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Review and analysis of demonstration projects on power-to-X pathways in the world

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HIGHLIGHTS

- 192 Power-to-X demonstrations in 32 countries were identified.
- Results show that the investigated pathways diversified (towards industry recently).
- Balancing services are increasingly investigated via grid-connected demos.

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ABSTRACT

Transforming the energy system towards more sustainability can only be achieved through a combination of low-carbon energy, energy efficiency, and the coupling of energy sectors. In this context, the application of Power-to-Hydrogen concepts for managing demand, providing seasonal storage, and linking elements between different sectors has attracted significant interest during the last decade.

Demonstration is a key first step towards large-scale market introduction. This paper presents the results of a review of 192 Power-to-X demo projects in 32 countries. Results show that the features of demonstrations have evolved significantly over the years: electrolysis capacity has increased, both for PEM and alkaline systems, and the potential for balancing and ancillary services is increasingly investigated via grid-connected demos. The scope of Hydrogen-to-X pathways has also evolved over the years, mainly to include industry applications. This work was carried out under the umbrella of Task 38 of the IEA Hydrogen Technology Collaboration Programme.

Introduction

Transforming the energy system to a more sustainable system, with a significant reduction of CO_2 emissions in accordance with the Paris COP21 agreement [1], is the guiding principle of the national energy policies. 175 Parties of 197 have ratified the COP21 agreement [1], with the following goals: limit global warming below 2 °C above pre-industrial levels and aim to limit

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the increase to 1.5 °C, set global emissions to peak as soon as possible, reduce emissions in accordance with the best available science. Developing countries shall receive support for adapting to the targets and specific climate actions are developed in Parties. In Europe for instance, the climate goals are threefold [2]: i/At least 20% (2020), 40% (2030) and 80% (2050) cut in greenhouse gas emissions should be achieved compared to 1990 levels; ii/At least 20% (2020), 32% (2030) of total energy consumption from renewable energy should be reached, and iii/At least 20% (2020), 27% (2030) increase in energy efficiency should be gained.

Such a transformation is demanding and all the means need to be leveraged, i.e. a combination of low-carbon energy, energy efficiency, and the coupling of energy sectors [3]. Due to the increasing penetration of renewable energies in the energy mix, balancing generation and demand for grid stability is becoming increasingly challenging. Solutions like creating a transmission super-grid, smart grids and demand management, or back-up capacity implementation could assist in overcoming this issue; but new measures that go beyond increasing transmission and distribution capacity and flexible generation or consumption will need to be introduced to manage the grid efficiently, as the level of renewable energy sources is increased. In this context, hydrogen systems are included in the global discussion on energy system progression [4,5]. The application of Power-to-Hydrogen concepts for managing demand, providing seasonal storage, and the linking element between different sectors (electricity generation, gas grids, transport and industry), has attracted significant interest during the last decade [5].

Power-to-Hydrogen (PtH) can support the integration of fluctuating renewable sources of power generation and convert (surplus) electricity to hydrogen. Power-to-Hydrogen systems can be used on- or off-grid and serve as a measure to avoid curtailment of excess electricity, or adjust the power demand they represent to provide load balancing, stabilization, or other electricity grid services. This is made possible by the characteristics of hydrogen production through water electrolysis to quickly adjust the power consumption: electrolysers can reach full load operation in a few minutes, even a few seconds [6]. In addition, chemical energy carriers such as hydrogen can also facilitate large-scale long-term storage due to its high specific energy density and the comparatively low storage costs.

Further down the value chain the hydrogen can be deployed in a large portfolio of applications – termed as "Hydrogen-to-X" (HtX). Possible applications for hydrogen are: fuel cells in transport (HtF-H_2); other transport pathways include using hydrogen to produce synfuels such as methanol or biofuels (HtF-S), or gas fuels for transport (HtF-G), "green" gas through methanation (PtG-M) or direct blending of hydrogen with natural gas (PtG-H2) [7], in the industry e.g. refineries (HtI), heat generation (HtQ), production of chemicals (HtCh), and for re-electrification into the electricity grid or remote areas (HtP). Thereby, hydrogen interlinks the power sector to other energy intensive sectors (heat, transport, industry). This leads to consider an integrated energy system with interconnections between the energy carriers [8].

The total value chain from power generation to the usage of hydrogen in diverse applications is commonly termed "Power-to-X". Note that "Power-to-Gas" can be used in the literature to refer to PtH systems or PtG-M and PtG-H2 pathways. An attempt at categorizing precisely the different PtH – HtX pathways was presented in Dickinson et al. (2017) [9]. Fig. 1 summarizes the different Power-to-X pathways. 6 categories and 9 sub-categories are identified downstream hydrogen production ("Hydrogen-to-X" part).

In this context, Power-to-X demonstrations are developed throughout the world to explore the potential of Power-to-X by identifying previously established knowledge and remaining concepts which should be further developed, before reaching the market. This work, carried out under the umbrella of Task 38 of the International Energy Agency's Hydrogen Technology Collaboration Programme [10], aims at reviewing all the PtH and HtX demonstrations that have been implemented around the world, to analyse the general trends and coverage, and remaining unknowns. The focus is put on the existing demonstrations, i.e. projects having a purpose of learning about the technology or system. Investigating the commercial plants is beyond the scope of this paper. So is a prospective study on planned projects. Indeed, the ultimate goal is to propose a roadmap depicting the needs for future projects based on what was demonstrated so far (be it in technical, economic or other terms such as regulation), which will be done in collaboration with the IEA.

The following section briefly describes the methodology and selected parameters for a review of 192 demonstration projects in 32 regions (see Appendix 1). Section Results then provides the analysis of the results, focussing first on the Hydrogen-to-X part, and then on the electrolysis system (Power-to-Hydrogen). The aim is to provide insights about the general trends, and obviously not an in-depth analysis of each demonstration project.

Methodology

As stated in the introduction, 192 demonstration projects were reviewed using a methodology developed in several steps.

The demonstration projects were first identified, using the expertise of the Task 38 members. The time coverage started from the oldest demonstration that was identified (in the eighties) up to now.

