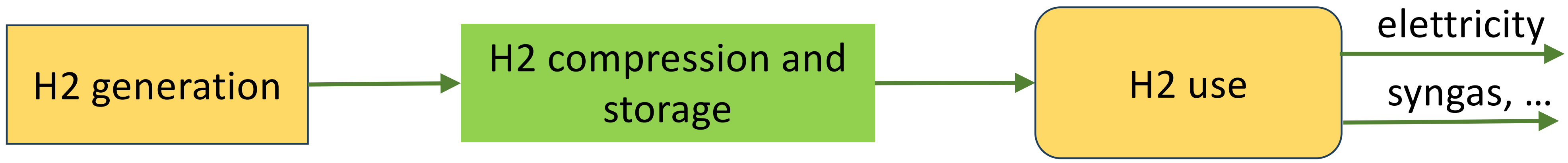
Hydrogen energy storage systems: experiences at the LPG of Veritas (VE)

Massimo Guarnieri

Workshop on Long Duration Energy Storage **PADOVA 28/07/2023**

Hydrogen use process



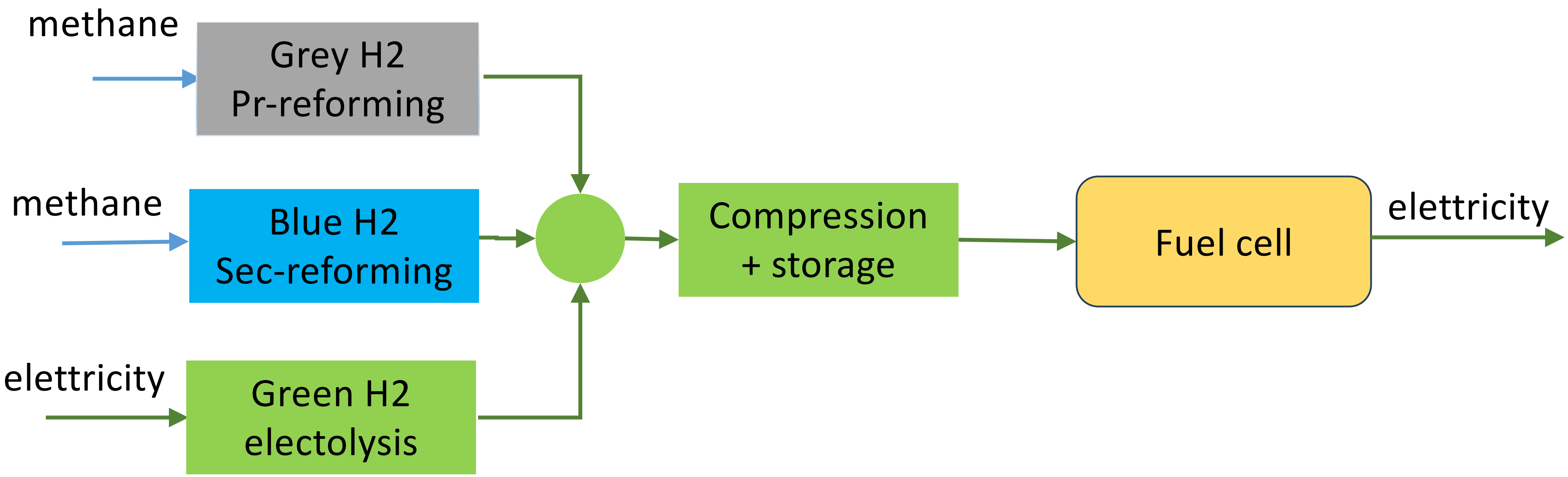
Hydrogen generation

elettricity + water → **Green H2 electolysis** → $H_2 + O_2$ – 11.3 €/kg (BZ)

methane + steam → **Blue H2 Sec-reforming** → $H_2 + CO$ – 1.4-1.9 €/kg

methane + steam → **Grey H2 Pr-reforming** → $H_2 + CO$ – 1.0-1.5 €/kg

Possible processes



Electrolizers

electricity → Green H2 electrolysis → H_2

Alcaline | PEM | AEM | SO

		Alkaline	PEM	AEM	SO
		commercial	early commercial	initial	initial
efficiency	%	60–65	50–60	60-70	70–84
capacity	Nm^3/h	0.25–1000	0.01–240	0.1–1	200
pressure	bar	1–20	1–30	1–20	1–10
temperature	°C	60-220	60-90	30–80	500-850
power	kW	1.8–5300	0.2–1150	0.7–4.5	25–150
H_2 purity	9	2–5	3–6	2	5
Cost	k€/kW	1–1.2	1.9–2.3	–	5.6

PEM = proton exchange membrane
AEM = anion exchange membrane (combines Alka+PEM)
SO = solid oxide

Celle a combustibile

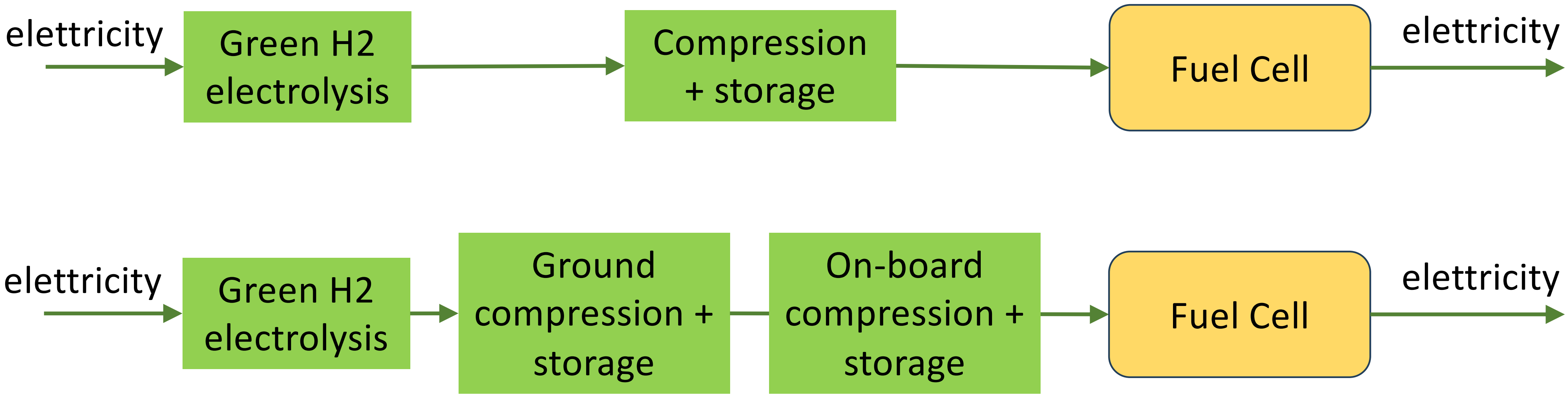
H_2 → Fuel Cell → elettricity

Alkaline | PEM | MC | SO

		Alkaline	PEM	MC	SO
		commercial	commercial	commercial	commercial
efficiency	%	60–65	50–55	50-60	55-65
pressure	Bar	1–20	1–30	1–8	1
temperature	°C	60-220	60-90	600-650	500-1000
power	kW	1.8–5300	1-250	100-10000	10-100000
Cost	k€/kW	1–1.2	1.9–2.3	3	5.6

PEM = proton exchange membrane
MC = molten carbonate
SO = solid oxide

High level synthesis



η_{ELmax} = 60%

η_{FCmax}=53%

→ η_{STO}=31.8%

VERITAS

carbon-free energy services deployment division

GPL: QUASI-ZERO-EMISSION MULTI-TECHNOLOGY TEST PLANT

Funding: MATTM (Italian Ministry for Environment and Land and Sea Protection)

