# EERA

## EUROPEAN ENERGY RESEARCH ALLIANCE

## Joint Research Programme on Fuel Cells and Hydrogen technologies (JP FCH)

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## HYDROGEN EUROPE RESEARCH (HER)

## Research Grouping of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

# KEY PERFORMANCE INDICATORS (KPIs) FOR FCH RESEARCH AND INNOVATION, 2020 - 2030

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# Contents

# Introduction

The EERA Joint Programme on Fuel Cells and Hydrogen (JP FCH), in collaboration with Hydrogen Europe Research, aims to provide the community of technology developers and relevant policy makers with useful instruments to manage the successful entry into market of fuel cell and hydrogen (FCH) solutions and their full-scale penetration into energy and transport infrastructures. To this effect, it is necessary to establish key performance indicators (KPIs) that mark the progress of FCH technologies along the technology and market readiness scales. The need being felt that Europe should refer to indicators that are defined by its own establishment of experts – considered to be leaders in the field – has prompted the writers of this Implementation Plan to work on and provide a set of research and development KPIs that complement and redefine those currently mainly covered by the USA Department of Energy (https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_myrdd_fuel_cells.pdf) or in Japan (https://jglobal.jst.go.jp/en/detail?JGLOBAL_ID=200902260959503056&rel=0).

The KPIs are thought as being quantative targets and/or benchmarks that provide readily consultable, ambitious and performance-specific references to developers, integrators and strategy-makers alike. They aim to provide guidance and focus in the areas of FCH development that are considered crucial to sustainable FCH adoption in real-world applications and to their overall contribution within the Energy transition. The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has defined application-level KPIs in their latest version of the Multi-Annual Work Programme (MAWP): these are repeated in section A.1 for high-level referencing. Concentrating on translating these high-level KPIs to intermediate technical milestones for research and development, the R&D KPIs are conceived horizontally across applications, focusing on specific scientific topics. This follows the logic of the structure of the EERA JP FCH, with the aim of pooling as many scientific experts as possible in addressing the topic under consideration, thereby overcoming product-specific limitations and increasing the opportunity for uptake of key technological breakthroughs. The ultimate link to, and impact on, application-specific KPIs – i.e. those that are most important from the end-user perspective – is in any case explicitely provided for each R&D-specific KPI.
The Appendix form of these R&D KPIs within this Implementation Plan will allow to update the values more easily as technology progresses.

# A.1. Application-specific KPIs established in the FCH JU MAWP (2014-2020)

Table A.1.1 State-of-the-art and future targets for **fuel cell electric buses**

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | Fuel cell system durability | h | 10000 | 16000 | 20000 | 24000 | 28000 |
| 2 | Hydrogen consumption | kg/100 km | 9 | 8.5 | 8.0 | 7.5 | 7.1 |
| 3 | Availability | % | 85 | 90 | 90 | 93 | 93 |
| 4 | Yearly operation cost (including labour) | EUR/a | Na | -20% | 16,000 | 14,000 | 11,000 |
| 5 | Fuel cell system cost | EUR/kW | 3500 | 1500 | 900 (250 units) | 750 (500 units) | 600 (900 units) |
| 6 | Bus cost | EUR | 1300 | 650 | 625 (150 units) | 600 (250 units) | 500 (300 units) |

*Notes:*

1) *Durability of the fuel cell system subject to EoL criterion, fuel cell stack life 10% degradation in power or H2 leak rate as per SAE2578;*
2) *Hydrogen consumption for 100 km driven under operations using exclusively hydrogen feed acc. to SORT 1 and 2 drive cycle;*
3) *Percent amount of time that the bus is able to operate versus the overall time that it is intended to operate for a fleet availability same as diesel buses;*
4) *Costs for spare parts and man-hours of labour for the drivetrain maintenance;*
5) *Actual cost of the fuel cell system - excluding overheads and profits subject to yearly overall fuel cell bus module volume as stated;*
6) *Cost of manufacturing the vehicle. In case of buses for which a replacement of the fuel cell stack is foreseen, the cost of stack replacement is included in the calculation. Subject to yearly volumes per OEM as assumed in R. Berger FC bus com. study.*

Table A.1.2 State-of-the-art and future targets for **fuel cell electric trains** (300 passengers, 150 seated)

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | Fuel cell system durability | h | n.a. | 12.000 | 20.000 | 25.000 | 30.000 |
| 2 | Hydrogen consumption | kg/100 km | n.a. | 24 – 34 | 22 – 32 | 21 – 30 | 20 – 28 |
| 3 | Availability | % | n.a. | 87 | 94 | 97 | >99 |
| 4 | Yearly operation cost (including labour) | €/a | n.a. | | | | |
| 5 | Fuel cell system cost | €/kW | n.a. | 1321[1] | | | |
| 6 | Train cost | M€ | n.a. | 5-5.5[2] or 4.23[3] | | | |

*Notes:*

1) *Durability of the fuel cell system subject to EoL criterion output voltage at max. power;*
2) *Hydrogen consumption for 100 km driven under operations using exclusively hydrogen feed;*
3) *Percent amount of time that the train is able to operate versus the overall time that it is intended to operate;*
4) *Costs for spare parts and man-hours of labour for the drivetrain maintenance;*
5) *Actual cost of the fuel cell system - excluding overheads and profits;*

[1] http://www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf *(extrapolated by gi 4-19 pag1 "Ballard"*

[2] https://www.fch.europa.eu/sites/default/files/171121_FCH2JU_Application-Package_WG1_Trains%20%28ID%202910561%29%20%28ID%202911647%29.pdf

[3] http://www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf *from pag 145*

6) *Cost of manufacturing the vehicle. In case of trains for which a replacement of the fuel cell stack is foreseen, include the cost of stack replacement in the calculation.*

Table A.1.3 State-of-the-art and future targets for **fuel cell light duty vehicles**

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | Fuel cell system durability | h | 2500 | 4000 | 5000 | 6000 | 7000 |
| 2 | Hydrogen consumption | kg/100 km | n.a. | 1.2 | 1.15 | 1,1 | 1 |
| 3 | Availability | % | 95 | 98 | 98 | 99 | >99 |
| 4 | Maintenance | €/km | n.a. | 0,04 | 0,03 | 0,02 | 0,01 |
| 5 | Fuel cell system cost | €/kW | 500 | 100 | 60 | 50 | 40 |
| 6 | Areal power density | W/cm2 | n.a. | 1,0 | 1,5 | 1,8 | 2,0 |
| 7 | PGM loading | mg/cm2 | n.a. | 0,4 | 0,25 | 0,15 | 0,10 |
| 8 | Cell Volumetric power density | kW/l | n.a. | 5,0 | 7,3 | 9,3 | 10,0 |

*Notes:*

1) *Durability of the fuel cell system until 10% power degradation. The typical vehicle lifetime requirement is 6000-7000h of operation;*
2) *Hydrogen consumption for 100 km driven under real life operation using exclusively hydrogen feed;*
3) *Percent of time that the vehicle is able to operate versus the overall time that it is intended to operate, assuming only FC related technical issues;*
4) *Costs for spare parts and labour for the drivetrain maintenance per km travelled over the vehicle's complete lifetime of 6000 to 7000 hours;*
5) *Actual cost of the fuel cell system - excluding overheads and profits, assuming 100.000 systems/year as cost calculation basis;*
6) *Power per cell area @ 0,66V: Ratio of the operating power of the fuel cell to the active surface area of the fuel cell;*
7) *Overall loading in Platinum Group Metals at cathode + anode. (To be used as guidance, not development target);*
8) *Power for single cell (cathode plate, MEA, anode plate) per unit volume, ref: Autostackcore Evo 2 dimensions: cell pitch 1,0mm and cell area: 595cm$^2$.*

Table A.1.4 State-of-the-art and future targets for **fuel cell electric aircrafts**

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | Fuel cell system durability | h | 2000 | 5000 | 10000 | 15000 | 20000 |
| 2 | Availability | % | - | - | 60 | 75 | 90 |
| 3 | Fuel cell system cost | €/kW | 3500 | >20000<br>>10000<br>>15000 | 20000<br>10000<br>15000 | 6000<br>3000<br>5000 | 3000<br>1500<br>3000 |
| 4 | Gravimetric Power density | kW/kg | - | 2<br>5 | 2,5<br>6 | 3<br>7 | 3,5<br>8 |
| 5 | Est. bus cost @ mass prod. | k€ | n.a. | 650 [4]<br>(JIVE) | <400 (>100 bus for year) | <400 (>100 bus for year) | <400 (>100 bus for year) |

