Annex I to the Seed Paper on Production:

KPIs for electrolysers technologies

The following key performance indicators (KPI) are taken from two reports published by the International Renewable Energy Agency (IRENA 2020: GREEN HYDROGEN COST REDUCTION: SCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL) and a joint initiative of the European Energy Research Alliance, Joint Research Programme on Fuel Cells and Hydrogen technologies (JP FCH), Hydrogen Europe Research (HER) and the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) (EERA, JP FCH, HER, FCH JU 2020: KEY PERFORMANCE INDICATORS (KPIS) FOR FCH RESEARCH AND INNOVATION, 2020 – 2030).

2020 KPIs

The research and development of materials, thin films, components, cells, stacks, systems peripherals, and integration for water electrolysers is very much dependent on the definition of a solid and trustworthy state-of-the-art that correctly represents what can currently be found at the commercial level. Only a reliable state-of-the-art allows the implementation of solid baselines to different metrics, such as the physicochemical characteristics of materials, performance, selectivity, durability, cost, and so on. PEM and alkaline electrolysers have historically relatively well-defined benchmarks, with metrics fairly well known by the R&D community and industry. This is unfortunately not the case for solid oxide and AEM electrolysers. These are of high potential, but are also much less mature technologies, with only a few companies and OEMs interested or involved in their manufacture and commercialisation.

Alkaline electrolysers

Concerning stacks for alkaline electrolysers, the key areas to focus on are the electrodes and the diaphragms. Bipolar plates and PTLs have less priority, since they are based on stainless steel plates coated with nickel, which are already significant, cost-effective components. Strategies to integrate PTLs into electrodes and consequently diaphragms can also be of key importance in reducing costs, as outlined below:

Increase current densities: The current densities of the stacks can be increased, from the current, 0.5 A/cm² to more advanced units of 2-3 A/cm². This current density increase cannot be made, however, at the penalty of lower efficiency.

Higher current densities have already been accomplished by some manufacturers, too, with electrode-separator packages that can deliver a performance range as high as 1.2 A/cm^2 at 2 volts (V) now available. Power densities of 2-3 W/cm^2 could be achieved by demonstrating thinner diaphragms or membranes for alkaline electrolysers. As with PEM, alkaline electrolysers also need to improve their voltage efficiency levels, reducing ohmic losses and increasing electrode kinetics.

Reducing diaphragm thickness: This could improve efficiency and reduce electricity consumption. The thinner the diaphragms, the lower the resistance to transporting the OH^- species from the cathode to the anode. Eventually, however, this comes at a cost of higher gas permeation, which contributes to higher safety concerns. The other downside is the lower durability, given the higher chance of pinhole formation in the diaphragm and less mechanical robustness. Overall, the diaphragm thickness should reach values that approach those of PEM and AEM. State-of-the-art membranes for PEM are about 125-175 micrometres (µm) (Babic, 2017) with a potential decrease to 20 µm or lower. Below this point (for PEM), there are limited efficiency benefits. For alkaline electrolysers, the current diaphragm thickness is about 460 µm. Decreasing this to 50 µm would contribute to improving the efficiency from 53% to 75% at 1 A/cm².

Re-designing catalyst compositions and electrode architectures into electrodes with a high specific surface area: Despite using cheap and widely available Nickel based catalysts for their electrodes, alkaline electrolysers have traditionally encountered many challenges in moving away from rudimentary, or archaic electrode designs and reaching much higher efficiencies for both hydrogen and oxygen evolution reactions. Efficiency differences with other technologies are small and best-in-class designs result in even higher efficiencies. Table 2 shows a list with the ten main R&D aspects that need to be addressed, so that electrodes used in these stacks can be transformed and implemented in more advanced stack concepts.

Apart from increasing surface area, which was traditionally and simply achieved with Raney-Ni catalysts (nickel-aluminium [Ni-Al], or nickelzinc [Ni-Zn]), the other points are considered moderate and difficult challenges. In addition, any novel concept still needs to keep long-term durability, comparable to those presented by current nickelcoated stainless steel perforated sheets. That is the reason why Raney-Ni electrodes have not been commercially deployed, at least not in large-scale electrodes, since they have presented some critical durability aspects for long-term operation (low mechanical robustness) and much higher costs, due to the use of expensive manufacturing techniques.