Pilot technologies for de-carbonized generation, storage and use of energy

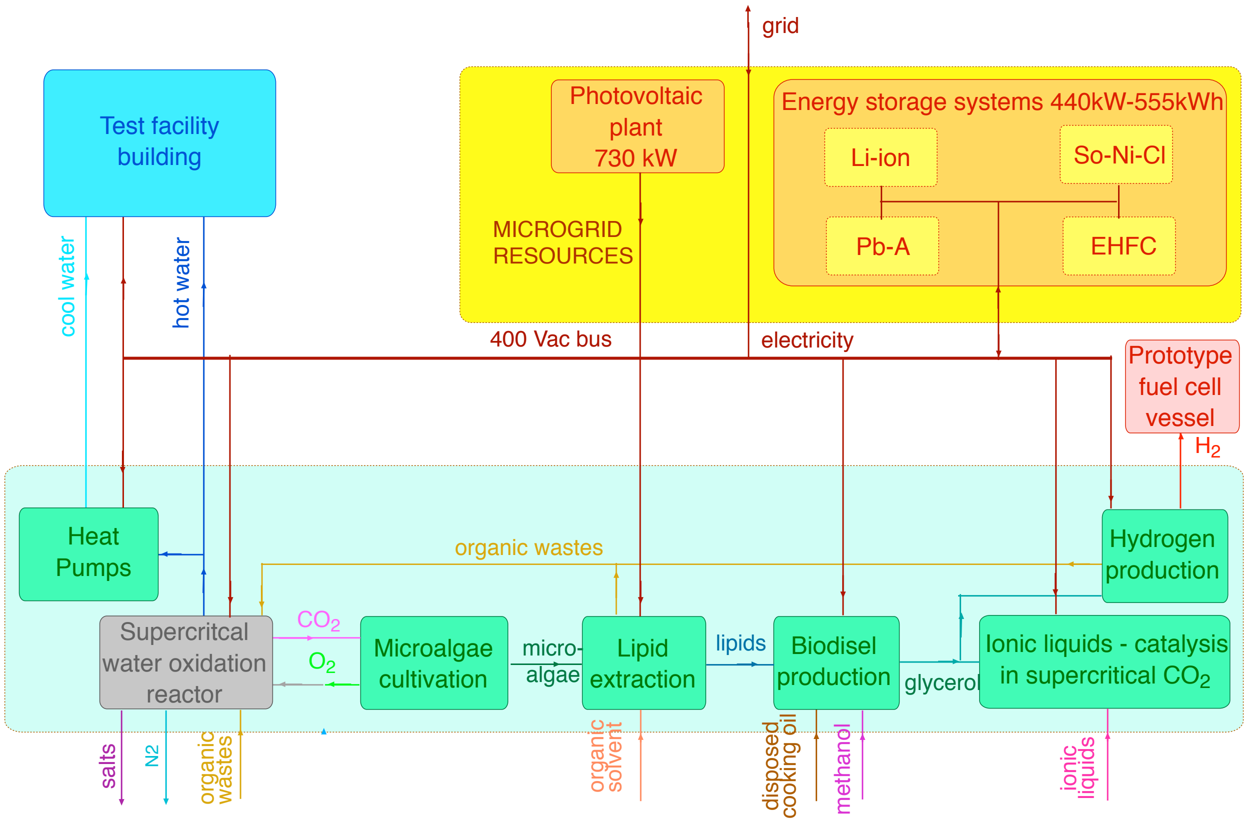
Powered by a **Microgrid**

Near-zero-impact units:

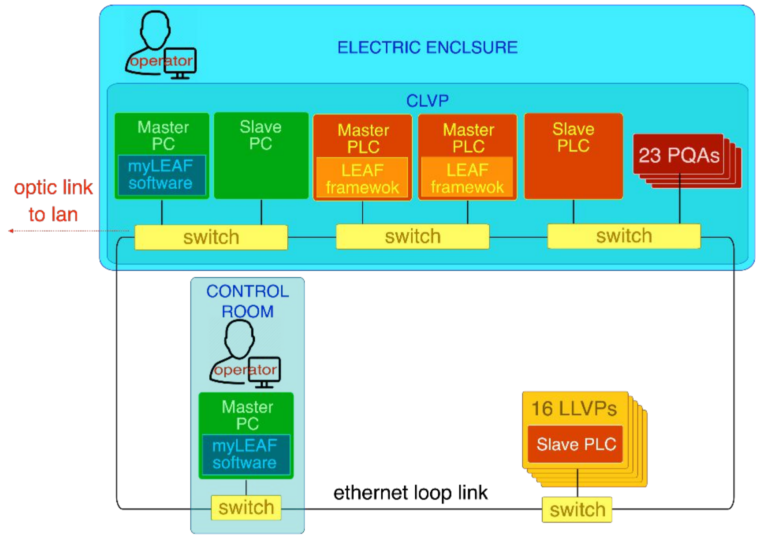
- **1+1 renewable power source (RPS)**
- **4 energy-storage systems (ESSs)**
- **Supervisors: PMS + EMS**
- Bio-additive production by means of nanotechnologies, biotechnologies and superfluids
- Supercritical chemical processes for waste treatment operating at near-zero impact
- Power-to-gas pilot plant converting CO_2 and H_2 in CH_4.
- Prototype hybrid-electric water vessels and road vehicles powered by biofuels produced onsite

M. Guarnieri, et al. "A Real Multitechnology Microgrid in Venice: A Design Review," *IEEE Ind Electron Mag*, 12 (3), (2018): 19-31.