Over 40 parameters characterizing the demonstrations were identified (see Appendix 2 for the list):

- Overview: Project location, start date, duration of demonstration, investigated pathways, consideration of services to the grid;
- Technical specifications: Type of electrolysis system, installed capacity of electrolyser, power supply scheme (on-grid, off-grid, on-grid + connection to renewable energy source (RES)), in case of renewable connection: type of power supply (e.g. all-in, excess power) and RES capacity, type of hydrogen storage (CHG, MH, CNG, salt cavern, etc.), capacity of hydrogen storage, hydrogen production mode (baseload, flexible), load factor and efficiency;
- Objectives: overall scope and demonstration objective(s); for example, technical, economic, other, and more

Category		Acronym	Definition
Power-to-Hydrogen	H_2	PtH	Hydrogen production (and storage when requested) from low-carbon electricity either from the grid or off-grid.
Hydrogen-to-Power		HtP	Supply of electricity to the grid from hydrogen with a fuel cell or a gas turbine
Hydrogen-to-Gas		HtG-H2	Hydrogen injection in natural gas grid
		HtG-M	synthetic methane injection in natural gas grid, synthetic methane is obtained from Hydrogen from PtH through methanation processes
Hydrogen-to-Fuel		HtF-H2	Hydrogen in a vehicle to be injected in a fuel cell
		HtF-S	Hydrogen for liquid synfuel applications: liquid biofuels, synthetic liquid fuels, methanol
		HtF-G	Hydrogen for mobility through gas fuels (Hythane®, biogas, synthetic methane)
Hydrogen-to-Industry		HtI	Hydrogen from PtH and for industrial applications (e.g. Refinery)
Hydrogen-to-Heat		HtQ	Hydrogen-to-heat via H2-fired boilers; Hydrogen-to-heat and power via CHPs (fuel cells, turbine etc.)
Hydrogen-to-Chemicals		HtCh	Other pathways to industrial chemical intermediates from hydrogen which we may want to include explicitly: 1. H2 to methanol to C2, C3 olefins 2. H2 to syngas to C2, C3 olefins 3. Methanol/syngas to >C1 hydrocarbons and >C1 alcohols 4. H2 to ammonia and formic acid (which could also be used as alternative renewable energy storage)

Fig. 1 – Power-to-X pathways.

specifically, when relevant: focus of technical objective (component, system, pathway), type of technical objective (operation validation, efficiency improvement, upscaling, etc.), type of economic objective (e.g. hydrogen production cost optimisation), type of regulatory objective;

- Results and maturity: Major technical results of the demonstrations, major economic results, technology readiness level (TRL) and market readiness level (MRL).
- Legal aspects: Specific regulations taken into account, certification scheme considered, green labeling for hydrogen production, policy support scheme, avoidance of grid fees, maximum hydrogen concentration in the natural gas grid, and incentives if any.
- Future plans: Planned future demonstrations, connection with other demonstrations, links to a roadmap, steps towards the market and messages to policy makers.

To collect the data for all the demonstrations, the demonstration coordinators were contacted directly using a template questionnaire. Also, data was collected from the literature. Over 200 references were consulted, including scientific papers, specific studies on Power-to-Gas projects, articles and news, dedicated platforms (European Power to Gas, DOE global energy storage database, EASE, Dena, etc.) [11–230].

The results are detailed and discussed in the following section. Note that the information regarding each demonstration project is not always available; therefore, the demonstration numbers may not always sum up to 192 (and each indicator listed in the Appendix 2 was not used). Moreover, multiple nominations may be allowed on certain indicators (such as the investigated pathways), which explains that, on the contrary, totals higher than 192 may be noticed.

Results

General outlook

192 demonstration projects were examined in 32 different countries, the HYSOLAR project being the first demonstration being identified in 1985, designed by the German Aerospace Center (DLR) and the University of Stuttgart, and implemented in two different countries (Saudi Arabia and Germany). Demonstration projects are implemented in each continent except for Africa (cf. Fig. 2), Europe leading the way with 154 projects, and more specifically Germany being far from the other countries with 50 demonstration plants. Demonstration projects have been installed for over twenty years, and we can notice a considerable increase from 2010 onwards. Of these projects, 69% are completed and 31% are still ongoing, which reflects hydrogen being on the current research agenda.

Pathway trends ("hydrogen-to-X")

Hydrogen is versatile. To investigate which pathways are more explored, Fig. 3 shows the number of demonstrations for each of the Hydrogen-to-X (HtX) pathways being identified in Fig. 1. Since each demonstration project can address more than one pathway, multiple nominations in different categories have been taken into account. Overall, the pathways that have been addressed most extensively are Hydrogen-to-Power (HtP) and Hydrogen-to-Fuel (HtF). As to the first, this is even more so if we take into account that 85% of the Hydrogen-to-heat (HtQ) projects are related to HtP as well through Combined Heat and Power (CHP) concepts. At first

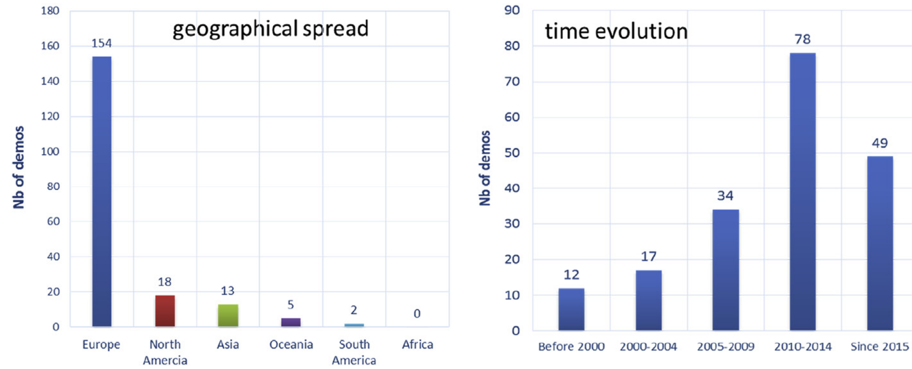

Fig. 2 – Geographical spread (left) and temporal evolution (right) of the number of demonstration projects.