*Notes:*

1) *Durability of the fuel cell system until 10% power degradation;*
2) *Percent amount of time that the aircraft is able to operate versus the overall time that it is intended to operate;*
3) *Actual cost of the fuel cell system - excluding overheads and profits for mass production volumes;*
4) *Ram air turbine – emergency system replacement (RAT) (15-50 kW);*
5) *Propulsion (40 kW);*
6) *Cabin Loads – APU (5-20 kW);*

[4] *European hydrogen bus activity October 2018 Element Energy Limited. Project JIVE, pag 16*

7) *FC Stack, Power converter;*
8) *Estimated bus production cost at an assumed up-scaled production level.*

Table A.1.5 State-of-the-art and future targets for **fuel cell forklifts**

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | Vehicle lifetime | h | na | ? | 20000 | 20000 | 20000 |
| 2 | Hydrogen consumption | kg/h | na | ? | 6,67 | 6,3 | 6,0 |
| 3 | System electrical efficiency | % | 45 | 45 | 50 | 53 | 55 |
| 4 | Availability | % | 90 | ? | 98 | 98 | 98 |
| 5 | Mean time between failures (MTBF) | h | na | ? | 750 | 1000 | 1250 |
| 6 | Cost of spare parts | €/h | na | ?* | 7 | 5 | 4 |
| 7 | Labour | manh/kh | na | ? | 10 | 7 | 5 |
| 8 | Fuel cell system cost (10 kW) | €/kW | 4000 | ?* | 2500 | 1250 | 450 |
| 9 | Est. FC system cost @ mass prod. | EUR/kW | na | ?* | - | 1250 | 450 |

*Notes:*

1) *Total number of hours of vehicle operation until end of life (assuming >98% availability in the fleet in heavy duty 3/7 or 3/5 shift operation);*
2) *Hydrogen consumption for h of operations under operations using exclusively hydrogen feed for Class 1 forklift load cycle @ 10kW avg. system power output (Begin-of-Life);*
3) *Percentage (%) of electricity generated by the fuel cell vs. energy contained in the hydrogen delivered to fuel cell (LHV) for Class 1 forklift load cycle @ 10kW avg. system power output (Begin-of-Life);*
4) *Percent amount of time that the forklift is able to operate versus the overall time that it is intended to operate;*
5) *Average time between successive failures leading to downtime (MTBF in the fleet in heavy duty 3/7 or 3/5 shift operation);*
6) *Costs for spare parts for the system maintenance as percentage of system investment over the vehicle's complete lifetime;*
7) *Man-hours of labour for the system maintenance per 1000 h of operations over the vehicle's complete lifetime;*
8) *Actual cost of the fuel cell system - excluding overheads and profits;*
9) *Estimated fuel cell system cost at an assumed up-scaled production level of 2024: 20000 units/production & 2030: FC cost level benefits from automotive, bus and truck volumes.*

Table A.1.6 State-of-the-art and future targets for **on-board gaseous hydrogen storage tank**

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | CAPEX - Storage tank | €/kg H2 | 3000 | 1000 | 500 | 400 | 300 |
| 2 | Volumetric capacity | kg/l | 0,02 | 0,023 | 0,03 | 0,033 | 0,035 |
| 3 | Gravimetric capacity | % | 4 | 5 | 5,3 | 5,7 | 6 |

*Notes:*

1) *Total cost of the storage tank, including one end-plug, INCLUDING the in-tank valve injector assembly assuming 100.000 parts/year;*
2) *Weight of hydrogen that can be stored over the volume of the tank (including in-tank valve injector assembly, tank walls, bosses, plug and the volume for the hydrogen itself);*
3) *Percent weight of hydrogen that can be stored over the total tank weight (including in-tank valve injector assembly, tank walls, bosses, plug and the weight of the max amount of hydrogen).*

Table A.1.7 State-of-the-art and future targets for **Hydrogen Refuelling Stations (HRS)**

| No. | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | Lifetime | years | na | 10 years | 12 | 15 | 20 |
| 2 | Durability | years | na | - | 5 | 10 | 15 |
| 3 | Energy consumption | kWh/kg | na | 10 | 5 | 4 | 3 |
| 4 | Availability | % | na | 95 | 96 | 98 | 99 |
| 5 | Mean time between failures (MTBF) | h | na | 20 | 48 | 72 | 168 |
| 6 | Annual maintenance cost | €/kg | na | - | 1.0 | 0.5 | 0.3 |
| 7 | Labour | manh/kh | na | - | 70 | 28 | 16 |
| 8 | CAPEX for the HRS | k€/ (kg/day) | 7,5 | 7 | 4-2,1 | 3-1,6 | 2,4-1,3 |
| 9 | Cost of renewable hydrogen | €/kg | 13 | 12* | 11 | 9 | 6 |

*Notes:*

1) *Total number of hours of station operation;*
2) *Time that the HRS without its major components/parts (storage, compressor, pump) being replaced, is able to operate (storage shall be changed when the number of cycles reaches the regulatory limit. Replacement of hydraulic compressor is forecasted between 10 to 15 years);*
3) *Station energy consumption per kg of hydrogen dispensed when station is loaded at 80% of its daily capacity – For HRS which stores H2 in gaseous form, at ambient temperature, and dispense H2 at 700bar in GH2 from a source of ≥30 bar hydrogen;*
4) *Percent amount of hours that the hydrogen refuelling station is able to operate versus the total number of hours that it is intended to be able to operate (consider any amount of time for maintenance or upgrades as time at which the station should have been operational);*
5) *Average time between successive failures leading to HRS downtime;*
6) *Parts and labour based on a 200kg/day throughput of the HRS. Includes also local maintenance infrastructure. Does not include the costs of the remote and central operating and maintenance centre;*
7) *Man-hours of labour for the system maintenance per 1000 h of operations over the vehicle's complete lifetime;*
8) *Total costs incurred for the construction or acquisition of the hydrogen refuelling station, including on-site storage. Exclude land cost & excluding the hydrogen production unit. Target ranges refer to a 200 kg/day station and a 1000kg/day station;*
9) *Cost for the hydrogen dispensed (at the pump), considering OPEX and CAPEX according to the operator's business mode.*

Table A.1.8 State-of-the-art and future targets for hydrogen production from renewable electricity for energy storage and grid balancing using **alkaline electrolysers**

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| **Generic system*** | | | | | | | |
| 1 | Electricity consumption @nominal capacity | kWh/kg | 57 | 51 | 50 | 49 | 48 |
| 2 | Capital cost | €/(kg/d) (€/kW) | 8,000 (~3000) | 1,600 (750) | 1,250 (600) | 1,000 (480) | 800 (400) |
| 3 | O&M cost | €/(kg/d)/yr | 160 | 32 | 26 | 20 | 16 |
| **Stack** | | | | | | | |
| 4 | Degradation | %/1000hrs | - | 0,13 | 0,12 | 0,11 | 0,10 |
| 5 | Current density | $A/cm^2$ | 0,3 | 0,5 | 0,7 | 0,7 | 0,8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | Use of critical raw materials as catalysts | mg/W | - | 7,3 | 3,4 | 2,1 | 0,7 |

*Notes:*

**Standard boundary conditions that apply to all system KPIs: input of 6kV AC power and tap water; output of hydrogen meeting ISO 14687-2 at a pressure of 30 bar. Correction factors may be applied if actual boundary conditions are different.*

2) *Capital cost are based on 100MW production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby end of life is defined as 10% increase in energy required for production of hydrogen. Stack replacements are not included in capital cost. Cost are for installation on a pre-prepared site (fundament/building and necessary connections are available). Transformers and rectifiers are to be included in the capital cost;*
3) *Operation and maintenance cost averaged over the first 10 years of the system. Potential stack replacements are included in O&M cost. Electricity costs are not included in O&M cost;*
4) *Stack degradation defined as percentage efficiency loss when run at nominal capacity. For example, 0.125%/1000h results in 10% increase in energy consumption over a 10-year lifespan with 8000 operating hours per year;*
6) *The critical raw material considered here is Cobalt. Other materials can be used as the anode or cathode catalysts for alkaline electrolysers. 7,3 mg/W derives from a cell potential of 1,7 V and a current density of 0,5 A/cm$^2$, equivalent to 6,2 mg/cm$^2$.*