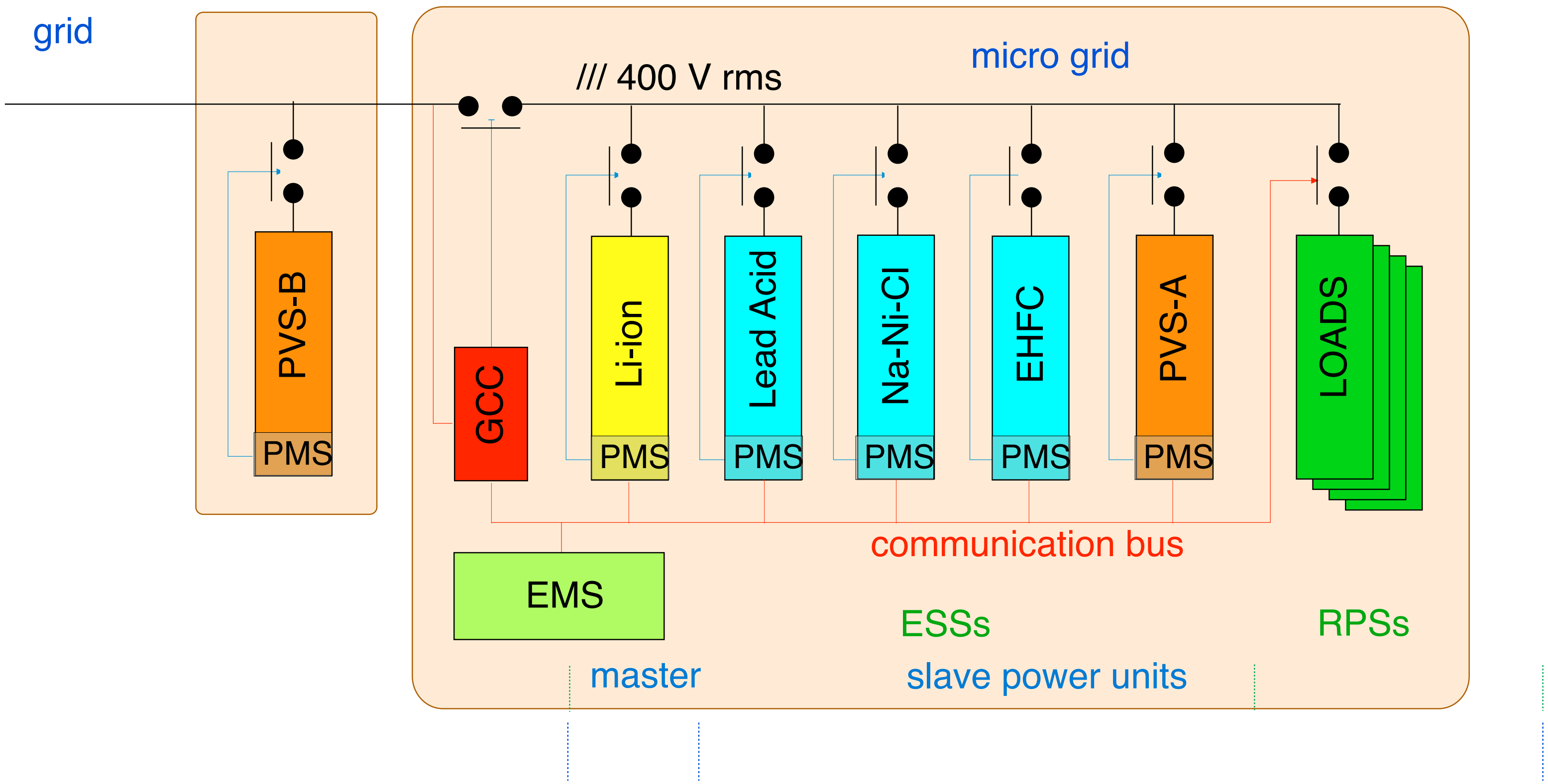
GPL scheme



Control room



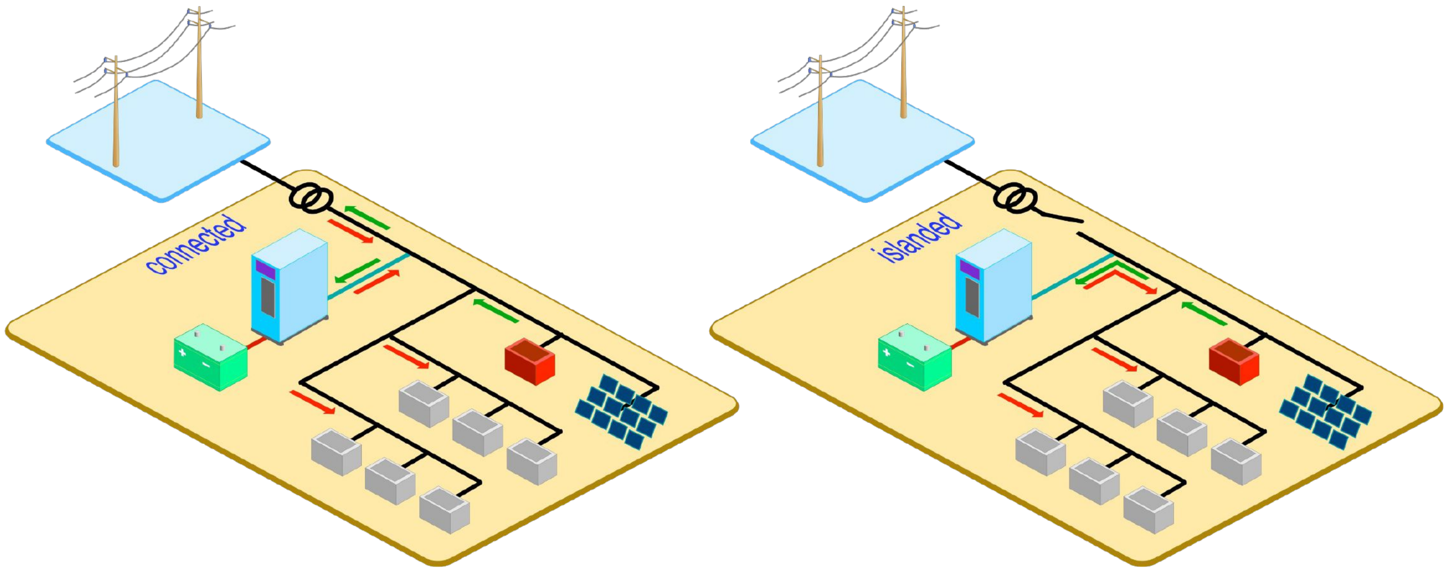
GPL Microgrid



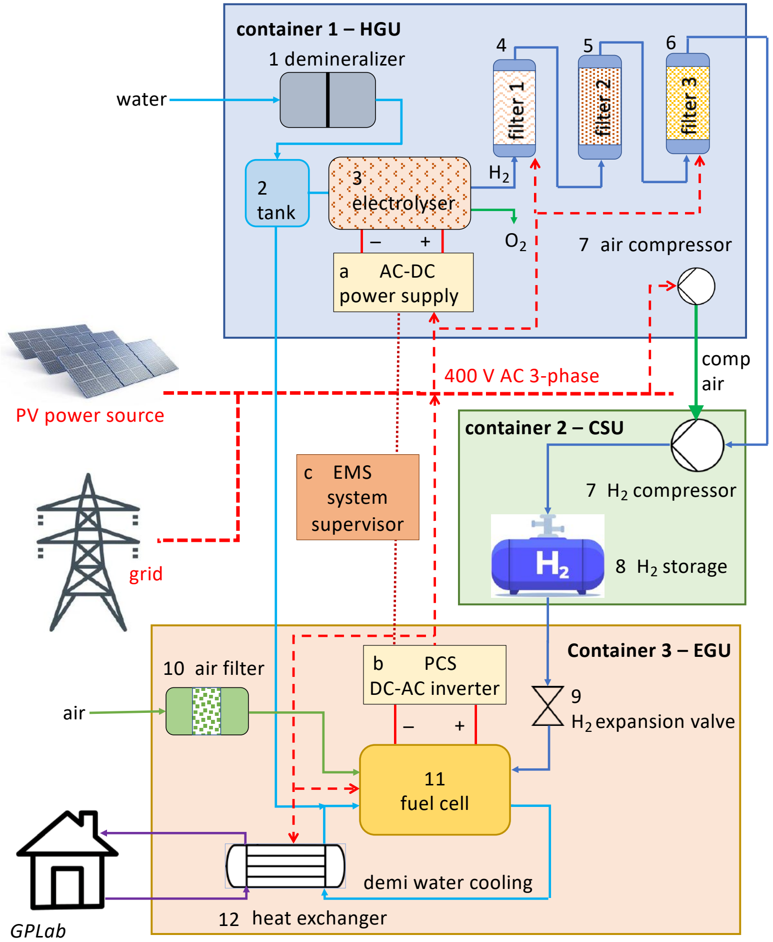
Operation: connected / islanded

Included services

- power quality
- black start
- low-voltage-ridethrough
- optimized power flow
- …



H2-EES: EHFC



c) container 1:
hydrogen generation unit

d) container 2:
compression and storage unit

e) container 3:
electric generation unit

H2-EES : EHFC

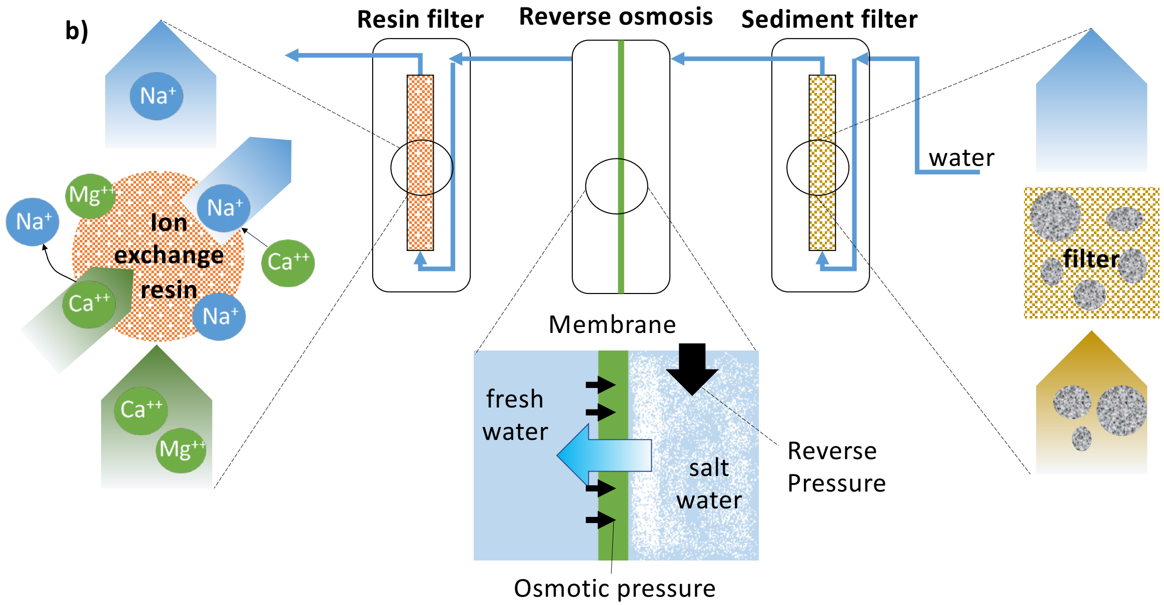
- Container 1
  - 23.3-kW alkaline electrolyzer: H2 generation 4 Nm^3/h di H_2 (e 2 Nm^3/h di O_2) @ 12 bar with power supply (PS) + water demineralizing + H2 purifier
- Container 2
  - H2 compression @ 220 bar + storage cylinders
- Container 3
  - 30-kW proton exchange membrane fuel cell (PEMFC): electricity generation + power conditioning system (PCS) interconnected to the microgrid

A. Bovo, M. Guarnieri, et al., "Hydrogen Energy Storage System in a Multi–Technology Microgrid: technical features and performance", *Int. J. Hydrogen En.*, 48 (2023): pp. 12072–12088.

