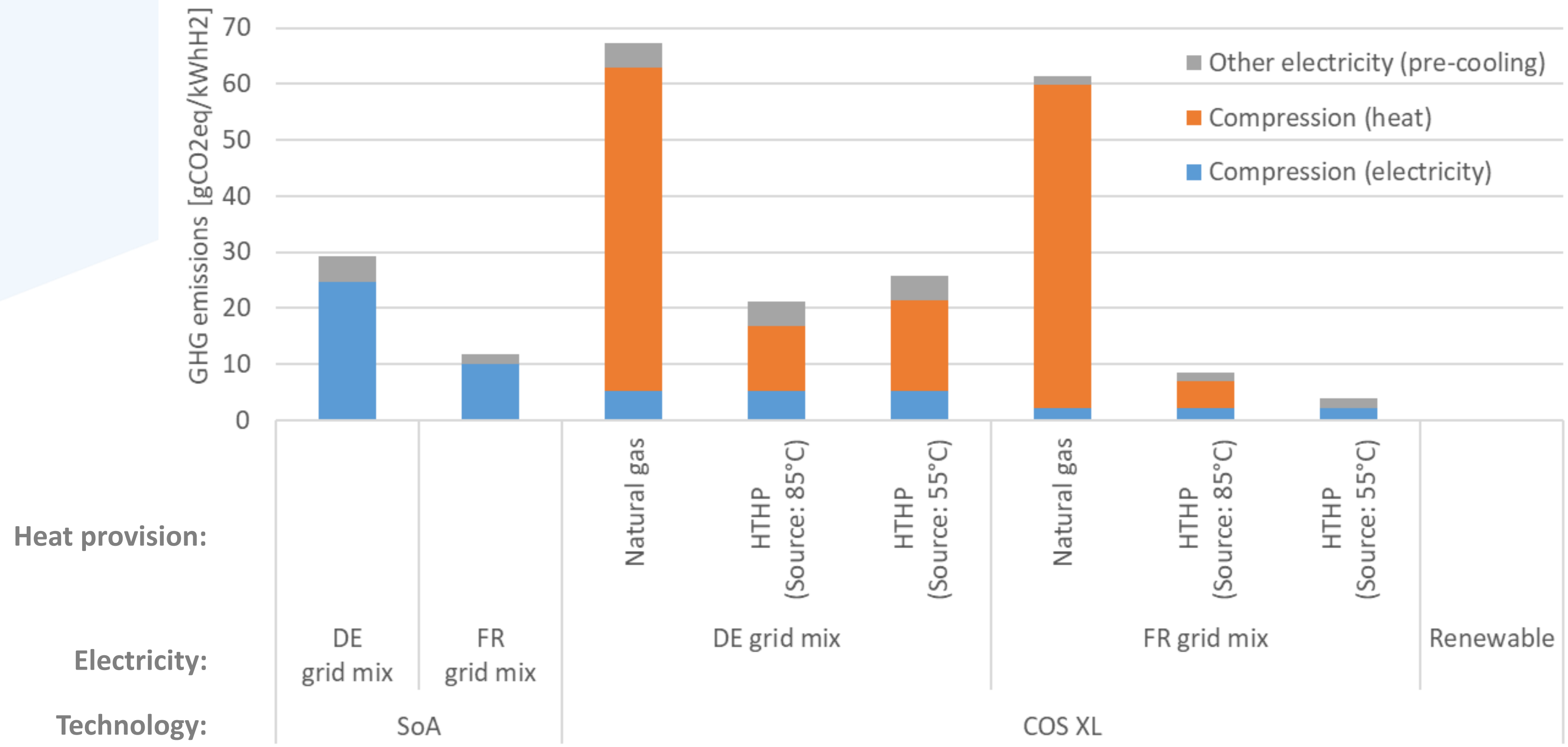
WP 2 Techno-economic evaluation – GHG emissions (preliminary)

70 MPa hydrogen fuel
2 MPa suction pressure

Electricity and especially heat source determine the GHG emissions from the COSMHYC XL concept

Year: 2030



Assumptions:

- Grid mix for the year 2030
- Heat source for HTHP assumed to have no GHG emissions

Results:

- Fossil energy for heat provision not an option
- HTHP can be an option even with grid electricity