Table A.1.9. State-of-the-art and future targets for hydrogen production from renewable electricity for energy storage and grid balancing using **PEM electrolysers**

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | **2012** | **2017** | **2020** | **2024** | **2030** |
| **Generic system** | | | | | | | |
| 1 | Electricity consumption @nominal capacity | kWh/kg | 60 | 58 | 55 | 52 | 50 |
| 2 | Capital cost | €/(kg/d) (€/kW) | 8000 (~3000) | 2900 (1200) | 2000 (900) | 1500 (700) | 1000 (500) |
| 3 | O&M cost | €/(kg/d)/yr | 160 | 58 | 41 | 30 | 21 |
| **Specific system** | | | | | | | |
| 4 | Hot idle ramp time | sec | 60 | 10 | 2 | 1 | 1 |
| 5 | Cold start ramp time | sec | 300 | 120 | 30 | 10 | 10 |
| 6 | Footprint | m$^2$/MW | - | 120 | 100 | 80 | 45 |
| **Stack** | | | | | | | |
| 7 | Degradation | %/1000hrs | 0,375 | 0,250 | 0,190 | 0,125 | 0,12 |
| 8 | Current density PEM | A/cm$^2$ | 1,7 | 2,0 | 2,2 | 2,4 | 2,5 |
| 9 | Use of critical raw materials as catalysts | mg/W | - | 5,0 | 2,7 | 1,25 | 0,4 |

*Notes:*

1) *to 3) and 7) similar conditions as for alkaline technology (previous table);*
4) *The time from hot idle to nominal power production, whereby hot idle means readiness of the system for immediate ramp-up. Power consumption at hot idle as percentage of nominal power, measured at 15°C outside temperature;*
5) *The time from cold start from -20°C to nominal power;*
9) *This is mainly including ruthenium and iridium as the anode catalyst and platinum as the cathode catalyst (2,0 mg/cm2 at the anode and 0,5 mg/cm2 at the cathode). The reduction of critical raw materials content is reported feasible reducing the catalysts at a nano-scale.*

Table A.1.10. State-of-the-art and future targets for Hydrogen production from renewable electricity for energy storage and grid balancing using **high-temperature SOE**

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| **Generic system*** | | | | | | | |
| 1 | Electricity consumption @rated capacity | kWh/kg | n.a. | 41 | 40 | 39 | 37 |
| 2 | Availability | % | n.a. | na | 95% | 98% | 99% |
| 3 | Capital cost | €/(kg/d) | n.a. | 12 000 | 4500 | 2400 | 1500 |
| 4 | O&M cost | €/(kg/d)/yr | n.a. | 600 | 225 | 120 | 75 |
| **Specific system** | | | | | | | |
| 5 | Reversible efficiency | % | n.a. | 50% | 54% | 57% | 60% |
| 6 | Reversible capacity | % | n.a. | 20% | 25% | 30% | 40% |
| **Stack** | | | | | | | |
| 7 | Production loss rate | %/1000hrs | n.a. | 2,8 | 1,9 | 1,2 | 0,5 |

*Notes:*

**Standard boundary conditions that apply to all system KPIs: input of AC power and tap water; output of hydrogen meeting ISO 14687-2 at atmospheric pressure. Correction factors may be applied if actual boundary conditions are different.*

3) *and 4) similar conditions as for alkaline technology (previous tables);*
5) *Reversible efficiency is defined as the electricity generated in reversible mode of the electrolyser, divided by the lower heating value of hydrogen consumed;*
6) *Reversible capacity is defined as a percentage of the electric capacity in electrolyser mode;*
7) *Degradation at thermo-neutral conditions in percent loss of production-rate (hydrogen power output) at constant efficiency. Note this is a different definition as for low temperature electrolysis, reflecting the difference in technology.*

Table A.1.11 State-of-the-art and future targets for **Hydrogen production with low carbon footprint from other resources**

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| **Hydrogen from raw biogas[1]** | | | | | | | |
| 1 | System energy use | kWh/kg | 62 | 56 | 56 | 55 | 53 |
| 2 | System capital cost | €/(kg/d) | 4200 | 3800 | 3100 | 2500 | 1500 |
| **High temp. water splitting[1]** | | | | | | | |
| 3 | System energy use | kWh/kg | 120 | 110 | 100 | 94 | 88 |
| 4 | System capital cost | €/(kg/d) | 4000 | 3500 | 2500 | 1700 | 1400 |
| 5 | System lifetime | years | 0,5 | 1 | 2 | 10 | 10 |
| **Biological H2 production** | | | | | | | |
| 6 | System carbon yield | $H_2/C$ | 0,60 | 0,62 | 0,64 | 0,65 | 0,65 |
| 7 | Reactor production rate | $kg/m^3$ reactor | 2 | 10 | 40 | 100 | 200 |
| 8 | Reactor scale | $m^3$ | 0.05 | 0.5 | 1 | 10 | 10 |

Table A.1.12 State-of-the-art and future targets for **hydrogen storage and large scale storage**

| N | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| **Compressed gas tube trailers** | | | | | | | |
| 1 | Capacity | kg | 400 | 850 | 1000 | 1000 | 1000 |
| 2 | Capital cost | €/kg | 550 | 400 | 350 | 350 | 350 |
| **Large scale H2 storage*** | | | | | | | |
| 3 | Chain efficiency | % | n.a. | 60 | 67 | 70 | 72 |
| 4 | Release energy use | kWh/kg | n.a. | 13,3 | 11 | 10 | 9,3 |
| 5 | System capital cost | €/kg | 1,2 | 1,1 | 1,0 | 0,8 | 0,6 |

*Notes:*

**Storage of at least 10 tonnes of hydrogen for at least 48 hours, including all necessary conversion steps from clean H2 input to clean H2 output at 30 bar. Correction factors may be applied if actual boundary conditions are different.*

Table A.1.13 State-of-the-art and future targets for **Residential micro CHP** for single family homes and small buildings (0,3 - 5 kW)

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | CAPEX1 | €/kW | 16 000 | 13 000 | 10 000 | 5500 | 3500 |
| 2 | Lifetime | years of appliance operation | 10 | 12 | 13 | 14 | 15 |
| 3 | Availability | % of the appliance | 97 | 97 | 97 | 97 | 98 |
| 4 | Durability of key component (stack) | hrs | 25 000 | 40 000 | 50 000 | 60 000 | 80 000 |
| 5 | Reliability | MTBF (hrs) | 10 000 | 30 000 | 50 000 | 75 000 | 100k |
| 6 | Electrical efficiency | % LHV | 30-60 | 33-60 | 35-60 | 37-63 | 39-65 |
| 7 | Thermal efficiency | % LHV | 25-55 | 25-55 | 30-55 | 30-55 | 30-55 |
| 8 | Maintenance costs | € ct/kWh | 40 | 20 | 5 | 3,5 | 2,5 |
| 9 | Tolerated H2 content in NG | % (Volume) | 5% | 5% | 100% | 100% | 100% |
| 10 | Installation volume/unit | l/kW | 330 | 240 | 230 | 225 | 220 |

Table A.1.14 State-of-the-art and future targets **mid-sized CHP installations** for commercial and larger buildings (5 - 400 kW)

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | CAPEX[1] | €/kW | 6000 – 10 000 | 5000 - 8500 | 4500 - 7500 | 3500 - 6500 | 1500 – 4000 |
| 2 | Lifetime | years of plant operation | 2 - 20 | 6 – 20 | 8 – 20 | 8 – 20 | 15-20 |
| 3 | Availability | % of the plant | 97 | 97 | 97 | 97 | 98 |
| 4 | Durability of key component (stack) | khrs | 25 | 30 | 50 | 60 | 80 |
| 5 | Reliability | MTTF (hrs) | 10 000 | 20 000 | 30 000 | 50 000 | 80 000 |
| 6 | Electrical efficiency | % LHV | 40-45 | 41-55 | 42-60 | 42-62 | 50-65 |
| 7 | Thermal efficiency | % LHV | 24-40 | 24-41 | 24-42 | 24-42 | 30-50 |
| 8 | Maintenance costs [2] | € Ct/kWh | 8,6 | 7,6 | 2,3 | 1,8 | 1,2 |
| 9 | Tolerated H2 content in NG | % (Volume) | 50% | 50% | 100% | 100% | 100% |
| 10 | Land use/ footprint | $m^2$/kW | 0,25 | 0,15 | 0,08 | 0,07 | 0,06 |