EHFC: container 1

H_2O demineralization in 3 steps for EL protection

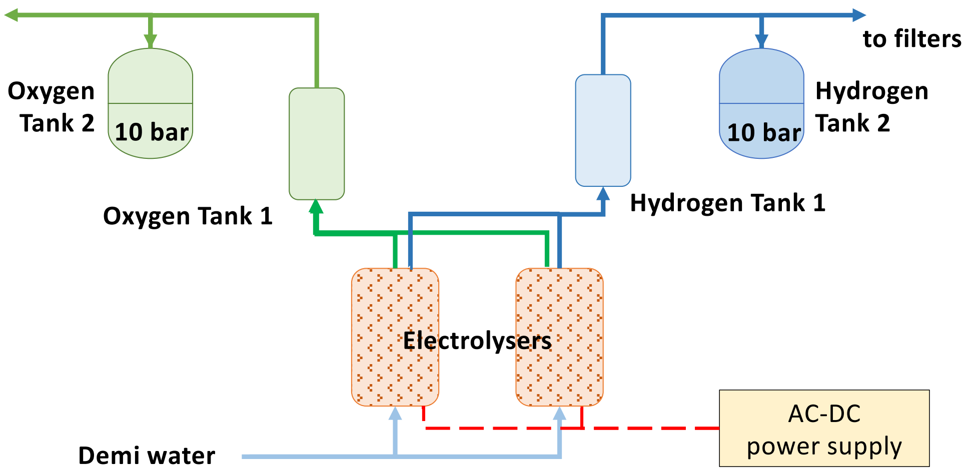
- Filter against particle sediments up to 10 µm
- Reverse osmosis against dissolved species
- Ionic exchange filter against aggressive ions

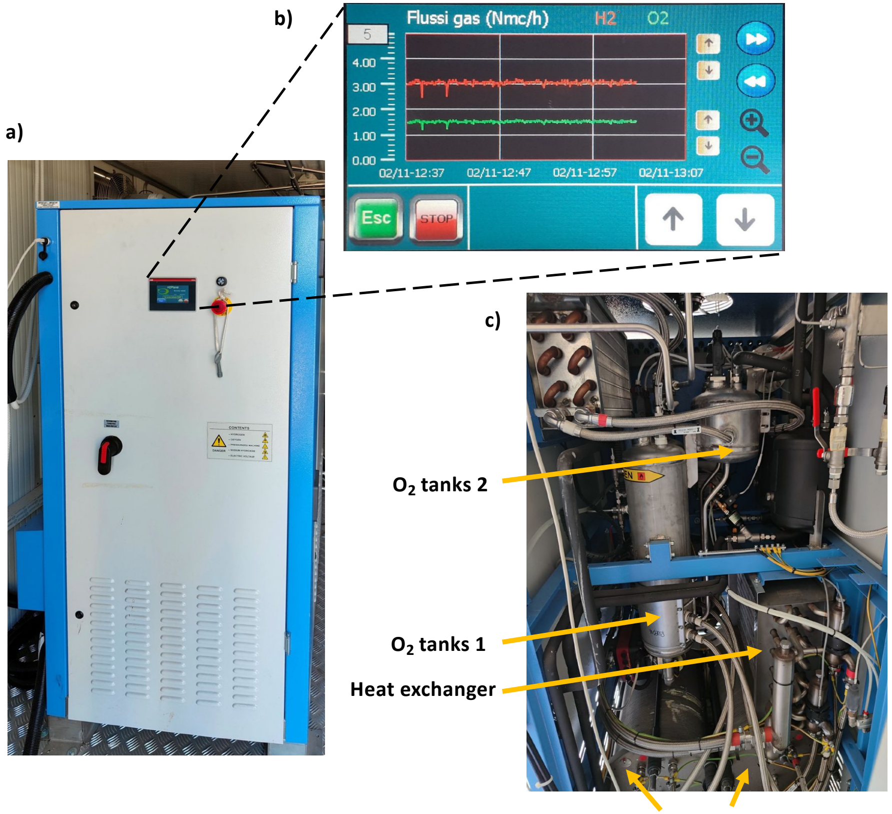


EHFC: container 1

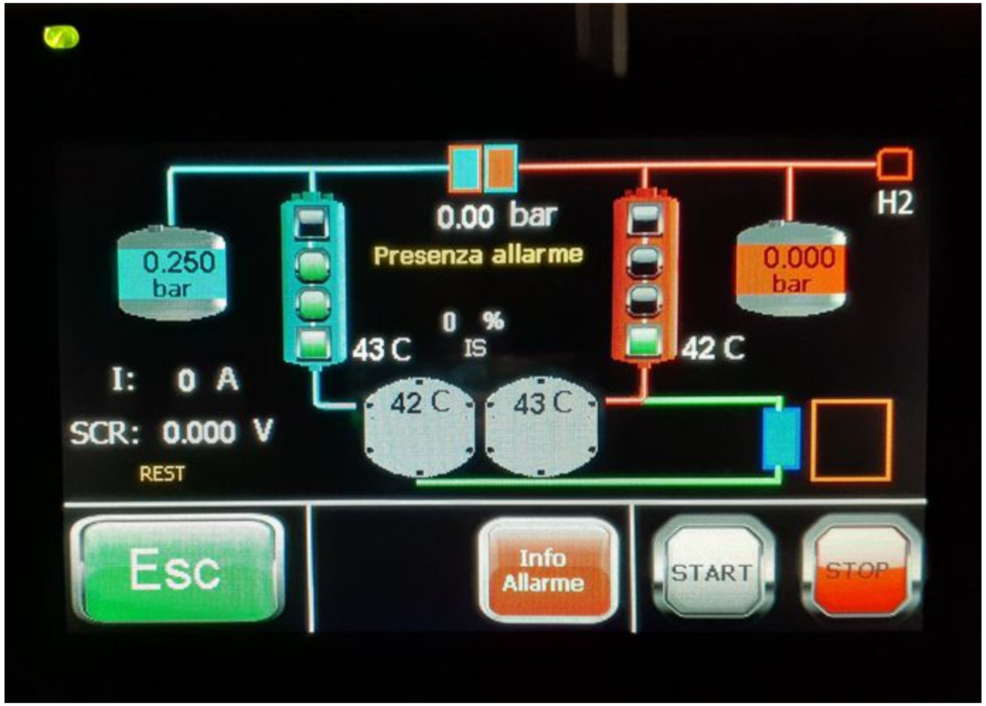
Alkaline electrolyser

- 23.3-kW G6 by ErreDue: 4 Nm^3/h di H_2 (+ 2 Nm^3/h di O2) @ 12 bar η_{EL} = 60%
- AC-DC power supply (PS, η_{ELU} = 54%)
- closet: 2 electrolysers + heat exchanger (refreshing)
  + 2 oxygen tanks (temporary),
  + 2 hydrogen tanks @ P=10 bar