HTHP: High-Temperature Heat Pump

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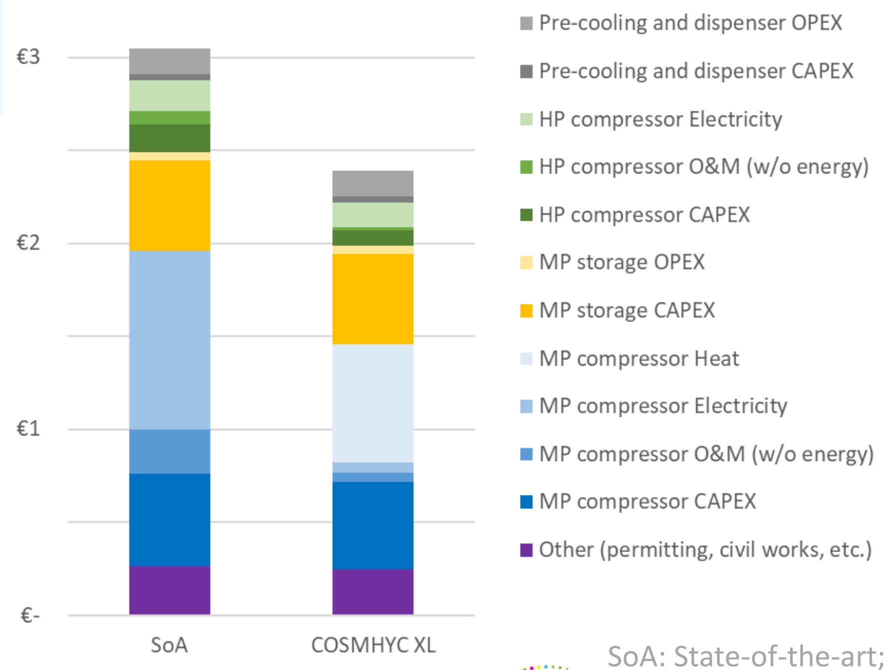
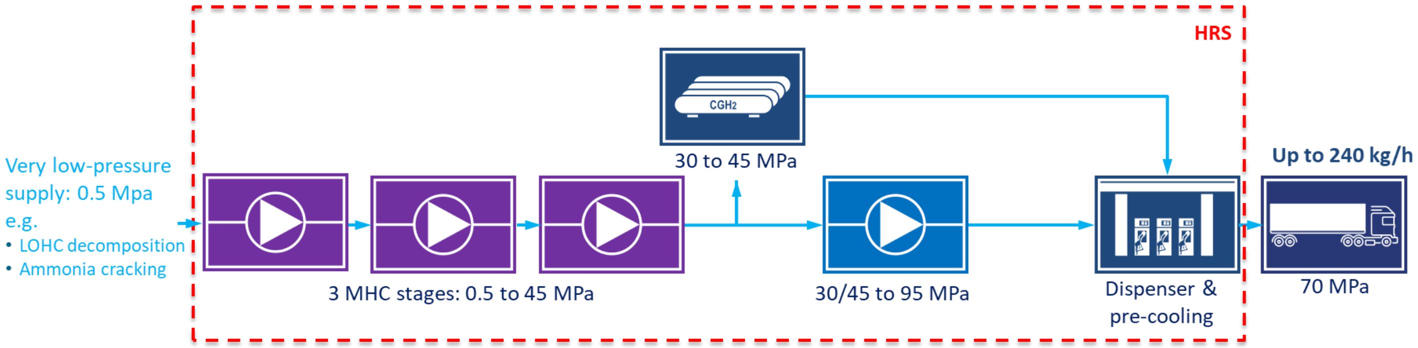
WP 2 Techno-economic evaluation – Very-low pressure supply

70 MPa hydrogen fuel
0.5 MPa suction pressure

Application: 70 MPa refueling of trucks, very-low pressure supply to HRS (e.g. from LOHC)
(0.5 MPa minimum suction pressure from bulk storage, intermediate pressure storage 30 to 45 MPa)





Result:
- Very low hydrogen supply pressure requires one additional metal hydride compression stage
- COSMHYC XL technologies can play out their full advantage
- Compared to 2 MPa supply pressure, costs for compression energy increase less for metal hydride technology

SoA: State-of-the-art; prior to the project

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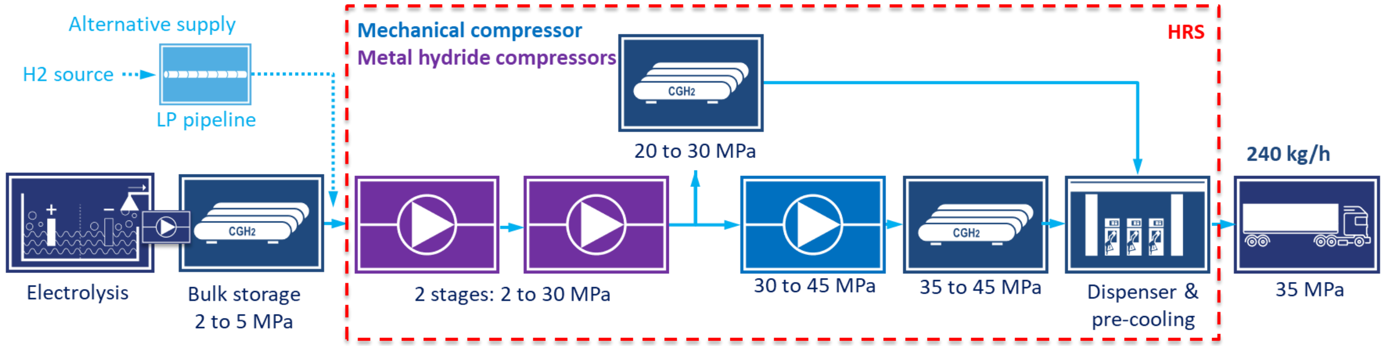
WP 2 Techno-economic evaluation – HRS setup