Novel PTL concepts: Alkaline electrolysers are also not well developed in the use of efficient PTLs, potentially based on nickel. This is especially so in regard to optimising these for reduction of mass transport limitations (*e.g.* gas bubble resistance, trapped inside alkaline PTLs), and optimal protective coating alternatives to decrease interface resistances on the anode side.

PEM electrolysers

Re-designing the stacks can achieve large cost reductions, since it enables the reaching of higher power densities, up from the current (conservative) 2A/cm² to 6A/cm² or more in the next few decades. Next, electrodes should be scaled up from the current 1 500-2 000 cm², up to 5 000 cm² and eventually 10 000 cm². The larger area should go in tandem with more mechanically robust membranes that can use the same thickness. Such a strategy would allow an increase in the size of the PEM stacks, from the current 1 MW/unit to next generation stacks of 5 MW or even 10 MW per stack. These need to run at much lower levels of cell voltage to allow for an increase in efficiency and the simplification of waste heat management. Reducing membrane thickness: This enables an increase in efficiency, which in turn enables a reduction in electricity consumption. Thick membranes (Nafion N117 with approximately 180 µm thickness, for example) are still state-of the-art and are responsible for efficiency losses of about 25% (at 2A/cm²). There are much thinner membranes that are commercially available, with thicknesses as low as 20 µm, yet these are not designed for electrolysis requirements. This thickness reduction would allow a reduction in efficiency losses to about 6% (at 2A/cm²). Further reduction of membrane thickness, down to 5.0 µm or lower (membraneless electrolysis), is not encouraged, since a decrease of no more than 0.5 kWh/Kg H2 can be extrapolated. In this case, R&D is therefore not justified. Looking at the experience in PEM fuel cells (reverse process of electrolysis), commercial stacks are already equipped with membranes that are 810 µm thick, as gas permeation is not a concern, since they operate a much lower pressures (36 bar) on the air side.

The two challenges that arise with thinner membranes are: their lower durability, given their potentially lower mechanical strength and being more prone to defects and pinhole failures; and the manufacturing of such membranes. During manufacturing, the process of enlarging the catalyst coated membranes and porous transport layers into large electrodes is challenging and therefore of high R&D risk. The thin membrane and electrodes need to be mechanically stabilised over the full area to avoid undesired mechanical stresses that can tear these films and delaminate thin electrodes. This is especially critical at differential pressure operations, where one side is subjected to much higher pressures coming from the other electrode.

Re-designing PTLs will be crucial – i.e. with finer structures at the catalyst interface that can better support a thinner membrane and prevent creep failure, thereby enabling lower membrane thickness.

Removing expensive coatings and redesigning the PTLs and bipolar plates: On the anode side, commercial stacks demand the use of platinum coated titanium porous sintered PTLs, which is not possible with non-PGMs at this stage. Platinum loadings on the anodic PTL vary from 1-5 milligrammes per square centimetre (mg/cm^2) or 1 2.5 g/kW. Platinum has a dual purpose: to protect the titanium against passivation17 and provide an optimal interface resistance. This is needed because titanium is prone to severe quick and detrimental passivation. Studies have shown that interface resistance at the PTL is responsible for an electricity consumption as high as 1.35 kWh/Kg H2 (4% of hydrogen LHV) (Liu et al., 2018; Kang et al., 2020). The bipolar plates made of titanium also possess protective layers of platinum on the anode side, and gold on the cathode. Alternatives are needed for titanium plates, based on such materials as niobium, tantalum and eventually stainless steel approaches, but using protective coatings that are stable and also free from platinum or gold.

Re-designing catalyst-coated membranes: For catalyst coated membranes (electrodes), the strategy can be divided into different timescale scenarios. An initial approach could be to tackle the economies of scale for CCM fabrication via automation over manufacturing, establishing more reliable and less expensive supply-chains for catalysts and membranes, and implementing quality control. If possible, parallel work can be done to reduce the amount of electrocatalysts by re-engineering the electrodes over the membrane. Supply chain for PFSA membranes: For PFSA membranes, various suppliers (e.g. Chemours, Solvay, Asahi-Kasei, 3M and Gore) are available. This is also one of the most solid supply chains for PEM components. Moreover, these membranes have been traditionally supplied at scale for chloroalkali electrolysers, with membranes reaching areas as high as 3 m^2. Therefore, significant cost reduction is expected as soon as PEM water electrolysers reach high market volumes.