Electrolyzer control panel

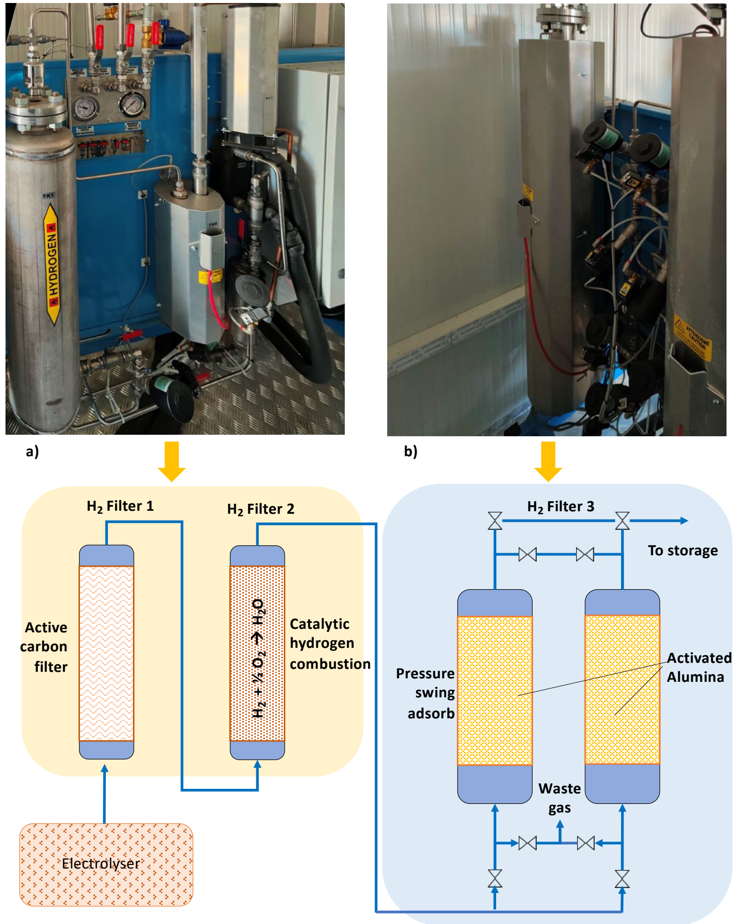


EHFC: container 1

H_2 purifier in 3 steps

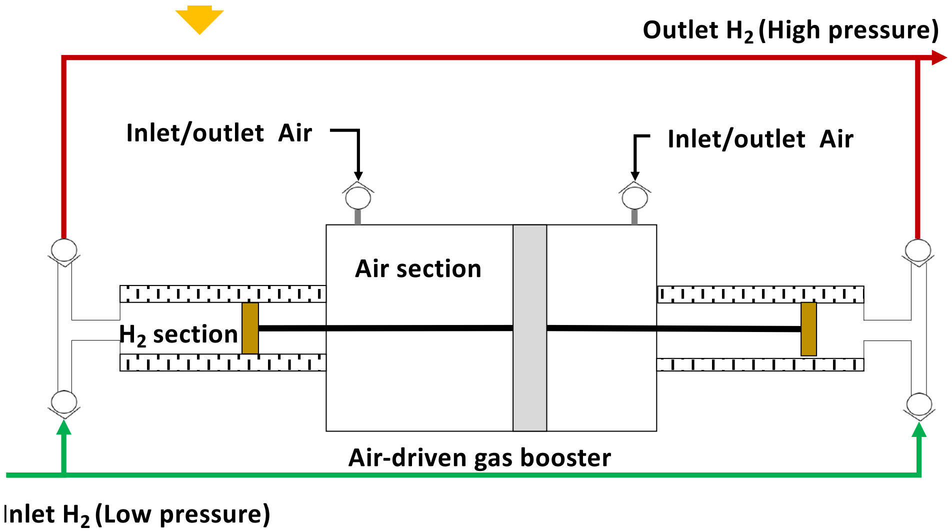
- active carbon filter
- catalytic combustion reactor – fed with 8% of H2 (Eliminates any traces of other gases, e.g. oxygen); gas refrigerator at ca 5 ° C
- 2 activated alumina adsorption columns (eliminates water traces); dew point –70 ° C

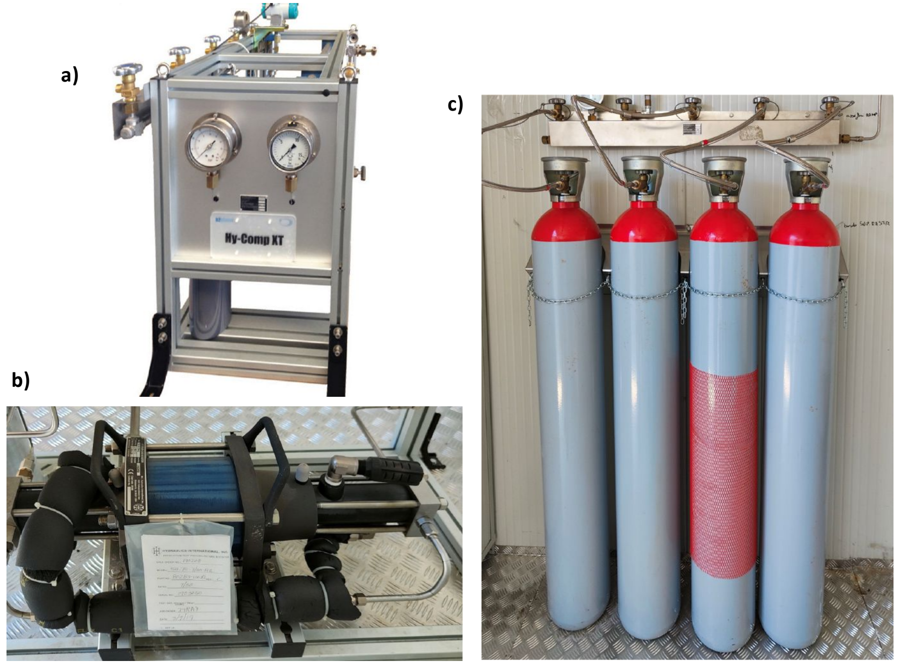
→ Hydrogen purification 99.5% → 99.9998%



Container 2: Compression + storage

- Hy-Comp XT HP compression system @ 220 bar
- PLC flow control up to 4 Nm^3/h
- Piston compressor to avoid gas contamination
- 4 50-L cylinders storing 34 Nm^3 @ 220 bar



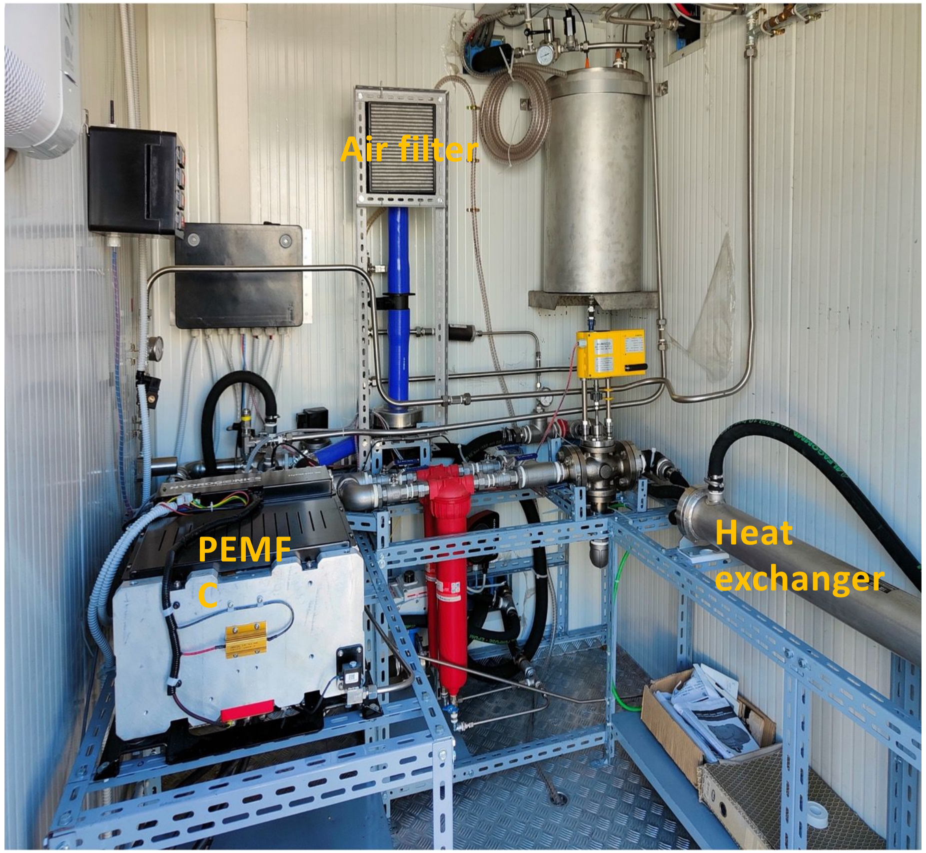


Pressure [bar]	10	50	100	150	200	220
Quantity [Nm^3]	1.86	9.08	17.62	25.66	33.22	36.11

Container 3: PEMFC

- 30 kW HyPM®HD30 PEMFC by Hydrogenics + brackish air filter
  efficiency: η_{FC9} = 53% – η_{FC30} = 37.7%

- Entropic heat exchanger
  (partial heat recovery for air conditioning)



Container 3: PCS – Power Conditioning System

31.5 kW DC-AC step-up inverter da 60-120 V_{DC} a 400 V_{AC} trifase

- efficienza: η_{PCS11} = 89.3% – $\eta_{PCS31.5}$=84.1%

Technical standards

Directive 2014-94-UE

DM 16/02/82 (H_2)

DM 24/11/84 (H_2)

DM 31/08/06 (H_2)

CEI 016 - MV (grid interface)

IEC / EN 62040 – Inverter (PCS)

CE 79-2009 (H2 vehicles)

H2-ESS control: Energy Management System - EMS

Storage > Idrogeno

Last 6 hours | 30s

Idrogeno energia

Search:

Time	Energia in	Energia out	Energia aux
2020-09-03 16:35:00	1.142 MWh	54.0 Wh	1.296 kWh
2020-09-03 16:30:00	1.142 MWh	54.0 Wh	1.296 kWh
2020-09-03 16:25:00	1.141 MWh	54.0 Wh	1.296 kWh
2020-09-03 16:20:00	1.141 MWh	54.0 Wh	1.296 kWh
2020-09-03 16:15:00	1.141 MWh	54.0 Wh	1.296 kWh