Table A.1.15 State-of-the-art and future targets for **large-scale FC installations**, converting (hydrogen) fuel into Power in various applications (0.4 - 30 MW)

| No | Parameter | Unit | State of the art | | FCH-JU target | | |
|---|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2024 | 2030 |
| 1 | CAPEX[1] | €/kW | 3000-4000 | 3000 - 3500 | 2000 - 3000 | 1500 - 2500 | 1200-1750 |
| 2 | Lifetime | years of plant operation | n.a. | 15 | 25 | 25 | 25 |
| 3 | Availability | % of the plant | 98 | 98 | 98 | 98 | 98 |
| 4 | Durability of key component (stack) | khrs | 15 | 20-60 | 20-60 | 20-60 | 25-60 |
| 5 | Reliability | MTTF (hrs) | n.a. | n.a.* | 25 000 | 30 000 | 75 000 |
| 6 | Electrical efficiency | % LHV | 45 | 45 | 45 | 45 | 50 |
| 7 | Thermal efficiency | % LHV | 20 | 20-40 | 22-40 | 22-40 | 22-40 |
| 8 | Maintenance costs [2] | €ct/kWh | n.a. | 2,8-5 | 3 | 3 | 2 |
| 9 | Start/Stop characteristics | - | n.a. | 4 hrs 0-100% | - | 100%/1 min | - |
| 10 | Land use/ footprint | $m^2$/kW | tbd | tbd | tbd | tbd | tbd |

**insufficient number of units installed to get statistically supported figure*

## A.2. Correlating R&D-specific KPIs

In the tables below, quantitative indicators are defined for the required progress in key areas of European FCH technology. These indicators are considered valid references on the pathway to the achievement of the high-level application specific KPIs defined by the FCH JU in Section A.1 above. To this effect the link to, and impact on, the latter KPIs is explained for each of the R&D KPIs, which are subdivided according to horizontal thematic areas.

This section is missing some specific values and should be considered as an open document to be continuously updated by the research community of HYDROGEN EUROPE RESEARCH, research grouping of the Fuel Cells and Hydrogen Joint Undertaking and the Joint Programme FUEL CELLS AND HYDROGEN of the European Energy Research Alliance.

## *A.2.1: KPIs 2020-2030 for Electrolytes*

Table A.2.1 State-of-the-art and future targets for **fuel cell and electrolyser electrolytes**

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, AEC, etc.) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 1 | Through-plane proton areal resistance | $m\Omega cm^2$ | PEMFC | 80°C, 100%RH | 10 | *6* | A.1.9 no.1,8 |
| | | | | 80°C, 50%RH | 50 | *20* | |
| 2 | Self-diffusion resistance | $x10^3$ $s.cm^{-1}$ | PEMFC | 30°C, 100%RH | 300 | | A.1.9 no.1,8 |
| 3 | Pervaporation resistance | $s.cm^{-1}$ | PEMFC | 30°C | 30 | | A.1.9 no.1,8 |
| 4 | Electroosmotic drag coefficient | - | PEMFC | 30°C | ≥ 1 [d] | | A.1.9 no.1,8 |
| 5 | Hydrogen cross-over current | $mA.cm^{-2}$ | PEMFC | 80°C, 100%RH, $P_{H2}$ =1 bar | 1.1 | | A.1.9 no.1,7, 8 |
| 6 | Oxygen cross-over current | $mA.cm^{-2}$ | PEMFC | 80°C, 100%RH, $P_{O2}$=1bar | 2.4 | | A.1.9 no.1,7, 8 |
| 7 | In-plane swelling | % | PEMFC | From dry to wet in water @ 80°C | 10 | *5* | A.1.9 no.4,5, 7 |
| 8 | Increase of performance through the adoption of innovative binders | % | Low-temperature FC & Electrolyser technologies | | Reference | >25% | A.1.8 no.4 ,5<br>A.1.9 no. 7,8 |
| 9 | Conductivity | S / cm | PCC | 400°C-700°C | $10^{-3}$ S / cm | | A.1.10 no. 1 |
| 10 | Cost | $€.m^{-2}$ | PEMFC | - | 15 | | A.1.9 no.2 |
| 11 | Durability | Cycles until >15 $mA.cm^{-2}$ $H_2$ cross-over or >20% loss in OCV | PEMFC | Combined chemical/mechanical | - | | A.1.9 no.4,5, 7 |

*Notes:*

The evaluation of many of the above technical criteria can be done in-situ or in a real fuel cell. This requires to put the membrane in an MEA. It would be interesting to have criteria which can be obtained ex-situ in order to obtain a relationship between properties and performance/durability, which is still missing. As such, giving values for the targets is hazardous. One good starting point would be to measure all these values on one type of sample, an EU reference sample like for example the membrane used in the MEA of the FCH JU project Autostack Core.

1) *Criterion taken from USA DoE (see Introduction). Measurement by impedance spectroscopy of the ohmic resistance due to the membrane ($R_{Ohm}$ in Ohm). The value is obtained by multipling the surface of the membrane (S) and $R_{Ohm}$.*
2) *Measured on Gore 820.15 membrane*
3) *Measurement by PFG-NMR of the water self-diffusion coefficient $D_{H2O}$ in $cm^2.s^{-1}$. Value obtained by dividing thickness of the membrane (e) in cm by $D_{H2O}$*
4) *Kusoglu, A., Weber, A.Z., Chem. Rev. 2017, 117, 987−1104*
5) *Criterion taken from USA DoE (see Introduction). Measurement of water flow across membrane when a gradient of RH is imposed on each side: 90%RH on one side and 20%RH.*
6) *Criterion taken from USA DoE (see Introduction). Measurement method to be defined*
7) *For H2 test methods, see M. Inaba et. al. Electrochimica Acta, 51, 5746, 2006. For O2 test methods, see Zhang et. al. Journal of The Electrochemical Society, 160, F616-F622, 2013. (Same methods as referenced by DoE.)*
8) *Indication for electrolyte manufacturing processes.*
9) *Optimizing the synthesis and manufacturing of highly dense crystalline electrolyte for application in Proton conducting Ceramic Cells*
10) *Criterion taken from USA DoE (see Introduction).*
11) *Cycle from DoE. Journal of The Electrochemical Society, 165 (6) F3085-F3093 (2018)*

### *A.2.2: KPIs 2020-2030 for Electrodes and catalysts*

Table A.2.2 State-of-the-art and future targets for **fuel cell and electrolyser electrodes and catalysts**

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 1 | Area-Specific Resistance | $\Omega cm^2$ | All cell technologies | At respective operation temperature | 0.25 | <0.1 | A.1.8 no.1,5<br>A.1.9 no.1,8<br>A.1.10 no.1 |
| 2 | Current density | $A/cm^2$ | Fuel Cell | At respective operation temperature,<br>50 mV overpotential (FC anode)<br>100 mV (FC cathode) | 0.3 | 0.8 | A1.13 no.6<br>A1.14 no.6<br>A1.15 no.6 |
| | | | Electrolysis | 100 mV (cathode)<br>200 mV (anode) | 0.6 | >1 | A.1.8 no.4<br>A.1.9 no.7<br>A.1.10 no.7 |
| 3 | Catalysts/electrode durability | hours | All cell technologies | Under relevant operation conditions | 5000-10000 | >40000 | A.1.8 no.4, 3<br>A.1.9 no.7, 3<br>A.1.10 no.7, 4 |
| 4 | Precious metal loading | $mg/cm^2$ | PEM fuel cells/electrolyzers | Under relevant operation conditions | 0.25 | <0.1 | A.1.9 no.9 |
| 5 | Sulfur Tolerance of Anodes | ppm | SOFC | 700°C-900°C | 0 ppm<br>for Ni-YSZ | 10 | A.1.13 no.4,5,8 |
| 6 | Redox cycling ability | No. | SOFC | 600-900 C | 10 | >100 | A.1.13 no.4,5,8 |
| 7 | Carbon Tolerant fuel electrodes for co-electrolysis (ASR) | $\Omega.cm^2$ | SOE | 700°C-900°C<br>P =1- 10 bar | >1 | 0,1 | A.1.10 no. 4 |

*Notes:*

5) *Development of materials /Structures/strategies for enhancing sulfur tolerance of SOFCs*
6) *Development of novel electrocatalysts for co-electrolysis and CO2 reduction*