AEM electrolysers

In terms of components, the AEM membrane and ionomer are the main and most challenging. In terms of performance, the most critical item is durability, but also conductivity. Research efforts are targeted to finding AEM membranes with desirable properties (high mechanical, thermal, and chemical stability, ionic conductivity, and lower permeability with respect to electrons and gases). The polymer backbone is responsible for mechanical and thermal stability. The functional group that transports the OH- anion is accountable for the ion exchange capacity, ionic conductivity, and transport number. The trade-off for AEM is between mechanical stability, ionic conductivity and cost. For instance, the production of commercial AEM that achieves a high mechanical stability and high ionic conductivity is challenging and therefore expensive. There are known chemical strategies to increase the AEM ionic conductivity, but it leads to loss of mechanical strength due to excessive water uptake. The AEM then becomes chemically unstable, which leads to poor ionic conductivity. Another major limitation of an AEM is degradation of the polymer due to KOH attack, which quickly reduces the conductivity of the membrane and ionomer within the catalyst layer. The ionic conductivity of an AEM plays a significant role in the performance of the AEM. Higher levels of ion conductivity allow much higher current densities to be achieved. Tasks to increase efficiency and durability of electrodes and PTLs are analogous to those related to alkaline electrolysers. A progress in this direction has been made by the company Dioxide Materials that produces AEMs for water electrolysers (e.g. Sustanion X37 type membranes).

Solid Oxide Electrolysers

The potential for this technology lies in its higher efficiency, while its main challenge is durability. Some of the areas to focus on are: the improvement of electrolyte conductivity, optimisation of chemical and mechanical stability, matching the thermal expansion coefficient to both electrodes, and ensuring minimal reactant crossover. State-of-the-art electrolytes used in these cells have already exhibited remarkable conductivity for stack operation for thousands of hours, but the degradation of the electrolyte (which translates into a reduction in performance) is still of high importance for research. Structural changes within the electrolyte accelerate the formation of voids within its structure, increasing electrolyte resistance. Moreover, electrolyte also reacts with vaporised water and forms volatile products such as nickel hydroxide (Ni(OH)2) that also deactivates it. As for the other electrolysis technologies, electrodes used for solid oxide stacks are key components, and many key properties are required to provide high efficiency and durability. Table 5 provides a list of challenges and their respective ranking related to future R&D tasks to improve them, both to reach higher efficiency and durability.

Table 1. State-of-the-art and future KPIs for all electrolyser technologies.

	2020	Target 2050	R&D focus
	PEM electrolysers		
Nominal current density	1-2 A/cm²	4-6 A/cm2	Design, membrane
Voltage range (limits)	1.4-2.5 V	< 1.7 V	Catalyst, membrane
Operating temperature	50-80°C	80°C	Effect on durability
Cell pressure	< 30 bar	> 70 bar	Membrane, reconversion catalysts
Load range	5%-120%	5%-300%	Membrane
H_2 purity	99.9%-99.9999%	Same	Membrane
Voltage efficiency (LHV)	50%-68%	>80%	Catalysts
Electrical efficiency (stack)	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2	Catalysts/membrane
Electrical efficiency (system)	50-83 kWh/Kg H_2	< 45 kWh/Kg H_2	Balance of plant
Lifetime (stack)	50 000-80 000 hours	100 000-120 000 hours	Membrane, catalysts, PTLs
Stack unit size	1 MW	10 MW	MEA, PTL
Electrode area	1 500 cm²	> 10 000 cm²	MEA, PTL
Cold start (to nominal load)	< 20 minutes	< 5 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	USD 400/kW	< USD 100/kW	MEA, PTLs, BPs