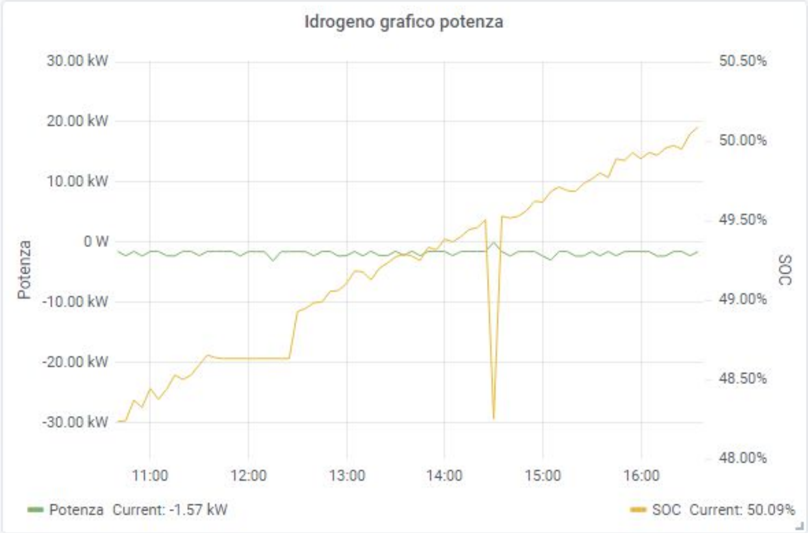
Showing 1 to 5 of 72 entries Previous 1 2 3 4 5 ... 15 Next

Idrogeno

Search:

Time	SOC	Potenza	Pot invert
2020-09-03 16:35:00	50.09%	-1.57 kW	0 kW
2020-09-03 16:30:00	50.05%	-2.24 kW	0 kW
2020-09-03 16:25:00	49.95%	-1.53 kW	0 kW
2020-09-03 16:20:00	49.97%	-1.54 kW	0 kW
2020-09-03 16:15:00	49.96%	-2.28 kW	0 kW

Showing 1 to 5 of 72 entries Previous 1 2 3 4 5 ... 15 Next



Potenza inverter

0 kW

SOC

Real efficiency: Container 1

Item	Unit	Nominal values	Experimental Full power	Experimental Half power
Hydrogen Generation Unit – HGU				
H_2 flow rate	$Nm^3\,h^{-1}$	4.00	3.32	2
H_2 energy flow rate	kW	12.0	9.94	6.00
ELU consumed power	kW	22.30	18.43	11.60
η_{ELU}: ELU efficiency	%	54.00	54.0	51.6
Duration of charging operation	h	9.02	10.9	18.1
Gross generated hydrogen volume	Nm^3	36.11	36.11	36.11
Gross generated hydrogen energy	kWh	108.1	108.1	108.1
Net generated hydrogen volume	Nm^3	33.22	33.22	33.22
Net generated hydrogen energy	kWh	99.49	99.49	99.49
ELU consumed energy	kWh	201.3	200.4	209.4
H_2 purifier and chiller consumed energy	kWh	24.35	29.37	48.75
HGU auxiliary devices energy	kWh	3.34	4.02	6.68
η_{ADD1}: ADD1 efficiency	%	80.5	78.9	72.7
η_{HGU}: HGU efficiency	%	43.4	42.6	37.6

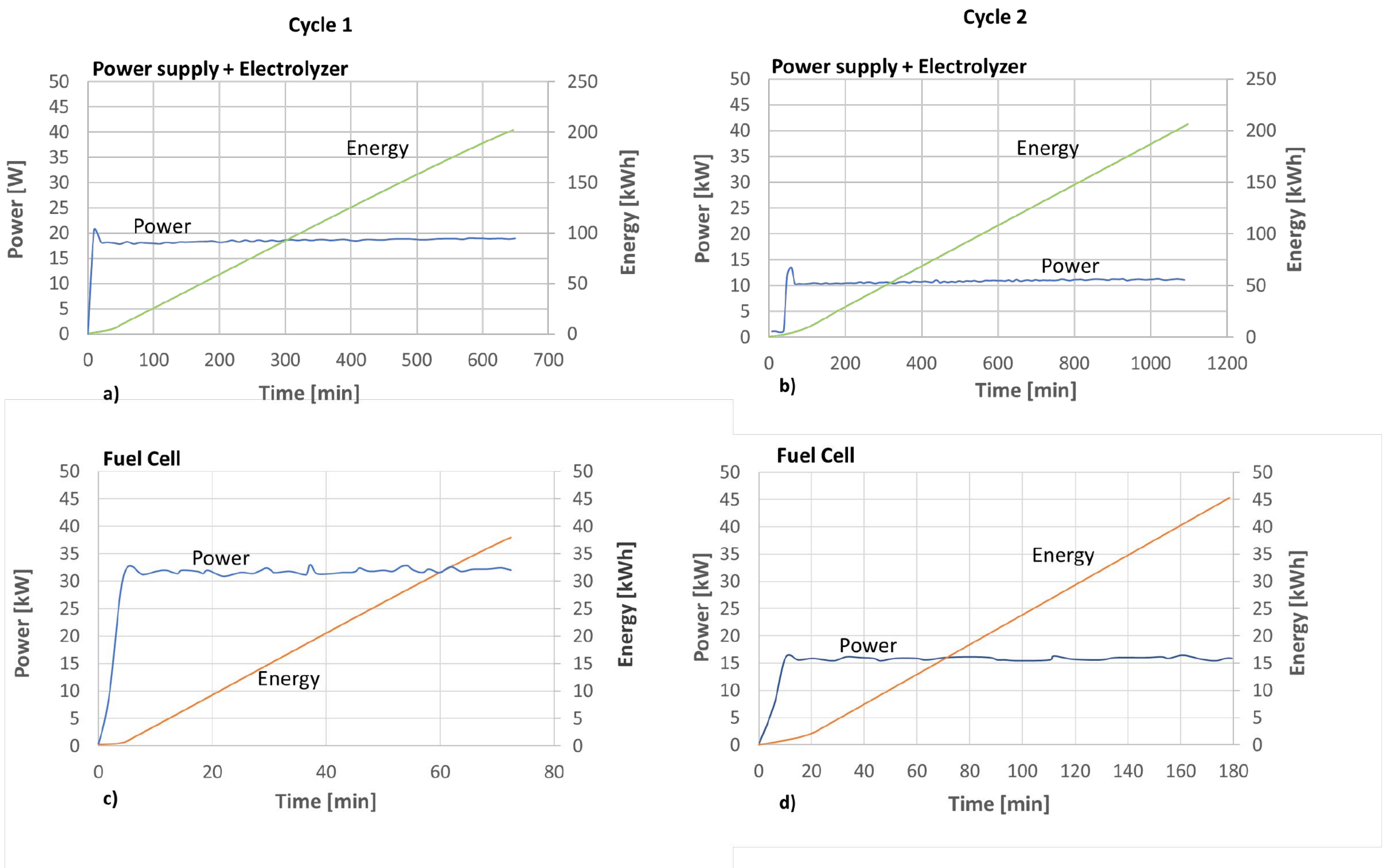
Real efficiency: Container 2

Item	Unit	Nominal values	Experimental Full power	Experimental Half power
Compression and Storage Unit – CSU				
Compressor H_2 flow rate	$Nm^3\ h^{-1}$	3.1	3.1	1.84
H_2 compression consumed energy	kWh	60.28	56.36	100.2
CSU auxiliary devices energy	kWh	3.34	4.02	6.66
Compressed hydrogen volume	Nm^3	33.22	33.22	33.22
Compressed hydrogen energy	kWh	99.49	99.49	99.49
η_{Comp}: Compression efficiency	%	79.3	91.5	81.3
η_{ADD2}: ADD2 efficiency deviation	%	98.7	86.5	87.6
η_{CSU} – CSU efficiency	%	78.3	79.5	71.2
η_{STO} – STO efficiency	%	34.0	33.8	25.2