### A.2.3: KPIs 2020-2030 for Stack materials and design

Table A.2.3 State-of-the-art and future targets for **fuel cell and electrolyser stack materials and design**

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 1 | Gas Diffusion Layer (GDL) Thickness | µm | PEMFC | | ~ 180-400 | <50 | |
| 2 | GDL Area weight | g/m² | PEMFC | | ~ 50-200 | 50 | |
| 3 | GDL Mean pore diameter | µm | PEMFC | | ~ 0.8-3 (GDM)<br>~ 0.01-0.5 (MPL) | | |
| 4 | GDL Cost | €/m² | PEMFC | | | 5 | |
| 5 | GDL Electrical resistance (in-plane/through-plane) (1) @1Mpa | mΩcm² | PEMFC | | ~ 1-5/<br>8-20 | ~ 0.5/2 | |
| 6 | GDL Gas permeability (in-plane/through-plane) (1) | m² | PEMFC | | ~ $10^{-11}$- to $10^{-12}$<br>~ $10^{-12}$- to $10^{-14}$ | | |
| 7 | GDL Relative gas diffusion coefficient (1) | - | PEMFC | | ~ 0.1-0.5 | ~ 0.7 | |
| 8 | GDL Thermal conductivity (1) | W/m/K | PEMFC | | ~ 0.4-0.7 | ~ 5 | |
| 9 | Contact resistance(4) | mΩcm² | PEMFC | | ~ 3-30 | ~ 0.5-2 | |
| 10 | GDL Wettability (global and local) | - | PEMFC | | Hydrophobic treatments are not stable (chemical/mechanical degradation), mixed wettability with hydrophilic and hydrophobic zones, not controlled distribution of wettability | Control and tune local wettability | |
| 11 | Young modulus | MPa | PEMFC | | Ex=Ey~5000-10000<br>Ez~10-100 | | |
| 12 | Open porosity | % | PEMFC | | ~ 70-80 (GDM)<br>~ 40 (MPL) | | |

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 13 | Interconnect lifetime | hours | PEMFC,PEMEC,AEC | | | >40 000 | A.1.8 no. 3<br>A.1.9 no. 3<br>A.1.13 no.2,4<br>A.1.14 no.2,4<br>A.1.15 no.2,4 |
| 14 | Interconnect cost target | €/kW | PEMFC,PEMEC,AEC | | | <3 | A.1.8 no.2<br>A.1.9 no. 2 |
| 15 | Electrical conductivity | S/cm | PEMFC,PEMEC,AEC | | | >100 | A.1.8 no.1<br>A.1.9 no. 1 |
| 16 | Interconnect lifetime | hours | SOFC, SOEC | | 40k | >100k | A.1.10 no. 4<br>A.1.13 no.2,4<br>A.1.14 no.2,4<br>A.1.15 no.2,4 |
| 17 | Interconnect (w/o Cr-barrier layer) cost target | €/kW | SOFC<br>(for SOEC, divide by 3) | Small series | 1300-1800 | <300 | A.1.10 no. 3<br>A.1.13 no.1<br>A.1.14 no.1<br>A.1.15 no.1 |
| 18 | Cost target Cr-barrier coating | €/kW | SOFC<br>(for SOEC, divide by 3) | | 1050 | 30 | A.1.10 no. 3<br>A.1.13 no.1<br>A.1.14 no.1<br>A.1.15 no.1 |
| 18a | Cost target Cr-barrier coating | €/kW | SOFC<br>(for SOEC, divide by 3) | MCF by APS | 1050 | 120 | Idem as 6. |
| 19 | ASR of Protective coating for the interconnect at the Fuel Side | mΩ.cm² | SOE<br>(steam electrolysis) | 700°C – 750°C (ASC)<br>800°C -900°C (ESC)<br>Steady state | - | <10 | A.1.10 no. 1, 5 |
| 20 | ASR of Anti coking protective coatings for the interconnect at the fuel side | mΩ.cm² | SOE<br>co-electrolysis | 700°C – 750°C (ASC)<br>800°C -900°C (ESC)<br>Steady state | - | <10 | A.1.10 no. 1, 5 |
| 21 | Deagradation by cycling<br>(contact losses?) | % V/cycle | SOFC | | 1 | 0,05 | |

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 21a | Deagradation by cycling<br>(contact losses?) | % V/cycle | SOEC | | 0,3 | 0,05 | |
| 22 | SOFC sealing life time | Thermal cycles | SOFC, SOEC | Ambient – 700°C | <100 | 200-1000 (TBD, 2 different inputs provided) | A.1.10 no. 4<br>A.1.13 no.2,4<br>A.1.14 no.2,4<br>A.1.15 no.2,4 |
| 23 | Cost of stack sealant | €/kW | SOFC<br>(for SOEC, divide by 3 to 4) | Small series production | 500 | 45 | A.1.10 no. 3<br>A.1.13 no.1<br>A.1.14 no.1<br>A.1.15 no.1 |
| 24 | Cost of electrode contact material | €/kW | SOFC<br>(for SOEC, divide by 3 to 4) | Mesh of Nickel wire | 70 | 5 | A.1.10 no. 3<br>A.1.13 no.1<br>A.1.14 no.1<br>A.1.15 no.1 |
| 25 | ASR of electrode-contact-layer | mOhm/cm² | SOFC, SOEC | At xxx°C | 40 | 20 | |
| 26 | Heat-up time of stack from ambient to operating temperature | min | SOFC | Ambient – 700°C | 120 | 30 | |

*Notes:*

1) *This value varies with clamping pressure and so also between rib and channel;*
2) *Uncompressed;*
3) *Large variations depending on the GDL grade, especially with and without MPL. Optimum value could be different depending on operating conditions and position inside the cell (inlet/outlet;*
4) *With stainless steel plate, compressed;*
6) *Optimum value could be different depending on operating conditions and position inside the cell (inlet/outlet);*
7) *Optimum value could be different depending on operating conditions and position inside the cell (inlet/outlet);*
11) *Optimum value could be different depending on operating conditions and position inside the cell (inlet/outlet);*
15) *Depends on the stack design;*
23) *Operating temperature should be defined in order for these numbers to have a meaning. Perhaps one should instead define the number in terms of the total stack resistance. I.e. contact layer resistance should equal less than XX % of total resistance of a stack single reapeating unit (See 13a);*
24) *SoA value taken from Juelich light-weight design.*

## *A.2.4: KPIs 2020-2030 for Systems*

Table A.2.4 State-of-the-art and future targets for **fuel cell and electrolyser systems**

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| *Balance of Plant (BoP) components* | | | | | | | |
| 1 | Corrosion rate | μA/cm² | BoP parts in alkaline or acidic media | n.a. | | < 0.1 | A.1.8-9 no.3 (O&M)<br>A.1.13-15 no.5 (MTBF) |
| | Oxidation mass gain | mg/1000 hrs | Steel components in HT systems | Operating conditions | | < 0.2 | A.1.10 no.4 (O&M)<br>A.1.13-15 no.5 (MTBF) |
| 2 | Cost of materials | €/kg | All BoP parts | n.a. | | < 5 | A.1.8-9 no.2 (CAPEX)<br>A.1.10 no.3 (CAPEX)<br>A.1.13-15 no.1 (CAPEX) |
| 3 | Cumulative Cr evaporation from BOP parts | kg/m² for 1000 hrs | Steel components in HT systems | n.a. | | < 0.0002 | A.1.13-15 no.2 (Lifetime) |
| 4 | Coating resistance | hrs | Heat exchangers | n.a. | | > 40kh | A.1.13-15 no.5 (MTBF) |
| 5 | Coating costs | €/m² | Coatings and linings for corrosion resistance in alkaline and acidic media in BoP | n.a. | | < 700 | A.1.8-9 no.2 (CAPEX)<br>A.1.10 no.3 (CAPEX)<br>A.1.13-15 no.1 (CAPEX) |
| 6 | Influence of coating on funtional properties of the parts | % | Coatings and linings for corrosion resistance in alkaline and acidic media in BoP | n.a. | | < 10 | A.1.8 no.1 A.1.9 no.1 A.1.13 no.6,7<br>A.1.14 no.6, 7<br>A.1.15 no.6, 7 |
| 7 | Degradation | % | Catalysts/support for reforming and POX | n.a. | | < 10 | A.1.13-15 no.2 (Lifetime) |
| *BoP integration* | | | | | | | |
| 8 | BoP Cost | €/kW | Total system, All FC & electrolyser technologies | n.a. | | < 400 | A.1.8 no.2 A.1.9 no.2 A.1.10 no.3<br>A.1.13 no.1<br>A.1.14 no.1<br>A.1.15 no.1 |
| 9 | Footprint reduction | % | Total system, All FC & electrolyser technologies | n.a. | | > 15 | A.1.9 no.6 |
| 10 | System efficiency gain | % | Total system, All FC & electrolyser technologies | n.a. | | > 3 | A.1.8 no.1 A.1.9 no.1 A.1.13 no.6,7<br>A.1.14 no.6, 7<br>A.1.15 no.6, 7 |