Capital Costs (system) minimum 10 MW	700-1400 USD/kW	< 200 USD/kW	Rectifier, water purification
	Alkaline electrolysers		
Nominal current density	0.2-0.8 A/cm²	> 2 A/cm²	Diaphragm
Voltage range (limits)	1.4-3 V	< 1.7 V	Catalysts
Operating temperature	70-90°C	> 90°C	Diaphragm, frames, balance of plant components
Cell pressure	< 30 bar	> 70 bar	Diaphragm, cell, frames
Load range	15%-100%	5%-300%	Diaphragm
H_2 purity	99.9%-99.9998%	> 99.9999%	Diaphragm
Voltage efficiency (LHV)	50%-68%	> 70%	Catalysts, temperature
Electrical efficiency (stack)	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2	Diaphragm, catalysts
Electrical efficiency (system)	50-78 kWh/Kg H_2	< 45 kWh/Kg H_2	Balance of plant
Lifetime (stack)	60 000 hours	100 000 hours	Electrodes
Stack unit size	1 MW	10 MW	Electrodes
Electrode area	10 000-30 000 cm²	30 000 cm²	Electrodes
Cold start (to nominal load)	< 50 minutes	< 30 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	USD 270/kW	< USD 100/kW	Electrodes
Capital costs (system) minimum 10 MW	USD 500-1 000/kW	< USD 200/kW	Balance of plant
	AEM electrolysers		
Nominal current density	0.2-2 A/cm²	> 2 A/cm2	Membrane, reconversion catalysts
Voltage range (limits)	1.4-2.0 V	< 2 V	Catalyst
Operating temperature	40-60°C	80°C	Effect on durability
Cell pressure	< 35 bar	> 70 bar	Membrane
Load range	5%-100%	5%-200%	Membrane
H_2 purity	99.9%-99.999%	> 99.9999%	Membrane
Voltage efficiency (LHV)	52%-67%	> 75%	Catalysts
Electrical efficiency (stack)	51.5-66 kWh/Kg H_2	< 42 kWh/Kg H_2	Catalysts/membrane
Electrical efficiency (system)	57-69 kWh/Kg H_2	< 45 kWh/Kg H_2	Balance of plant

Lifetime (stack)	> 5 000 hours	100 000 hours	Membrane, electrodes
Stack unit size	2.5 kW	2 MW	MEA
Electrode area	< 300 cm²	1 000 cm²	MEA
Cold start (to nominal load)	< 20 minutes	< 5 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	Unknown	< USD 100/kW	MEA
Capital costs (system) minimum 10 MW	Unknown	< USD 200/kW	Rectifier
	Solid oxide electrolysers		
Nominal current density	0.3-1 A/cm²	> 2 A/cm²	Electrolyte, electrodes
Voltage range (limits)	1.0-1.5 V	< 1.48 V	Catalysts
Operating temperature	700-850°C	< 600°C	Electrolyte
Cell pressure	1 bar	> 20 bar	Electrolyte, electrodes
Load range	30%-125%	0%-200%	Electrolyte, electrodes
H_2 purity	99.9%	> 99.9999%	Electrolyte, electrodes
Voltage efficiency (LHV)	75%-85 %	> 85%	Catalysts
Electrical efficiency (stack)	35-50 kWh/Kg H_2	< 35 kWh/Kg H_2	Electrolyte, electrodes
Electrical efficiency (system)	40-50 kWh/Kg H_2	< 40 kWh/Kg H_2	Balance of plant
Lifetime (stack)	< 20 000 hours	80 000 hours	All
Stack unit size	5 kW	200 kW	All
Electrode area	200 cm²	500 cm²	All
Cold start (to nominal load)	> 600 minutes	< 300 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	> USD 2 000/kW	< USD 200/kW	Electrolyte, electrodes
Capital costs (system) minimum 1 MW	Unknown	< USD 300/kW	All

EERA Key Performance Indicators (KPIs) for FCH research and innovation, 2020 – 2030

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 presented below 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. 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 explicitly provided for each R&D-specific KPI. The appendix form of these R&D KPIs will allow to update the values more easily as technology progresses. In this Annex I of the Seed Paper we provide only KPIs for various electrolyser technologies.

Application-specific KPIs established in the FCH JU MAWP (2014-2020)

Table 2. 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; outputof 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;*
5) *The critical raw material considered here is Cobalt. Other materials can be used as the anode or cathodecatalysts for alkaline electrolysers. 7,3 mg/W derives from a cell potential of 1,7 V and a current densityof 0,5 A/cm², equivalent to 6,2 mg/cm².*

Table 3. 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 forimmediate ramp-up. Power consumption at hot idle as percentage of nominal power, measured at 15°Coutside 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 4. 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)/y	n.a.	600	225	120	75

		r					
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 ofhydrogen 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, dividedby the lower heating value of hydrogen consumed;

6) Reversible capacity is defined as a percentage of the electric capacity in electrolyser mode;

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 5. 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	H2/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

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.