Real efficiency: Container 3

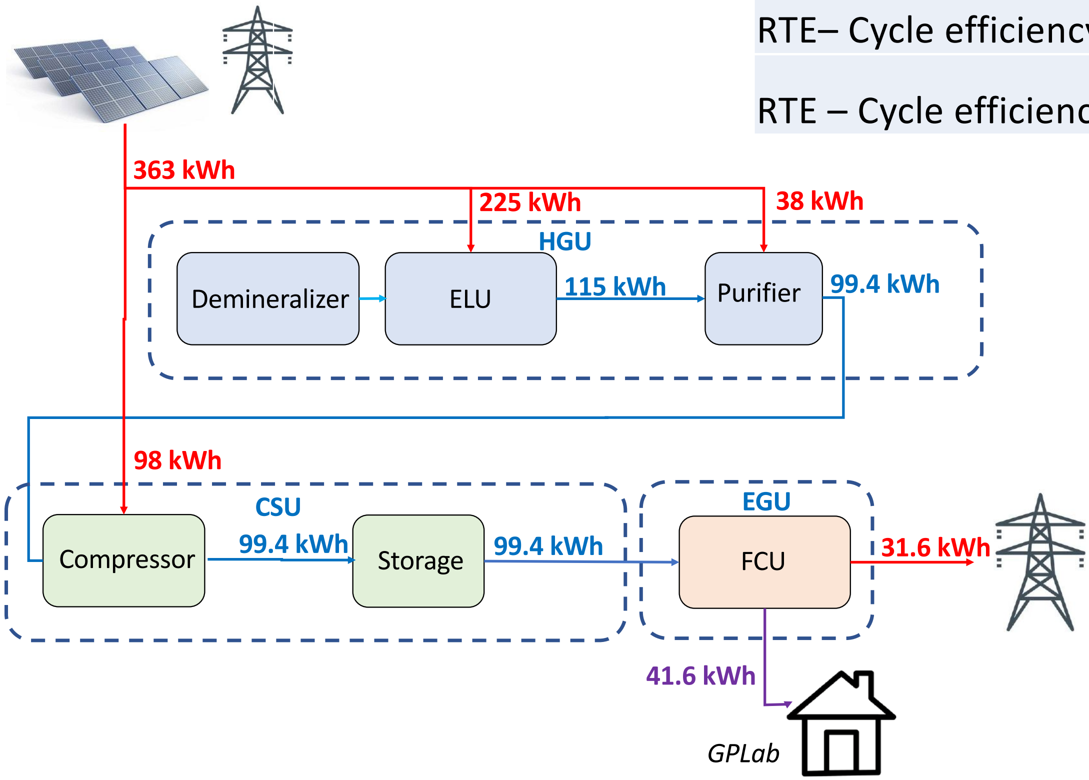
Item	Unit	Nominal values	Experimental Full power	Experimental Half power
Electric Generation Unit – EGU				
Supplied hydrogen energy	kWh	99.49	99.49	99.49
PEMFC net generated electric power	kW	31.50	31.00	15.22
η_{FC} – FC electric efficiency	%	37.2	38.0	45.5
Duration of discharging operation	h	1.18	1.22	2.97
PEMFC generated electric energy	kWh	37.06	37.82	45.23
η_{PCS} –Inverter efficiency	%	84.1	85.0	89.9
η_{FCU} – FCU efficiency	%	31.3	32.3	40.9
FCU generated electric energy	kWh	31.16	32.14	40.66
PEMFC generated useful thermal power	kW	35.6	33.3	11.6
PEMFC generated useful thermal energy	kWh	41.83	40.63	34.55
EGU auxiliary devices energy	kWh	1.25	1.28	3.12
η_{ADD2}: ADD3 efficiency	%	96.0	96.0	92.3
η_{EGU}: EGU efficiency – electric mode	%	30.1	31,0	37.7
η_{EGU}: EGU efficiency – CHP mode	%	72.1	71.9	72.6

Real overall efficiency: RTE

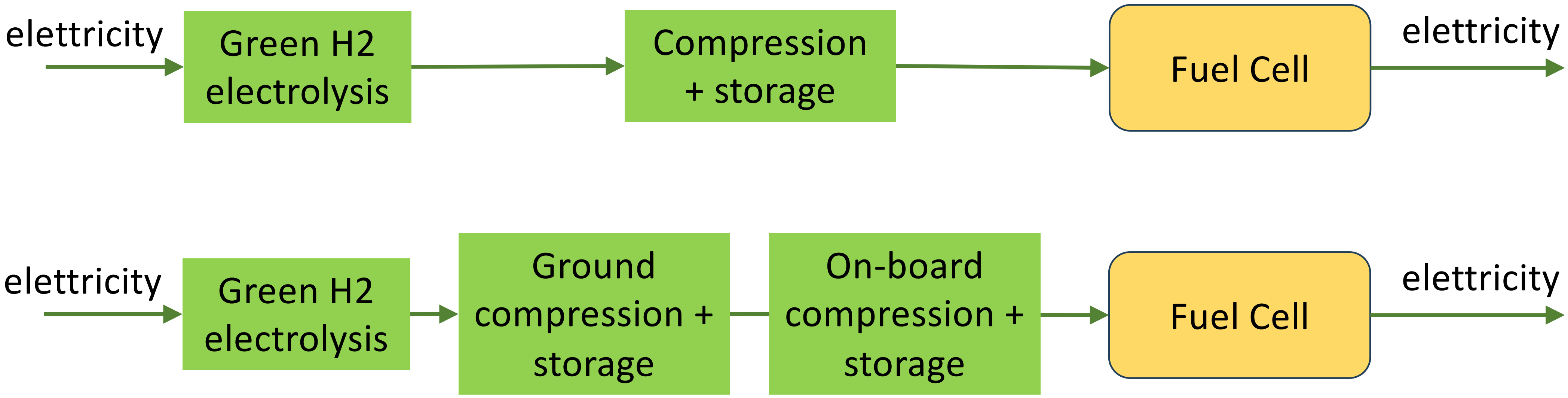


Real overall efficiency: RTE

	Unit	Nominal values	Exp. 100% power	Exp. 50% power
HESS-RTE				
RTE– Cycle efficiency (electric)	%	10.2	10.5	9.5
RTE – Cycle efficiency (CHP)	%	24.5	24.3	18.3



High level synthesis



η_{ELmax} = 60%

η_{FCmax}=53%

→ η_{STO}=31.8%

Conclusions

ELHFC EES

- Interesting features unavailable in other ESSs: power/energy decoupling, quasi-zero self-discharge rate:
  - long-term storage (LDES)
  - CHP, mobility H2 production
- low cyclical efficiency – RTE – proved
  - loses > 90% of supplied energy
- Suitable for specific applications
- A lot of development still needed to achieve real competitiveness with other systems

Thanks for your attention

massimo.guarnieri@unipd.it

Coradia iLint
Fuel cell & H_2 train

→ Producer
→ **Alstom (F / D)**
2 x 390kW
140 km/h, 130 seats

Regional transportation
2018: in service (D, DK, NL, CAN, …)

Competitiveness
vs Diesel trains
(emissions, efficiency, noise, …)
vs pure electric & electrical lines?
(to be assessed: line extension, number of of trains, on board generators, **H_2 production/supply**, …)

BEV-FCEV: Two zero-emission competing concepts

BEV:
Tesla Model 3
- 307 kW
- 82 kWh
- 568 km
- 250 km/h
- 0-100 km/h 3,7 s
- 48 k€
- recharging time: 27 h @ 3 kW
  41 min @ 120 kW

FCEV:
Toyota Mirai
- 136 kW
- H2: 122.4 L @ 70 Mpa, 5.0 kg
- 528 km
- 178 km/h
- 0-100 km/h 9.6 s
- 49 k€
- refuelling time: < 5 mins