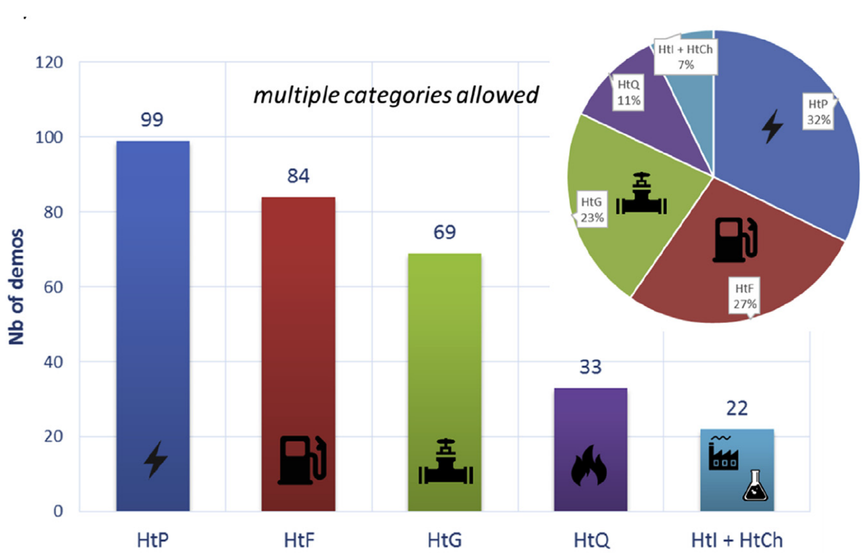

Fig. 3 – Share of each HtX application of the demonstration projects (multiple nomination allowed).

glance, hydrogen use for industry or chemical applications seems less investigated, with only 7% of demonstrations covering this pathway.

If we look at the temporal progression of the different pathways (cf. Fig. 4), HtP and HtF have also been the pathways that have raised interest first, which contributes to explain that they appear more often among the demonstrations: they have been investigated since the beginning and still are. Hydrogen-to-Gas (HtG) applications have emerged in the early 2000's and had a boom ten years later. Most recently, the number of demonstrations on Hydrogen-to-Industry (HtI) and Hydrogen-to-Chemicals (HtCh) have risen significantly, and are now close in number to the other pathways. Since they raised interest later, it is quite logical that, overall, there are fewer of them.

When we consider more specifically the role of H_2 as a fuel (HtF) or a gas (HtG), it can be seen in Fig. 5 that pure hydrogen as a fuel is the most investigated pathway, rather than H_2-based mixtures. It should be noted however that demonstrations on liquid synfuels only started in 2010, along with the interest for Hydrogen-to-Industry and Hydrogen-to-Chemicals as in the literature [230], making them as of today a viable alternative to pure H_2 gas for fuelling applications.

With respect to Hydrogen-to-Gas, Fig. 5 indicates that the injection of synthetic methane is more investigated than the direct injection and blending of pure hydrogen into the natural gas grid. This may be explained by the regulation challenges regarding the latter pathway (the allowed hydrogen concentration in the natural gas network may vary significantly from one region to another) [231]. However, this state of affairs also calls for demonstrations in order to establish the actual technical limits, push them back, and make regulation advance on this topic.

Fig. 6 illustrates how the different HtX pathways are being spread throughout the world. It is striking that the 2 demo projects identified in South-America are focussing only on HtP. This corroborates in a sense to the fact that HtP has also been the very first HtX pathway being investigated. There have been so far no demonstration project on Hydrogen-to-Industry or Chemicals in America, and none on Hydrogen-to-Heat in Asia. As to the first, Europe is clearly leading the way.

Finally, with respect to the multiple nominations, it can be seen in Fig. 7 that in most cases demonstration projects still focus on one specific application. However, demonstrations have gradually examined multiple pathways (up to 5) within

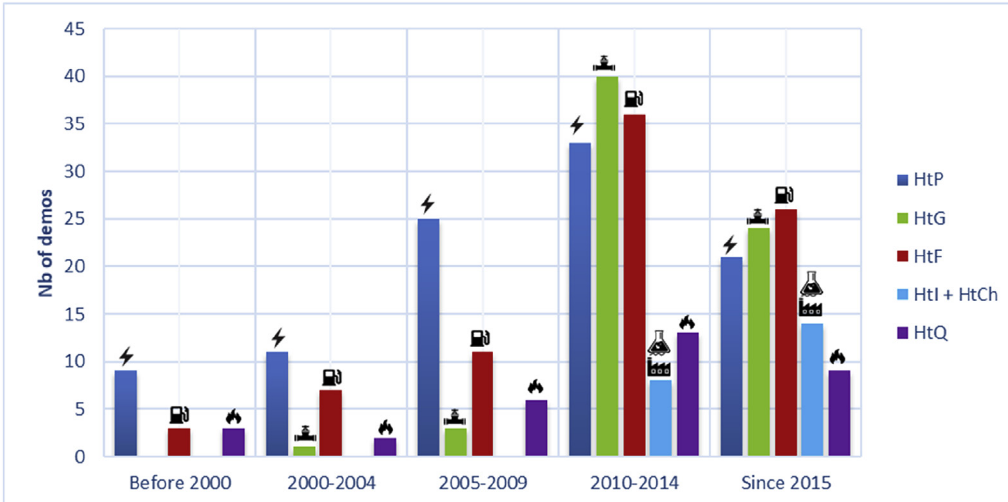

Fig. 4 – Evolution of HtX applications as a function of time (multiple nominations allowed).