Table 6. State-of-the-art and future KPIs 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	mΩcm^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 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)*

Table 7. 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	Ωcm^2	All cell technologies	At respective operation temperature	0.25	<0.1	A.1.8 no.1,5 A.1.9 no.1,8 A.1.10 no.1
2	Current density	A/cm^2	Fuel Cell	At respective operation temperature, 50 mV overpotential (FC anode) 100 mV (FC cathode)	0.3	0.8	A1.13 no.6 A1.14 no.6 A1.15 no.6
			Electrolysis	100 mV (cathode) 200 mV (anode)	0.6	>1	A.1.8 no.4 A.1.9 no.7 A.1.10 no.7

3	Catalysts/electro dedurability	hours	All cell technologies	Under relevant operation conditions	5000-10000	>40000	A.1.8 no.4, 3 A.1.9 no.7, 3 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 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)	Ω.cm²	SOE	700°C-900°C 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*

Table 8. 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) ~ 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/ 8-20	~ 0.5/2	
6	GDL Gas permeability (in-plane/through-plane) (1)	m²	PEMFC		~ 10^{-11}- to 10^{-12} ~ 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 Ez~10-100		
12	Open porosity	%	PEMFC		~ 70-80 (GDM) ~ 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 A.1.9 no. 3 A.1.13 no.2,4 A.1.14 no.2,4 A.1.15 no.2,4
14	Interconnect cost target	€/kW	PEMFC,PEMEC,AEC			<3	A.1.8 no.2 A.1.9 no. 2
15	Electrical conductivity	S/cm	PEMFC,PEMEC,AEC			>100	A.1.8 no.1 A.1.9 no. 1
16	Interconnect lifetime	hours	SOFC, SOEC		40k	>100k	A.1.10 no. 4 A.1.13 no.2,4 A.1.14 no.2,4 A.1.15 no.2,4

17	Interconnect (w/o Cr-barrier layer)cost target	€/kW	SOFC (for SOEC, divide by 3)	Small series	1300-1800	<300	A.1.10 no. 3 A.1.13 no.1 A.1.14 no.1 A.1.15 no.1
18	Cost target Cr-barrier coating	€/kW	SOFC (for SOEC, divide by 3)		1050	30	A.1.10 no. 3 A.1.13 no.1 A.1.14 no.1 A.1.15 no.1
18a	Cost target Cr-barrier coating	€/kW	SOFC (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 (steam electrolysis)	700°C – 750°C (ASC) 800°C -900°C (ESC) 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 co-electrolysis	700°C – 750°C (ASC) 800°C -900°C (ESC) Steady state	-	<10	A.1.10 no. 1, 5
21	Deagradation by cycling (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 (contact losses?)	% V/cycle	SOEC		0,3	0,05	
22	SOFC sealing life time	Therma lcycles	SOFC, SOEC	Ambient – 700°C	<100	200-1000 (TBD, 2 different inputs provide d)	A.1.10 no. 4 A.1.13 no.2,4 A.1.14 no.2,4 A.1.15 no.2,4
23	Cost of stack sealant	€/kW	SOFC (for SOEC, divide by 3to 4)	Small series productio	500	45	A.1.10 no. 3 A.1.13 no.1 A.1.14 no.1 A.1.15 no.1

				n			
24	Cost of electrode contact material	€/kW	SOFC (for SOEC, divide by 3to 4)	Mesh of Nickel wire	70	5	A.1.10 no. 3 A.1.13 no.1 A.1.14 no.1 A.1.15 no.1
25	ASR of electrode-contact-layer	mOhm/cm ^{2}	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.*

Table 9. 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) A.1.13-15 no.5 (MTBF)
	Oxidation mass gain	mg/1000	Steel components in HT systems	Operating		< 0.2	A.1.10 no.4 (O&M) A.1.13-15 no.5 (MTBF)

		hrs		conditions			
2	Cost of materials	€/kg	All BoP parts	n.a.		< 5	A.1.8-9 no.2 (CAPEX) A.1.10 no.3 (CAPEX) 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) A.1.10 no.3 (CAPEX) 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 A.1.14 no.6, 7 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 A.1.13 no.1 A.1.14 no.1 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 A.1.14 no.6, 7 A.1.15 no.6, 7