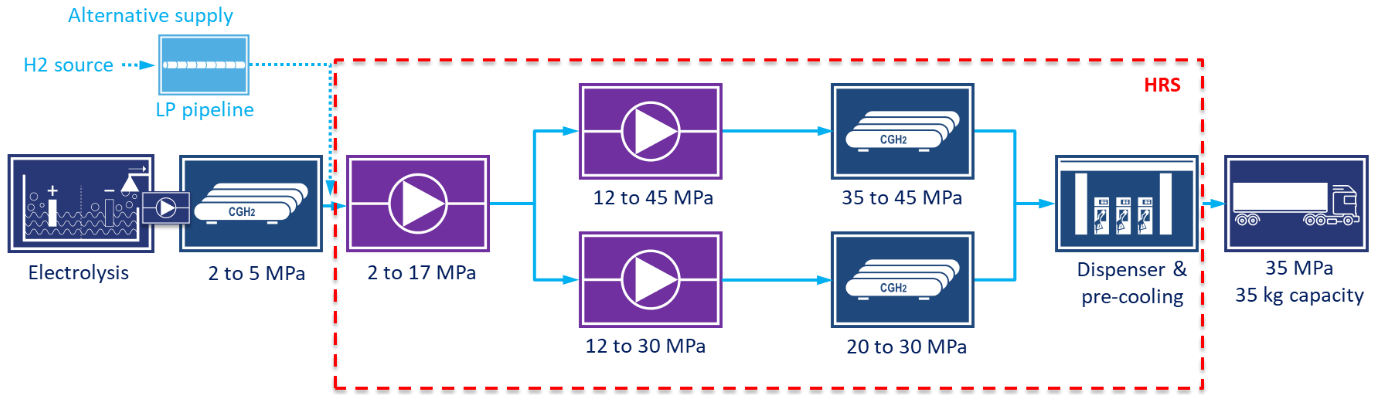
35 MPa hydrogen fuel
2 MPa suction pressure

Application: 35 MPa refueling of trucks, fuel pressure currently being used on the road
(2 MPa minimum suction pressure from bulk storage, pressure storage 30 to 45 MPa)

COSMHYC XL concept adapted to 35 MPa
- Metal hydride compression to 30 MPa
- Mechanic booster to 45 MPa



Refuelling without mechanical compressor
- Metal hydride compression to 30 & 45 MPa
- Requires additional storage capacity to balance continuously running compressor and fluctuating refuelling demand