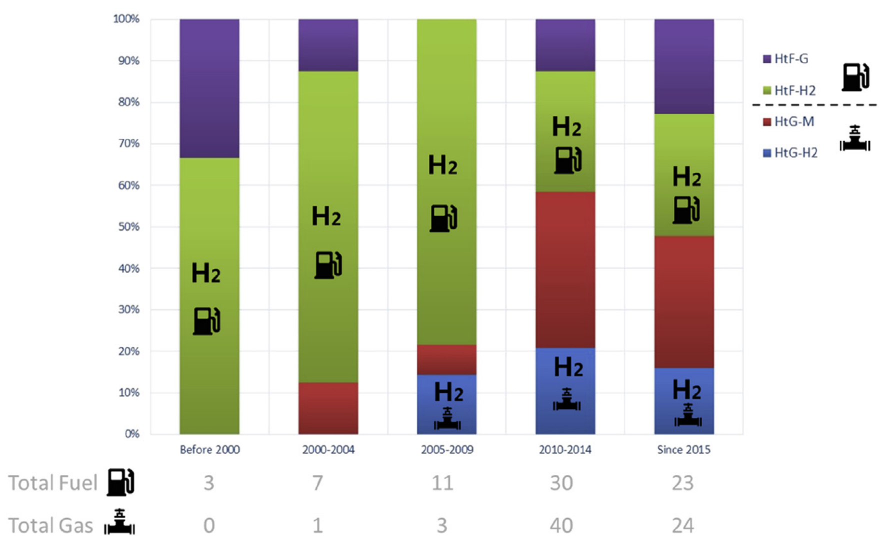

Fig. 5 – Time evolution of subcategories in Hydrogen-to-Fuel and Hydrogen-to-Gas.

the same project. In the recent years, the majority of demonstrations are dedicated to two or more applications. This trend reveals an increasing interest in investigating hydrogen versatility in the field.

Investigating a given pathway does not depend on how many applications are considered: all the pathways appear in the demonstrations, whatever how many pathways are being considered. In other words, each pathway seems relevant by itself.

Focus on power-to-hydrogen

In this section, the focus is put on the demonstration upstream: the Power-to-Hydrogen part, i.e. the production (and storage when requested) of hydrogen from low-carbon electricity, either from the grid or off-grid. As the power supply scheme is a crucial topic for the production of "green" or low-carbon hydrogen, the power source of the projects was identified and classified in three main categories: on-grid supply (connected to the power grid), off-grid supply (only powered by renewable energy installed nearby or micro-grids isolated from the public power grid), and "on-grid + RES", meaning that two connections co-exist: a direct connection with a renewable capacity, as well as a grid connection.

As shown in Fig. 8 (left), the majority of demonstrations have focused so far on off-grid systems (52% vs. 29% for on-grid demonstrations and 19% for on-grid + RES). Moreover, almost all of the renewables considered were coming from wind power (cf. Fig. 8 right). In recent years however, on-grid systems start to prevail (cf. Fig. 9). This may be due to the fact that the pathways may be investigated with a more

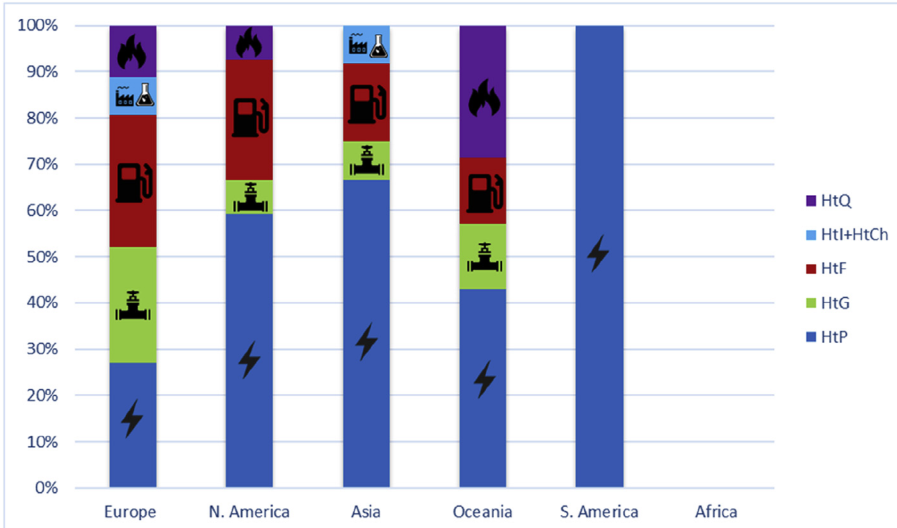

Fig. 6 – Geographical spread of HtX applications around the world.

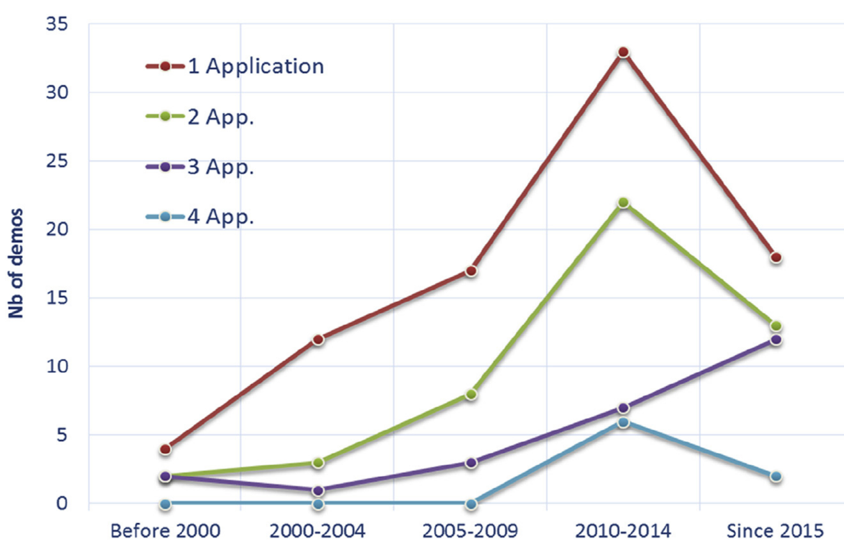

Fig. 7 – Time evolution of the versatility (number of HtX applications) of demonstrations.

holistic approach (what could be the contribution of hydrogen to the energy system), including the potential input to help balancing the electric system. Indeed, 41% of the demonstration projects that started after 2015 include grid balancing services, while only 22% in the period 2010–2014, 8% between 2000 and 2010, and zero before 2000.