### *A.2.5: KPIs 2020-2030 for Modelling, validation and diagnostics*

Table A.2.5 State-of-the-art and future targets for **fuel cell and electrolyser modelling, validation and diagnostics**

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| ***Diagnostics hardware and software*** | | | | | | | |
| 1 | Detection & Isolation accuracy | % | PEMFC, SOFC | nominal & faulty states | 93 | 97 | A.1.1 no. 3<br>A.1.2 no. 3<br>A.1.3 no. 3<br>A.1.4 no. 2<br>A.1.5 no. 4, 5<br>A.1.13 no. 3, 5<br>A.1.14 no. 3, 5<br>A.1.15 no. 3, 5 |
| 2 | Fault Detection & Isolation accuracy | % | PEMFC, SOFC | faulty states | 95 | 99 | A.1.1 no. 3<br>A.1.2 no. 3<br>A.1.3 no. 3<br>A.1.4 no. 2<br>A.1.5 no. 4, 5<br>A.1.13 no. 3, 5<br>A.1.14 no. 3, 5<br>A.1.15 no. 3, 5 |
| 3 | Fault Detection & Isolation precision | % | PEMFC, SOFC | faulty states | 95 | 99 | A.1.1 no. 3<br>A.1.2 no. 3<br>A.1.3 no. 3<br>A.1.4 no. 2<br>A.1.5 no. 4, 5<br>A.1.13 no. 3, 5<br>A.1.14 no. 3, 5<br>A.1.15 no. 3, 5 |
| 4 | False alarm rate | % | PEMFC, SOFC | nominal states | 5 | 2 | A.1.1 no. 3<br>A.1.2 no. 3<br>A.1.3 no. 3<br>A.1.4 no. 2<br>A.1.5 no. 4, 5<br>A.1.13 no. 3, 5<br>A.1.14 no. 3, 5<br>A.1.15 no. 3, 5 |

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 5 | Missed fault rate | % | PEMFC, SOFC | faulty states | 5 | 2 | A.1.1 no. 3<br>A.1.2 no. 3<br>A.1.3 no. 3<br>A.1.4 no. 2<br>A.1.5 no. 4, 5<br>A.1.13 no. 3, 5<br>A.1.14 no. 3, 5<br>A.1.15 no. 3, 5 |
| | | | | ***Modelling and validation*** | | | |
| 6 | Predictability of cell component model based on *ab-initio* properties calculation and material properties characterization | % | All cell technologies | All conditions | <80 | 90 | A.1.1 no. 1,3<br>A.1.2 no. 1,3<br>A.1.3 no. 1,3<br>A.1.4 no. 1,2,4<br>A.1.5 no. 4, 5<br>A.1.8 no. 4,5,6<br>A.1.9 no. 4,5,6 A.1.10 no. 5,7<br>A.1.13 no. 3, 5<br>A.1.14 no. 3, 5<br>A.1.15 no. 3, 5 |

*Notes:*

1) *Ratio between the correct number of detection & isolation assignments (both nominal & faulty) and the overall number of experienced/tested states;*
2) *Ratio between the correct number of fault detection & isolation assignments and the overall number of experienced/tested faulty states;*
3) *Ratio between the correct number of fault detection & isolation assignments and the overall number of faulty assignments;*
4) *Ratio between the incorrect faulty assignments and the overall number of experienced/tested states;*
5) *Ratio between the non-detected faulty states and the overall number of experienced/tested state;*

### *A.2.6: KPIs 2020-2030 for Hydrogen production and handling*

Table A.2.6 State-of-the-art and future targets for **(non-electrolytic) hydrogen production and hydrogen handling**

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| ***Compression & Liquefaction*** | | | | | | | |
| 1 | Capital cost compressor | €/(kg/day) | Electrochemical compressor | | 190-1900 | 500 | A.1.7 no. 9<br>A.1.11 no.2,4 |
| | | | Thermochemical compressor | 120 kg/day.<br>2.4 pressure ratio. | 1083-2550<br>1835 (24 kg/day)<br>1041 (2400 kg/day) | | |
| 2 | Operating cost compression | €/yr | Electrochemical compressor | n.a. | | 600 | A.1.7 no. 7 |
| | | | Thermochemical compressor | 120 kg/day.<br>2.4 pressure ratio.<br>2000 h/yr<br>0.1€/kWh | 1240 | | |
| 3 | Compression efficiency | kWh/kg<br>kWh/kg<br>kWh/kg | Electrochemical compressor | 0.8-100 MPa | 2 | | A.1.7 no. 3 |
| | | | Thermochemical compressor | 0.8-100 MPa | 10-25%.<br>6-10 kWh/kg | | |
| 4 | Durability | Hours | Electrochemical compressor | n.a. | 10 years | 20 years | A.1.7 no.2,4,5,6 |
| | | | Thermochemical compressor | n.a. | | | |
| 5 | Liquefation process efficiency | kWh/kg | Liquid Hydrogen | 0.1MPa, 25K | 12.5-15 | | A.1.12 no.3 |
| ***Purification*** | | | | | | | |
| 6 | | | PSA | | | | |

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| | Capital Cost purification system | €/(Kg/day) | (Pressure swing adsorption) | 500 kg/day | 1800 €/(kg/day) | 450 €/(kg/day) | A.1.7 no. 9<br>A.1.11 no.2,4 |
| | | | TSA (Temperature Swing Adsorption) | | | | |
| | | | Membrane | 25 kg/day | | | |
| 7 | Operative cost purification system | €/yr | PSA (Pressure swing adsorption) | 500kg/day | 333 000 – 1 232 000 €/yr | 249 750€/yr | A.1.7 no. 7 |
| | | | TSA (Temperature Swing Adsorption) | | | | |
| | | | Membrane | 25 kg/day | 16 650 – 61 605 €/yr | 12 487.5 €/yr | |
| 8 | Purification efficiency | % | PSA (Pressure swing adsorption) | 500kg/day | 90 | 95 | A.1.7 no. 3 |
| | | | TSA (Temperature Swing Adsorption) | | 95 | 98 | |
| | | | Membrane | | | | |
| 9 | Hydrogen selectivity | 1 | Membrane separator | 25 kg/day | | | A.1.11 no.1,6,7<br>A.1.12 no.3 |
| | | | ***Non-electrolytic hydrogen production*** | | | | |
| 10 | Stable, autonomous operation of biomass gasficiation process | hours | Biomass and waste gasification | n.a. | 10 000 | 88 000 | n.a. |
| 11 | Automatic adaption of operating conditions to feedstock quality in gasification | % | Biomass and waste gasification | n.a. | 0 | 100 | n/a |
| 12 | Production of homogeneous biomass feedstock for gasification | n.a. | Biomass and waste gasification | n.a. | n.a. | quality margin +/- 5% | n/a |

| No. | Parameter | Unit | Applicable technology (e.g. PEMFC, SOEC, …) | Applicable conditions (e.g. *T, J*, #cycles, …) | SoA 2020 | Target 2030 | Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 13 | Tar content after cracking/clean-up | $mg/Nm^3$ | Biomass and waste gasification | n.a. | <500 | <1 | n.a. |
| 14 | Purity of hydrogen produced | % | Algae | n.a. | 66 | 99.9 | A.1.11 |
| 15 | Quantum yield | % | Photocatalytic reforming of biomass derivatives (ethanol, glycerol, glucose) | Catalyst: PGM-free on titania Light: UV-A | 25-30 | 35 | n.a. |
| | | | | Catalyst: PGM on titania Light: UV-A | 50-70 | 80 | |
| 16 | Yield referred to photocatalyst activity (per gram of catalyst) | mmol $H_2$/ g.h | Photocatalytic reforming of alcohols (ethanol, glycerol) | Catalyst: PGM-free on titania Light: UV-A | 10-15 | >150 | n.a |
| | | | | Catalyst: PGM on titania Light: UV-A | 30-40 | >500 | |
| 17a | Efficiency of Hydrogen production | % | Algae | n.a. | 2 to 3 | 5 | A.1.11 no.1,2 |
| | | | Photocatalytic water splitting | n.a. | 5 | >10 | can apply to A.1.11 |
| | | | ***Transport*** | | | | |
| 18 | Transport size trail | Kg | Compressed gas storage | n.a. | | | n.a. |
| | | | Liquid storage | n.a. | 5000 | 4000 | n.a. |