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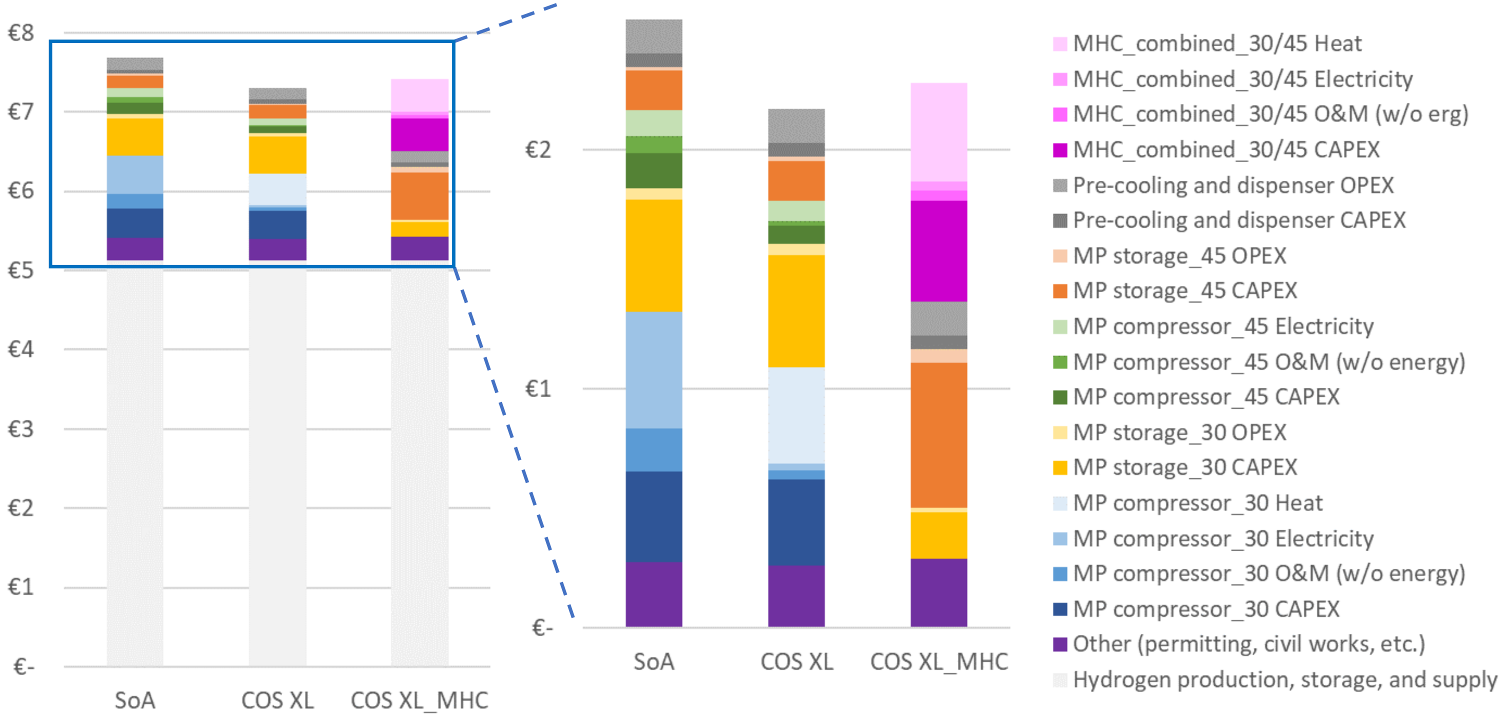
WP 2 Techno-economic evaluation – selected results

35 MPa hydrogen fuel
2 MPa suction pressure

Base case indicates a costs advantage of about 0.4 €/kg compared to pre-project technology data

(base case: **heat @ 0.05 €/kWh**, **electricity @ 0.15 €/kWh**, SoA compression: energy 4.8 kWh/kg @ 2 MPa input pressure, O&M @ 5% of CAPEX p.a.)

- COSMHYC XL advantage also for 35 MPa refuelling applications
- A configuration exclusively using metal hydride compression is a feasible solutions in terms of costs, despite the extra costs for the additional storage (orange)
- Metal hydride compression advantage increases if hydrogen demand is less fluctuating
- COSMHYC XL cost advantage also for HRS which are supplied by high-pressure trailer (e.g. 50 MPa)



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SWOT analysis COSMHYC XL technology

(Status: July 2023)

WP 2 SWOT analysis of COSMHYC XL technology

The SWOT analysis refers to the hybrid compression concept after the COSMHYC and COSMHYC XL projects.

Strength

- Low electricity consumption / increased electrical efficiency - advantageous especially at high electricity prices
- Low maintenance costs anticipated due to low number of moving parts (MHC) and increased durability of MC components
- Low noise from continuously running MHC
- Metal hydride advantageous especially at very low supply pressures
- Rare-earth free metal hydrides

Weaknesses

- Limited operation dynamic for MH compressor vs. variable H2 production and/or demand
- Intolerant to certain hydrogen impurities (e.g. relevant in industrial applications); however, less relevant for fuel grad hydrogen at the HRS

Opportunities

- Advantageous utilization of low-cost heat sources at certain locations/applications
- Economic advantage, especially at very low suctions pressures
- World leading know-how, technology and concept as a basis for new business
- Absorbs impurities instead of passing them on to end-use (e.g. fuel cell applications)
- Scalable capacity (MHC: number of reactors, MC: multi crank concepts)
- Adaptable to different applications and requirements (MHC: 2 or 3 stage config, MC: 2 stage or duplex configuration)
- Flexible in type of heat source
- Compression related GHG emission reduction at HRS feasible, depending on heat source
- Reduction in compression costs if anticipated performance parameters can be achieved in future commercial product
- MHC and MC technology can also be used independently of each other

Threats

- Improvements of competing compression technologies
- Low technology acceptance due to limited (external) knowledge and operating experience of MH compression technology
- Still low TRL for MH compression tech.
- Core technologies from different companies (hydrides, MHC integration, MC)
- Metal hydride and system integration know-how limited to few engineers
- Missing experience MHC series production
- Missing long-term experience in operation (e.g. performance after multiple years)

MH: Metal Hydride; MHC: Metal Hydride Compressor; MC: Mechanical Compressor

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