Three electrolyser technologies are considered in general: alkaline electrolysers, PEM (Proton Exchange Membrane) electrolysers, and SOEC (Solid Oxide Electrolysis Cell) electrolysers. PEM electrolysis is the technology often promoted in a context of rising renewable energy shares, due to interesting features: high current densities (>2 A/cm^2), gas purity, compact system design and dynamic operation [232]. Alkaline electrolysers are commercially-available but less flexible, even though they can still be operated between 20 and 100% of the design capacity, and overload operation up to 150% is possible [16]. By 2030, the capital costs of these technologies are expected to converge [233]. SOEC electrolysers are at an earlier stage of development but may become a key technology in the energy system to come, thanks to specific features such as the potential to work in a reversible mode or to co-electrolyse water and carbon dioxide to produce syngas [234]. All these technologies are investigated by the project demonstrations. It can be seen in Fig. 10 that alkaline and PEM electrolysers are almost as often selected (50% of the demonstrations assess alkaline electrolysers; 42% PEM). As a result, the total installed capacity over the years is similar: 45.7 MW of alkaline electrolysis vs. 37.5 MW for PEM. The situation differs greatly for SOEC electrolysers. This technology, even though promising, is much less mature. As a result, demonstrations are still at a different

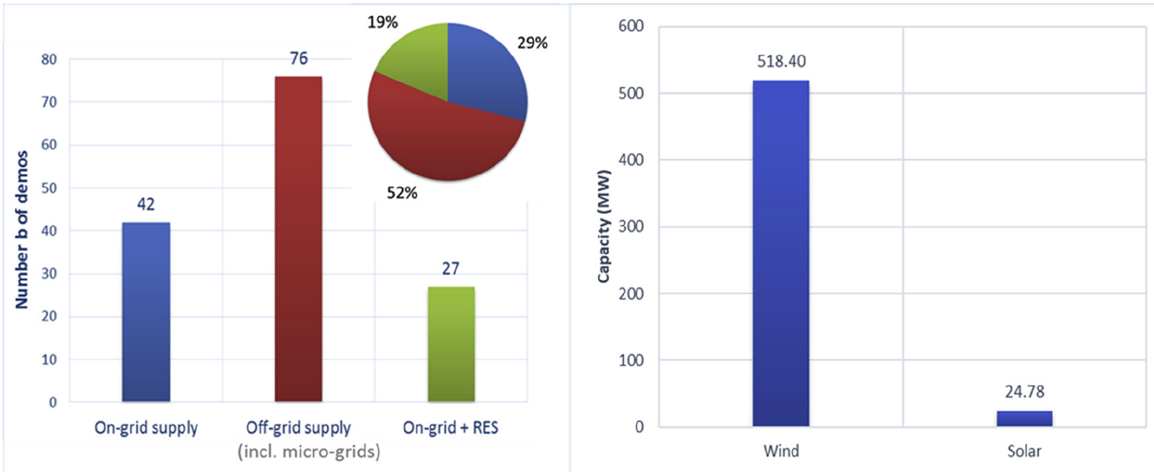

Fig. 8 – Power supply schemes (left) and origin of green power (right) for the P2H part of the demonstrations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 9 – Evolution of the power supply schemes as a function of time.

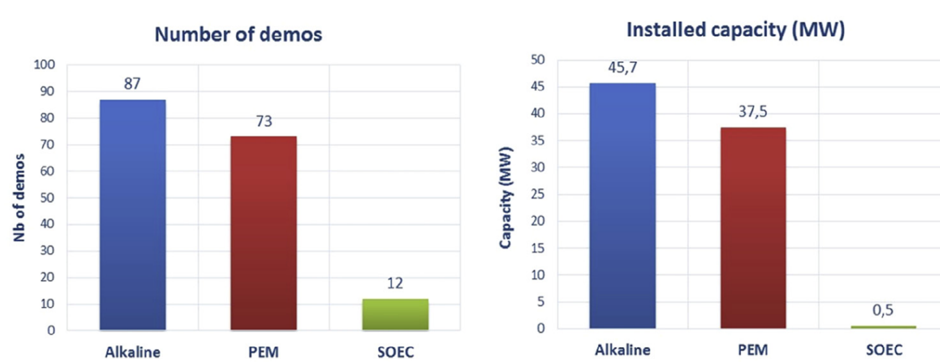

Fig. 10 – Number of demos (left) and total installed capacity (right) for the 3 types of electrolyser technologies.

scale: SOEC are investigated in only 8% of the demonstration projects, with a mere 0.55 MW being installed.

Figs. 11 and 12 consider in more detail the installed PtH electrolyser capacity as a function of starting date, both on a year-to-year basis (Fig. 11) and cumulatively (Fig. 12). Although alkaline is a more mature technology that was also installed first, very similar trends can be observed with a 5-year interval. Moreover, an upscaling phenomenon can be seen, the yearly total installed capacity per demonstration reaching 10 MW in recent years.