*Notes:*

1) *Capital cost of compression for kg of compressed Hydrogen.*
   *References:*
   - *SOA 2020, thermochemical compressor (24 kg/day): Stamatakis, E., Zoulias, E., Tzamalis, G., Massina, Z., Analytis, V., Christodoulou, C., & Stubos, A. (2018). Metal hydride hydrogen compressors: Current developments & early markets. Renewable Energy, 127, 850–862. doi:10.1016/j.renene.2018.04.073;*
   - *SOA 2020, thermochemical compressor (24 kg/day): DASILVA, E. (1993). Industrial prototype of a hydrogen compressor based on metallic hydride technology. International Journal of Hydrogen Energy, 18(4), 307–311;*
   - *SOA 2020, thermochemical compressor (240 kg/day): Stamatakis E. Benchmark Analysis & Pre-feasibility study for the market penetration of Metal Hydride Hydrogen Compressor. Integrated, Innovative Renewable Energy – Hydrogen Systems and Applications Workshop. July, 2017, 5-7. Athens, Greece;*

*The value of the maintenance costs has been estimated with the following calculation (0.06*(120/24)*2000 = 600 €/yr) by considering operational costs of 0.06 €/kg*

2) *Operative cost of compression for kg of compressed hydrogen;*

3) *Efficiency of compression expressed as kWh for any kg of compressed H2;*
4) *Durability of compressor in constant operation;*
5) *Efficiency of liquefaction process. Amount of energy spent to liquiefy 1 kg of hydrogen.*
   *Reference:*
   - *SOA 2020, liquefaction processes: Moradi, R., & Groth, K. M. (2019). Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. International Journal of Hydrogen Energy;*
6) *Capital cost of purification system for 500 kg/day hydrogen production system;*
7) *Operating cost of purification system for 500 kg/day hydrogen production system;*
   *The value has been estimated considering 8000 hpurs of operation per year and operating costs between 2.0 and 7.4 €/kg for the SoA and 1.5 €/kg by 2030.*
8) *Efficiency of purification. Percentage of wasted hydrogen with respect to hydrogen inlet mass flow rate;*
9) *Membrane selectivity is the ratio of hydrogen diffusion flow and overall diffusion flow through it. Hydrogen purity must be compliance to ISO 14687 and ISO/TS 19883. Protocol test to be described;*
13) *State of art 2020 from BLAZE project (H2020 Grant Agreement 815284, 2019);*
14) *Efficiency of hydrogen production as kWh spent for any kg of produced H2 for the different technologies reported (considering steam production, heat demand);*
15) *Hydrogen yield per absorbed photon. References:*
   - *"Heterogeneous photocatalytic hydrogen production from water and biomass derivatives". K. Shimura, H. Yoshida. Energy Environ. Sci. 4, 2011, 2467.*
   - *"CuOx−TiO2 Photocatalysts for H2 Production from Ethanol and Glycerol Solutions".* V. Gombac, L. Sordelli, T. Montini, J.J. Delgado, A. Adamski, G. Adami, M. Cargnello, S. Bernal. P. Fornasiero, J. Phys. Chem. A, 114, 2010, 3916;
   - *"Hydrogen Production by Photo-Induced Reforming of Biomass Components and Derivatives at Ambient Conditions".* D.I. Kondarides, V.M. Daskalaki, A. Patsoura, X.E. Verykios, Catal. Lett. 122, 2008, 26;
16) In comparison to photocatalytic (or photoelectrocatalytic) splitting of pure water, the addition of the sacrificial organic molecules leads to a higher efficiency of the process by facilitating the oxidation reaction with photogenerated holes. In addition the valorization of biomass/biowaste and the bioalcohols reforming processes are highlighted. *References:*
   - *"Performance comparison of Ni/TiO2 and Au/TiO2 photocatalysts for H2 production in different alcohol-water mixtures". Chen W-T, Chan A, Sun-Waterhouse D, Llorca J, Idriss H, Waterhouse GIN. J Catal, 367, 2018, 27-42;*
   - *"Hydrogen generation by photocatalytic reforming of potential biofuels: polyols, cyclic alcohols, and saccharides". Kennedy J, Bahruji H, Bowker M, Davies PR, Bouleghlimat E, Issarapanacheewin S. J Photochem Photobiol A, 356, 2018, 451-6;*
   - "Highly stabilized Ag2O-loaded nano TiO2 for hydrogen production from glycerol: water mixtures under solar light irradiation". *Sadanandam G, Valluri DK, Scurrell MS. Int J Hydrogen Energy, 42, 2017, 807-20;*
17) *Efficiency of non-electrolytic hydrogen production in kWh/kgH2 or in terms of primary energy (%);*
18) *Maximum amount of hydrogen transporting by trail. The estimation for the liquit storage expected by 2030 is condiered for $LH_2$ tank trailer payload*

### *A.2.7: KPIs 2020-2030 for Hydrogen Storage*

Table A.2.1 State-of-the-art and future targets for **hydrogen storage**

| No. | Parameter | Unit | Applicable technology | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 1. | Gravimetric density | wt.% i.e. 100*kg $H_2$/kg system (material) | Compressed gas | 15 °C, 35 MPa | 7 | 7.5 | A.1.6 no.1-3, A.1.12 no.1,2 |
| | | | | 15 °C, 70 MPa | 5.7 | 7.5 | A.1.6 no1-3 A.1.12 no.1,2 |
| | | | Carriers by physisorption | 77 K, 5.6 MPa | (10) | 15 | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C), 1MPa | 1-2 | 3.5 | A.1.6 no. 3 |
| | | | | MT (100-300°C), 1MPa | 2.5 - 5 | 5-8 | A.1.6.3: 6 |
| | | | | HT (>300°C), 1MPa | (7.1) | 10 | A.1.6 no. 3 |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | (6.2)-(7.2) | 12 | n.a. |
| 2. | Volumetric density | g $H_2$/liter system (material) | Compressed gas | 15 °C, 35 MPa | 30.8 | 40 | can apply to A.1.3, A.1.6 |
| | | | | 15 °C, 70 MPa | 23 - 42 | 70 | can apply to A.1.3, A.1.6 |
| | | | Carriers by physisorption | 15°C, 70 MPa | 58 | 80 | n.a. |
| | | | | 77 K, 5.6 MPa | 40 | 60 | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C), 1MPa | (90) | 120 | A.1.6 no. 2 |
| | | | | MT (100-300°C), 1MPa | 10 (50) | 80 | n.a. |
| | | | | HT (>300°C), 1MPa | 50 (130) | 150 | n.a. |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | (50 - 100)**Error! Bookmark not defined.** (56) | +20% | n.a. |
| | | | Liquid Hydrogen | 0.1 MPa, 20.25 K | 40**Error! Bookmark not** | +20% | n.a. |

| No. | Parameter | Unit | Applicable technology | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| | | | | | **defined.**-70**Error! Bookmark not defined.** | | |
| 3. | Scalability | kg $H_2$ | Carriers by physisorption | 77 K, 5.6 MPa | >1 | >1 | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C),1MPa | 5-10, 24 | 5000 | n.a. |
| | | | | MT (100-300°C),1MPa | 1 | 10 | n.a. |
| | | | | HT (>300°C), 1MPa | 150 | 500 | n.a. |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | >5000**Error! Bookmark not defined.** | | can apply to A.1.4 |
| 4. | Release energy use<br>Heat exchange | kWh/kg $H_2$ | Carriers by physisorption | 77 K, 5.6 MPa | | | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C), 1MPa | 3.5 | 1 | n.a. |
| | | | | MT (100-300°C), 1MPa | 3-10 | 1 | n.a. |
| | | | | HT (>300°C), 1MPa | 10 | 3 | n.a. |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | 9 - 10**Error! Bookmark not defined.** | 5 | n.a. |
| | | | Liquid Hydrogen | 0.1 MPa, 20.25 K | | | n.a. |
| 5. | Boiling Off | kW/kg | Liquid hydrogen | 0.1 MPa, 20.25 K | 0.3-3.0**Error! Bookmark not defined.** | 0.1 | n.a. |
| 6. | Degradation | wt. %/cycle | Compressed gas | 15 °C, 35 MPa | | | n.a. |
| | | | | 15 °C, 700 bar | | | n.a. |
| | | | Carriers by physisorption | 15 °C, 70 MPa | | | n.a. |