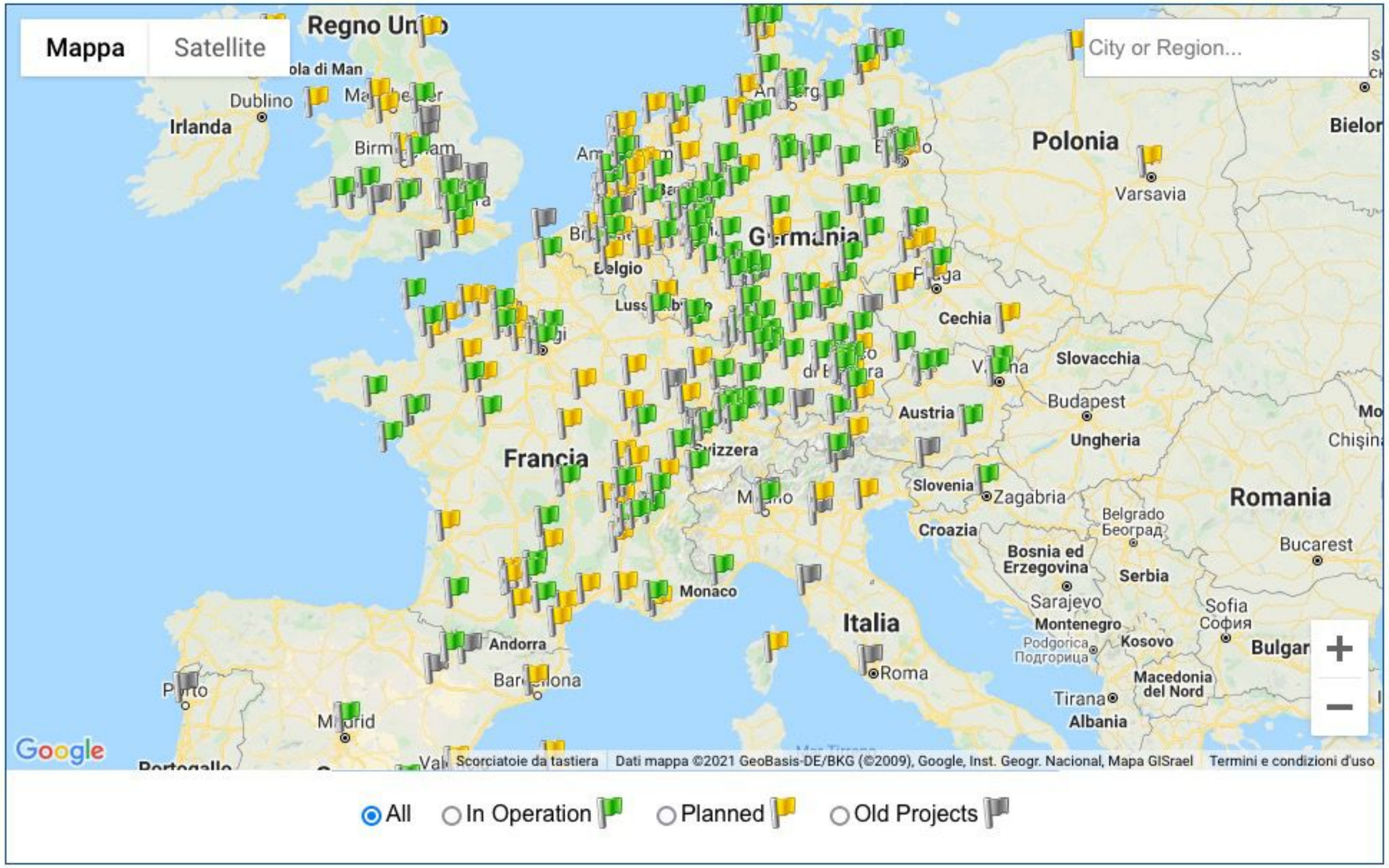
n.b.: gasoline/diesel refuelling power = 15-20 MW

- Toyota Mirai
- H_2 tank = 5 kg
- Range = 528 km

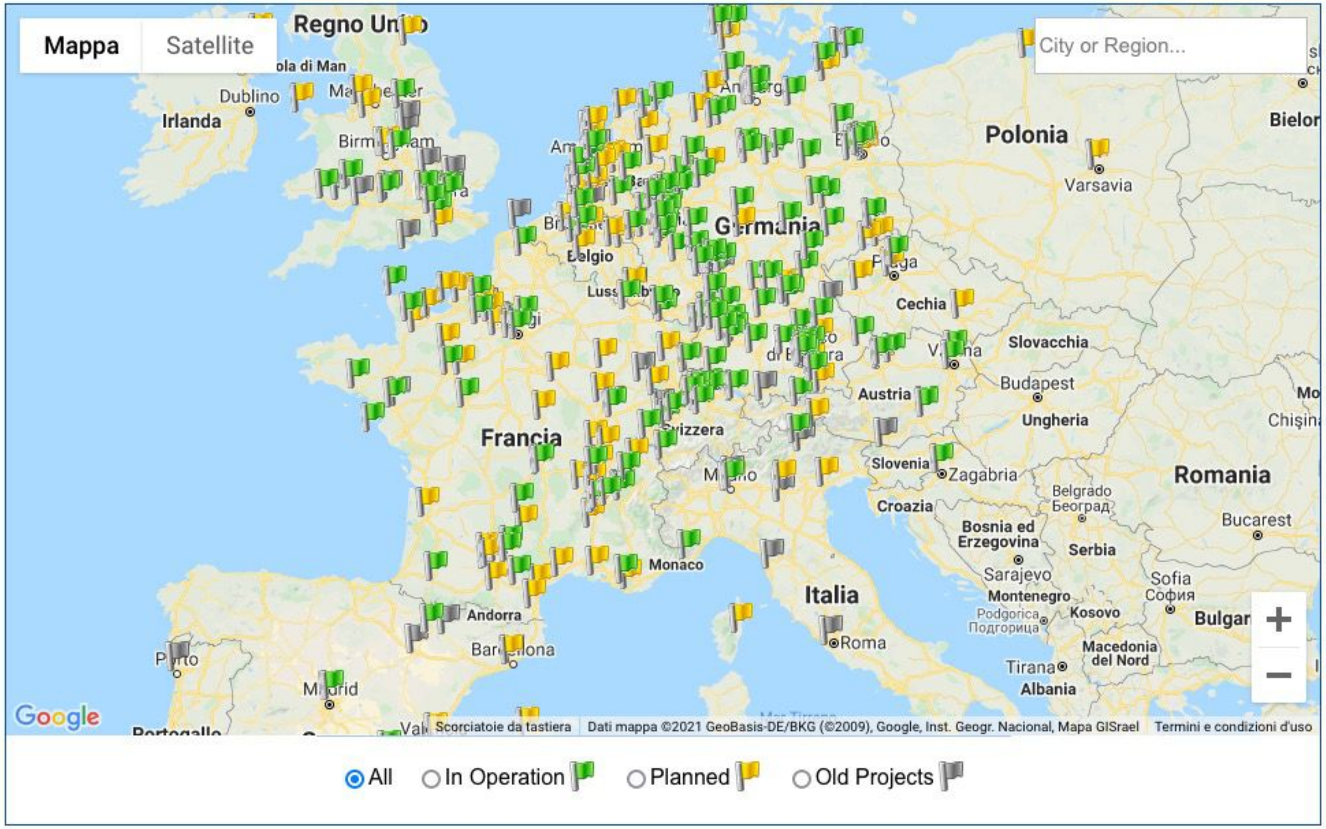
- Specific range = 105 km/kg
- Fuel price = 11.3 €/kg (BZ)
- Cost range= 9.3 km/€
- H2 energy = 33 kWh/kg

H2Stations.org

June 2021 – Refueling infrastructure



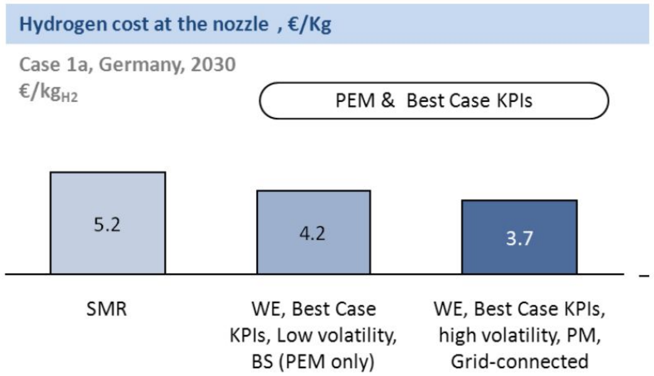
July 2023 – Refueling infrastructure



https://www.h2stations.org/stations-map/?lat=49.139384&lng=11.190114&zoom=2

Refueling infrastructure - HRS

- Methane reforming
- RES supply + **electrolyzer**
- mid pressure + compressor
- 0.5 – 1 M€ each



		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm^3_{H2}/h	0.25 – 760	0.01 – 240	0.1 – 1
	kW	1.8 – 5,300	0.2 - 1,150	0.7 – 4.5
Hydrogen purity [6]		99.5% – 99.9998%	99.9% – 99.9999%	99.4%
Indicative system cost	€/kW	1,000-1,200	1,900 – 2,300	N/A

PEM = proton exchange membrane
AEM = anion exchange membrane

Refueling infrastructure – HRS

Comparison H2 - Gasoline - Diesel fuel – Futuristic pictures

		H2 (1 bar)	H2 (690 bar)	Gasoline	Gasoline DI	Diesel Fuel TDI
specific energy	MJ/kg	141.86	141.86	46.4	46.4	45.6
energy density	MJ/L	0.01005	4.5	34.2	34.2	38.6
density	kg/L	7.08E-05	3.17E-02	0.74	0.74	0.85
price	€/L			1.57	1.57	1.49
price	€/kg	4.95*	4.95*	2.13	2.13	1.76
fuel energy price	c€/MJ	3.49	3.49	4.59	4.59	3.86
powerdrive efficiency at the wheel	%	60%*	60%*	26%	34%	45%
wheel energy price	c€/MJ	5.82	5.82	17.66	13.50	8.58

* cost: optimistic future target - at present: 13.7 €/kg

**efficiencies: optimistic future – targets: at present 35-40%