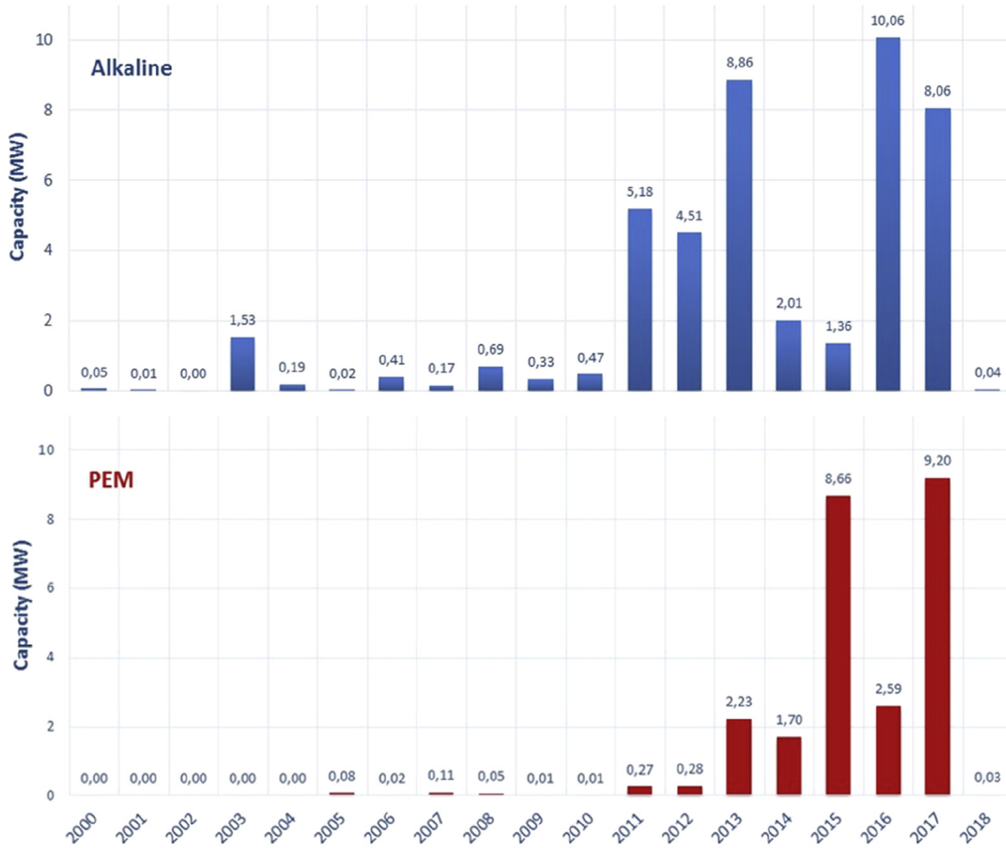

Fig. 11 – Total installed electrolyser capacity per demonstration project per year.

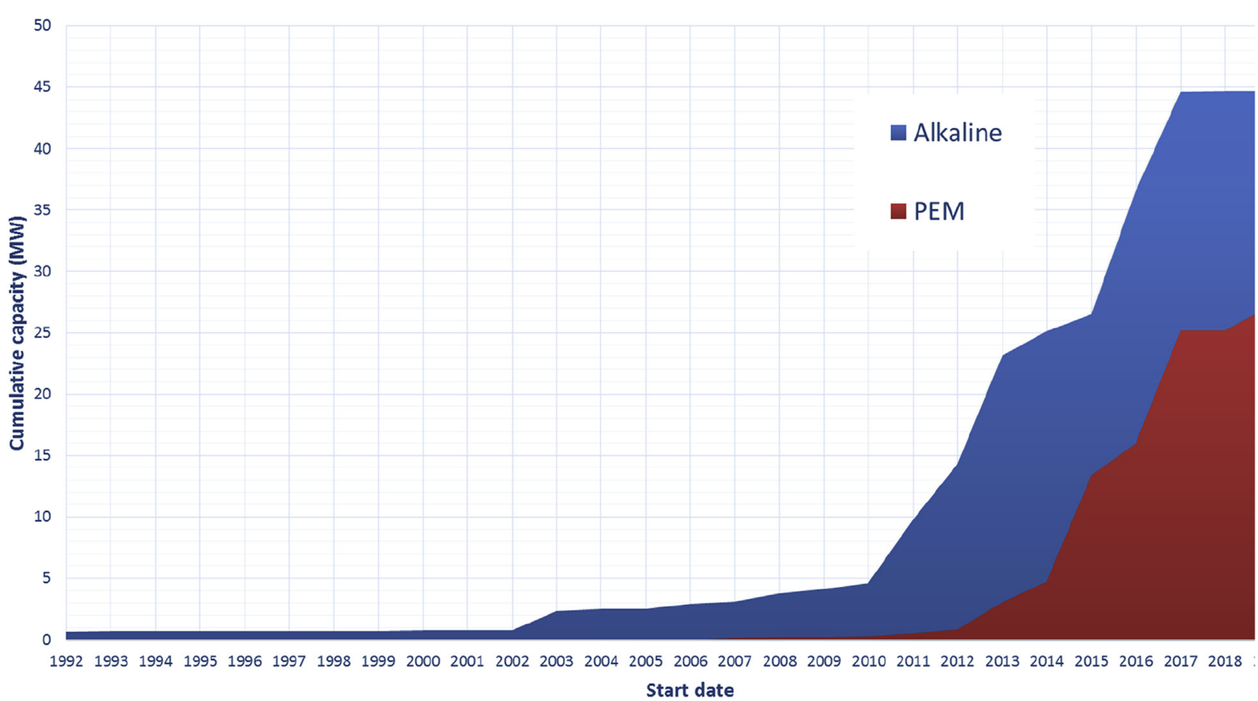

Fig. 12 – Comparison between the cumulative capacity of the Alkaline and PEM technologies.

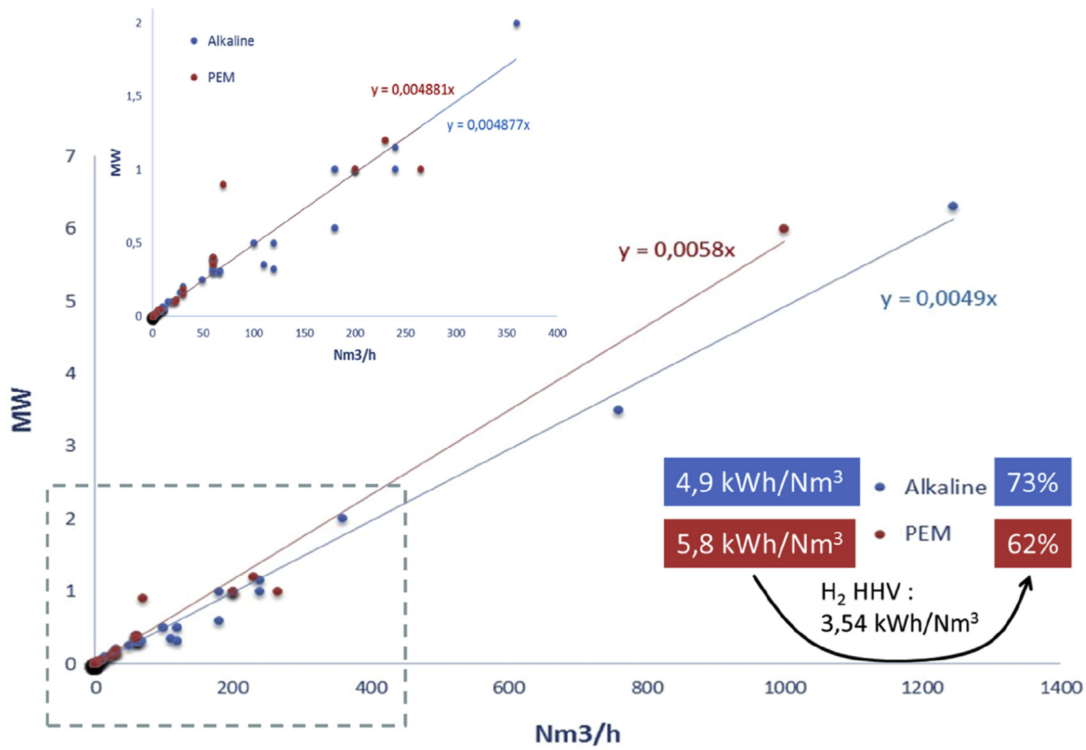

Fig. 13 – Installed electrolyser capacity (in MW) vs. H_2 output (in Nm^3/hr) for each demo project.