| No. | Parameter | Unit | Applicable technology | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| | | | | 77 K, 5.6 MPa | | | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C), 1MPa | | | n.a. |
| | | | | MT (100-300°C), 1MPa | | | n.a. |
| | | | | HT (>300°C), 1MPa | | | n.a. |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | 0.1 | 0.08 | n.a. |
| 7. | Gas permeability | NL/m$^2$/day | Compressed gas | 15°C, 35 MPa | | 0.05 | n.a. |
| | | | | 15 °C, 70 MPa | | | n.a. |
| 8. | Tensile strength | GPa | Compressed gas | 15°C, 35 MPa | | | n.a. |
| | | | | 15 °C, 70 MPa | | | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | 1 MPa | 1.0 | | n.a. |
| 9. | Storage system Cost | €/kg $H_2$ | Compressed gas | 15 °C, 35 MPa | | | n.a. |
| | | | | 15 °C, 70 MPa | 1500 | 300 | A.1.6 no. 1<br>A.1.12 no.2 |
| | | | Liquid Hydrogen | 0.1 MPa, 20.25 K | | | A.1.12 no.5 |
| | | | Carriers by physisorption | 77 K, 5.6 MPa | ? | 300 | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C),1MPa | 3000 | 300 | n.a. |
| | | | | MT (100-300°C),1MPa | 5000 | 300 | n.a. |
| | | | | HT (>300°C), 1MPa | | | n.a. |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | | | n.a. |

| No. | Parameter | Unit | Applicable technology | Applicable conditions (e.g. *T*, *J*, #cycles, …) | SoA 2020 | Target 2030 | FCH JU MAWP KPIs (e.g. A.1.1 no.1) |
|---|---|---|---|---|---|---|---|
| 10. | Kinetics sorption | %/min | Carriers by physisorption | 77 K, 5.6 MPa | | | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C),1MPa | 10 | 5 | n.a. |
| | | | | MT (100-300°C),1MPa | 10 | 5 | n.a. |
| | | | | HT (>300°C), 1MPa | | | n.a. |
| 11. | Cyclability | N° | Carriers by physisorption | 77 K, 5.6 MPa | | | n.a. |
| | | | Carriers by chemisorption (e.g. metal/complex hydrides) | LT (RT-100°C), 1MPa | | 10 000 | n.a. |
| | | | | MT (100-300°C), 1MPa | | 2000 | n.a. |
| | | | | HT (>300°C), 1MPa | | 2000 | n.a. |
| | | | Liquid Organic Hydrogen Carrier | 50-300 °C, 0.1 MPa | | | n.a. |

*Notes:*

1) *Gravimetric density of only storage tank or only sorbed material as. Kg of stored H2 with respect to the weight of storage system. For reversible metal hydride, three temperature category are included: low temperature (LT), mid temperature (MD) and high temperature (HT).*
   *References SOA 2020:*
   - *Compressed gas @ 35 MPa: Hexagon composite vessel: https://www.hexagonlincoln.com/;*
   - *Compressed gas @ 70 MPa: Hexagon composite vessel: https://www.hexagonlincoln.com/;*
   - *Carriers by physisorption: Concepts for improving hydrogen storage in nanoporous materials, D.P. Broom et al., IJHE (2019), doi: 10.1016/j.ijhydene.2019.01.224;*
   - *Carriers by Chemisorption, MT:* Application of hydrides in hydrogen storage andcompression: Achievements, outlook andperspectives, J.Bellosta von Colbe et al., IJHE (2019), doi: 10.1016/j.ijhydene.2019.01.104;
   - *Carriers by Chemisorption, MT:* Complex hydrides for energy storage, C.Milanese et al., IJHE (2019), doi: 10.1016/j.ijhydene.2018.11.208;
   - *Carriers by Chemisorption, HT:* http://www.h2eden.eu/;
   - *Liquid Organic Hydrogen Carriers:* Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy, Preuster, P., Papp, C., & Wasserscheid, P. (2016). . Accounts of Chemical Research, 50(1), 74–85;
   - *Liquid Organic Hydrogen Carriers:* Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain, : Energy Environ. Sci. (2019), doi: 10.1039/c8ee02700e;
2) *Volumetric density of only storage tank or sorbed material as. g of stored H2 with respect to the volume of storage system. For reversible metal hydride, three temperature categories are included: low temperature (LT), mid temperature (MD) and high temperature (HT).* This KPI is quite difficult to standardize, due to different value obtained by the same tank but with different dimensions.
   *References SOA 2020:*
   - *Volumetric density, compressed gas, 35 MPa: Hexagon composite vessel: https://www.hexagonlincoln.com/;*

- *Volumetric density, compressed gas, 70 MPa: Handbook of hydrogen storage: new materials for future energy storage, M. Hirscher, Wiley-VCH, Weinheim (2010);*
- *Volumetric density, compressed gas, 70 MPa:* Reversible ammonia-based and liquid organichydrogen carriers for high-density hydrogenstorage: Recent progress , J. W. Makepeace et al., IJHE (2019), doi: 10.1016/j.ijhydene.2019.01.144;
- *Volumetric density, carriers by physisorption, high pressure:* Mahytec: http://www.mahytec.com/en/;
- *Volumetric density, carriers by physisorption, low pressure:* Concepts for improving hydrogen storage in nanoporous materials, D.P. Broom et Al, International Journal of Hydrogen Energy,2019;
- *Volumetric density, carriers by chemisorption, HT:* http://www.h2eden.eu/project-results;
- *Volumetric density, liquid organic hydrogen carriers:* https://www.hydrogenious.net/wp-content/uploads/2018/08/Hydrogenious_Technologies_LOHC_Products.pdf.

3) *Maximum size of available storage system.*
   *References SOA 2020:*
   - *Scalability, carriers by chemisorption, LT:* HDW from Thyssen Krupp Marine Systems for U212 and U214 Submarines (Germany), but this is special military application;
   - *Scalability, carriers by chemisorption, LT:* LaNi5, H2OneE from Toshiba, https://www.toshiba-energy.com/en/hydrogen/product/h2one.htm;
   - *Scalability, carriers by chemisorption, HT:* McPhy INGRID project modules, https://mcphy.com/en/non-classe-en/ingrid/;
4) *Heat necessary for hydrogen release per kg of H2. Only desorption process for not reversible hydrydes. For carriers it can be defined as the enthalpy of reaction, but for the system it should take into account heat losses due to thermal exchanges.*
   *References SOA 2020:*
   - *Release hydrogen use heat exchange, carriers by chemisorption, MT:* Depending on type of hydrogen carrier;
   - *Release hydrogen use heat exchange, carriers by chemisorption, HT:* Magnesium based materials for hydrogen based energy storage: Past, present and future, V. A. Yartis et al., IJHE (2019), doi: 10.1016/j.ijhydene.2018.12.212;
   - *Release hydrogen use heat exchange, liquid organic hydrogen carriers:* Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy. Accounts of Chemical Research, Preuster, P., Papp, C., & Wasserscheid, P. (2016). *50(1), 74–85;*
5) *Removed heat power for Kg of stored hydrogen to maintain cryogenic storage at staedy state;*
6) *Degradation in hydrogen storage capacity as missing % for cycle with hydrogen purity 5N;*
   *References SOA 2020:*
   - *Degradation, Liquid organic hydrogen carriers:* Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain, : Energy Environ. Sci. (2019), doi: 10.1039/c8ee02700e;
7) *Hydrogen permeability in the hydroen storage tank. As NL for day and $m^2$ of storage tank surface. Reported value from: DOE MYYP targets in (g/h)/kg $H_{2\ stored}$ ;*
8) *Tensile streght of materials for vessel tank for $H_2$ storage;*
9) *Tensile streght of materials for vessel tank for $H_2$ storage;*
10) *Capital cost for hydrogen storage system per Kg of stored hydrogen;*
11) *Kinetic sorption expressed as percentage of hydrogen capacity (% w/w) per minute;*