Table 10. 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 A.1.2 no. 3 A.1.3 no. 3 A.1.4 no. 2 A.1.5 no. 4, 5 A.1.13 no. 3, 5 A.1.14 no. 3, 5 A.1.15 no. 3, 5
2	Fault Detection & Isolation accuracy	%	PEMFC, SOFC	faulty states	95	99	A.1.1 no. 3 A.1.2 no. 3 A.1.3 no. 3 A.1.4 no. 2 A.1.5 no. 4, 5 A.1.13 no. 3, 5 A.1.14 no. 3, 5 A.1.15 no. 3, 5
3	Fault Detection & Isolation precision	%	PEMFC, SOFC	faulty states	95	99	A.1.1 no. 3 A.1.2 no. 3 A.1.3 no. 3 A.1.4 no. 2 A.1.5 no. 4, 5 A.1.13 no. 3, 5 A.1.14 no. 3, 5 A.1.15 no. 3, 5
4	False alarm rate	%	PEMFC, SOFC	nominal states	5	2	A.1.1 no. 3 A.1.2 no. 3 A.1.3 no. 3 A.1.4 no. 2 A.1.5 no. 4, 5 A.1.13 no. 3, 5 A.1.14 no. 3, 5 A.1.15 no. 3, 5
No.	**Parameter**	**Uni**	**Applicable technology (e.g.**	**Applicable conditions (e.g.**	**SoA**	**Target 2030**	**Corresponding FCH JU MAWP KPIs**

		t	PEMFC, SOEC, …)	T, J, #cycles, …)	2020		(e.g. A.1.1 no.1)
5	Missed fault rate	%	PEMFC, SOFC	faulty states	5	2	A.1.1 no. 3 A.1.2 no. 3 A.1.3 no. 3 A.1.4 no. 2 A.1.5 no. 4, 5 A.1.13 no. 3, 5 A.1.14 no. 3, 5 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 A.1.2 no. 1,3 A.1.3 no. 1,3 A.1.4 no. 1,2,4 A.1.5 no. 4, 5 A.1.8 no. 4,5,6 A.1.9 no. 4,5,6 A.1.10 no. 5,7 A.1.13 no. 3, 5 A.1.14 no. 3, 5 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;*

Table 11. 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							
			Electrochemical		190-1900		

			compressor				
1	Capital cost compressor	€/(kg/day)	Thermochemical compressor	120 kg/day. 2.4 pressure ratio.	1083-2550 1835 (24 kg/day) 1041 (2400 kg/day)	500	A.1.7 no. 9 A.1.11 no.2,4
2	Operating cost compression	€/yr	Electrochemical compressor	n.a.		600	A.1.7 no. 7
			Thermochemical compressor	120 kg/day. 2.4 pressure ratio. 2000 h/yr 0.1€/kWh	1240		
3	Compression efficiency	kWh/kg kWh/kg kWh/kg	Electrochemical compressor	0.8-100 MPa	2		A.1.7 no. 3
			Thermochemical compressor	0.8-100 MPa	10-25%. 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)**

7	Capital Cost purificationsystem	€/(Kg/day)	(Pressure swing adsorption)	500 kg/day	1800 €/(kg/day)	450 €/(kg/day)	A.1.7 no. 9 A.1.11 no.2,4
			TSA (Temperature Swing Adsorption)				
			Membrane	25 kg/day			
7	Operative cost purificationsystem	€/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 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 H2/ g.h	Photocatalytic reforming ofalcohols (ethanol, glycerol)	Catalyst: PGM-free on titania Light: UV-A	10-15	>150	n.a
				Catalyst: PGM on titaniaLight: 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 hydridehydrogen 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. InternationalJournal 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 HydrogenCompressor. 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, BouleghlimatE, 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. IntJ 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*

Table 12. 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 H2/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 H2/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) (56)	+20%	n.a.

			Liquid Hydrogen	0.1 MPa, 20.25 K	40	+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)**
					70		
3.	Scalability	kg H2	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		can apply to A.1.4
4.	Release energyuse Heat exchange	kWh/kg H2	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	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	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 permeabilit y	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 systemCost	€/kg H2	Compressed gas	15 °C, 35 MPa			n.a.
				15 °C, 70 MPa	1500	300	A.1.6 no. 1 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)**
			Carriers by physisorption	77 K, 5.6 MPa			n.a.
				LT (RT-100°C),1MPa	10	5	n.a.

10.	Kinetics sorption	%/min	Carriers by chemisorption (e.g. metal/complex hydrides)	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 categoryare 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;*
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   - *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/;*

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- *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;
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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;*

Kinetic sorption expressed as percentage of hydrogen capacity (% w/w) per minute;

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