The electrolysis system efficiency was also assessed from the available data. To this end, the total installed electrolyser capacity (in MW) was plotted as a function of H_2 output (in Nm^3/hr), whenever available. The slope of a linear fit through such data is then inversely proportional to the system efficiency. The results are shown in Fig. 13. It appears that, contrary to what is often being claimed in the literature, no significant difference can be observed between alkaline and PEM systems. For ≤2 MW systems, the slopes are even identical, resulting in an average efficiency of 73%, based on a slope of 4.9 kWh/Nm^3 and a HHV value of 3.54 kWh/Nm^3.

Moreover, when looking at the temporal evolution in Fig. 14, the efficiency values are quite scattered, and no obvious trend can be observed. Also in the framework of Task 38 of IEA Hydrogen, an international network of experts assessed the techno-economic potential of Power-to-Hydrogen pathways. From their review of 230 internationally-published studies [235], two thirds of the studies assume an average electricity consumption of 45–50 kWh/kg_{H2}.

Finally, regarding storage, 79% of the demonstration projects that provide information on this matter, include a storage option. Most of these projects considered a compressed hydrogen gas technology to store the produced hydrogen (cf. Fig. 15).

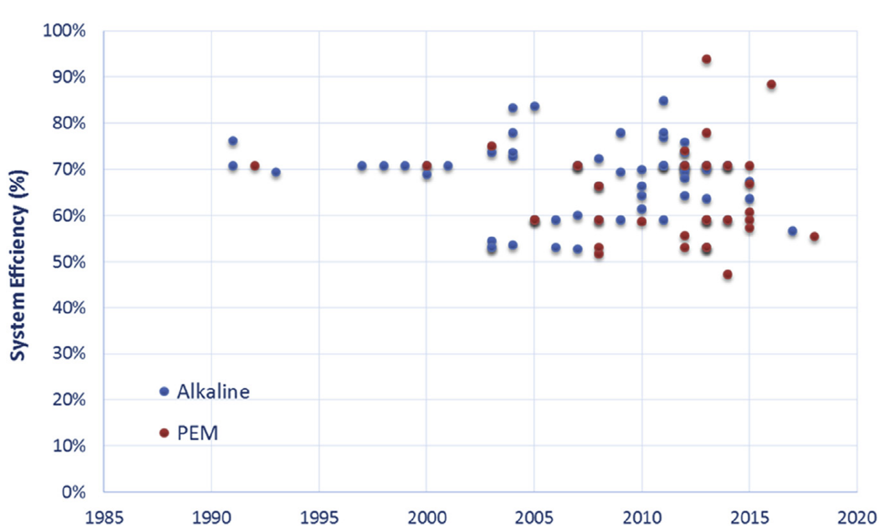

Fig. 14 – Evolution of Alkaline and PEM efficiencies in function of time, as calculated from Fig. 13.

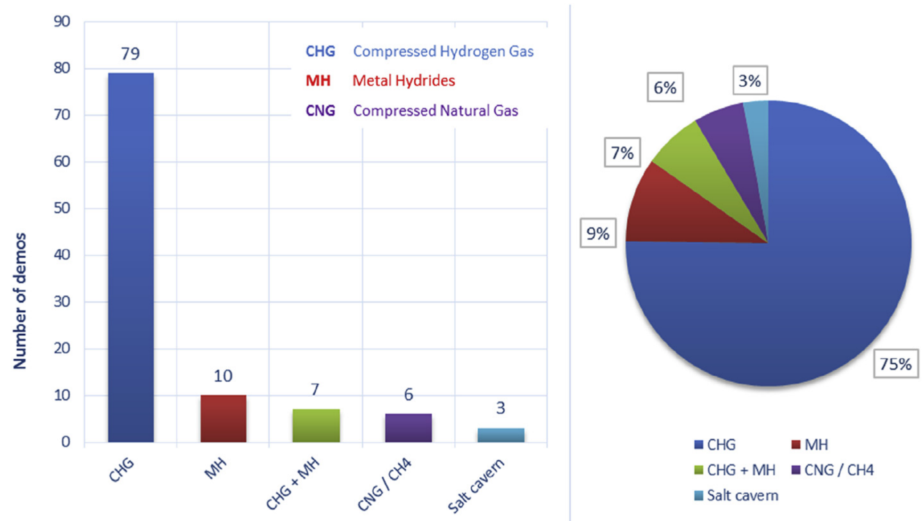

Fig. 15 – Demonstration storage technology.

Table 1 – Demonstration objectives.

Demonstration start date	Share of demonstrations with technical objective(s) only	Share of demonstrations with economic objective(s)
Before 2000	92%	8%
2000–2004	35%	47%
2005–2009	62%	18%
2010–2014	46%	41%
Since 2015	33%	39%
Total	58% (90 demos out of 156)	42% (66 demos out of 156)

Demonstration objectives

156 demonstration projects out of 192 have explicitly mentioned their objectives. In what follows, the percentages are based on these 156 projects.

100% of demonstrations have technical objectives, with 91% of these projects testing the operational validation, 88% evaluating the efficiency, and a mere 27% considering an upscaling plan. Since 2010, the interest in *only* the technical aspects of the demonstrations has been decreasing. Economic assessments are included in the demonstration objectives as well (cf. Table 1). 42% of the projects have an economic objective, of which only 14% consider the H_2 production cost though.

When studying the other targets of the projects, it appeared that most of the direct feedbacks received indicated a regulatory objective, while in the reviewed literature only 2% of the projects highlighted the regulatory aspect. This shows that the regulatory objectives are rather implicit subjects, yet crucial ones, as mentioned previously.

Conclusion

'Low-carbon' hydrogen (i.e. H_2 produced through low-carbon pathways) can be used by many energy-consuming services. It has a potential role to play in the electric, gas, transport, and industrial sectors. Demonstrations are a key step towards reaching the market.

A review of the Power-to-X projects in the world was carried out, identifying 192 demonstrations in 32 countries. Results show that the features of demonstrations evolved significantly in the recent years. The investigated pathways diversified, with a recent interest for industry applications. This is happening in the context of a recent and general momentum for industry applications, both at national and international levels [5,230] [236–238]. Also, recent studies showed that only approaches favoring synergies between sectors and acknowledging sector coupling can reveal the full potential of hydrogen to decarbonize the energy system [237–241]. Accordingly, demonstrations consider several applications simultaneously, together with an increase of on-grid systems investigating the potential of providing system balancing to the electric grid.

This reviewing work is the first step towards an international roadmap, to be designed with the IEA, in order to better identify what are the demonstrations that are required and focus the effort on the most relevant topics, in order to reach the different markets in the near term. The increasing installed capacities of electrolysers show that we are on the way.

Acknowledgements

The present work was carried out within the framework of Task 38 of the Hydrogen Technology Collaboration Programme of the International Energy Agency. The task is co-ordinated by the Institute for techno-economics of energy systems (I-tésé) of the CEA, supported by the ADEME. We would also like to acknowledge the support of Capenergies for this work. One of the authors (JP) wishes to acknowledge financial support from the Public Service of Wallonia – Dept. of Energy and Sustainable Building.

Appendix 1. list of the reviewed demonstration projects and location

Demo name	Location (country code)
Abalone Energie Nantes	FR
Aberdeen, Hydrogen bus project	UK
Aeropila	ES
Air Fuel Synthesis pilot plant	UK
Alzey, Exytron Null-E	DE
Ameland	NL
Baglan Energy Park Wales	UK
Balance	EU
Bio SNG Güssing	AT
BioPower2Gas, Allendorf, Eder	DE
BOEING (rSOC Demonstrator)	US
Carbazol pilot plant, University of Erlangen-Nürnberg	DE
CEC Denizli Turkey	TR
Cerro Pabellón Microgrid 450 kWh Hydrogen ESS - Enel S.p.A	CL
CHOCHCO	FR
CO2RRECT-Niederaussem	DE
Commercial Plant Svartsengi/George Olah plant	IS
CoSin: Synthetic Natural Gas from Sewage, Barcelona	ES
CUTE and HyFLEET:CUTE, Barcelona	ES
CUTE, Stockholm	SE
Delfzijl	NL
DEMETER	FR
Demo Plant Agricultural University Athens	GR
DEMO4GRID	AT
Demonstration of bio-CO2 products, Bio economy+	FI
Demonstration plant Kuala Terengganu, Malaysia	MY
DNV Kema/DNV GL	NL
Don Quichote	BE
DRI CO2 recycling	US
DTE Energy Hydrogen Technoly Park, Southfield Michigan	US
DVGW-EBI KIT - Demo-SNG	DE
ECTOS	IS
EE-Methan aus CO2	AT
Ekolyser (R&D)	DE
El Tubo	ES
ElectroHgena	FR
ELYGRID (R&D)	EU
Emden I Biogas upgrading	DE
Emden II Upscaling	DE
Enbridge P2G toronto	CA
EnBW H2 station, Stuttgart	DE
Energiepark Mainz	DE
EON PtG plant Falkenhagen	DE
EON PtG plant Hamburg-Reitbrook	DE
ETOGAS, Solar Fuel Alpha-plant 250 kW, ZSW	DE
ETOGAS, Solar Fuel Alpha-plant mobile device, ZSW	DE
ETOGAS, Solar Fuel Beta-plant AUDI, Werlte (Audi e-gas)	DE
Etzel, Salt caverns	DE
Eucolino Schwandorf	DE
Fife, Levenmouth Community Energy Project	UK
FIRST - Showcase II	ES
FIRST project, INTA facility	ES
Foulum Demonstration plant	DK
Freiburg solar house	DE
Fronius Energy Cell, self-sufficient house	AT
Fronius HyLOG-Fleet (Hydrogen powered Logistic System)	AT
Fukushima Power-to-gas Hydrogen Project	JP
GenHyPEM (R&D)	EU
Green Natural Gas	DK
Greenhouse heating, solar-H2	IT
Greenpeace Energy Windgas Suderburg	DE
GRHYD (Hythane)	FR
GRHYD (inj in NG grid)	FR
Grimstad Renewable Energy Park	NO
GrInHy	DE
H2 from the sun, Brunate	IT
H2 research center BTU Cottbus	DE
H2BER (Berlin airport)	DE
H2FUTURE	AT
H2Herten	DE
H2KT - Hydrogen Energy Storage in Nuuk	GL
H2Move, Fraunhofer ISE	DE
H2ORIZON	DE
H2SusBuild/RES-H2	GR
HAEOLUS	NO
Haldor Topsoe - El-Opgraderet Biogas	DK
Haldor Topsoe - El-Opgraderet Biogas II	DK
Hamburg - Schnackenburgallee	DE
Hamburg Hafen City, CEP	DE
Hanau, Wolfgang Industrial Park	DE
HARI project, West Beacon Farm	UK
HARP System, Bella Coola	CA
Hassfurt	DE
Hawaii Hydrogen Power Park (phase 2)	US
Hebei- China	CN
HELMETH	DE
Hidrolica, Tahivilla	ES
Hitachi Zosen/CO2 Conversion to Methane Project	TH
HPEM2GAS (R&D)	DE
HyBALANCE	DK
Hybrid energy storage system NFCRC, California	US
Hybrid Power Plant Enertrag, Prenzlau	DE
Hychico, Comodoro Rivadavia	AR
HyCycle - Center for renewable H2 (R&D)	DK
Hydepark	TR
Hydrogen Island Aitutaki	CK
Hydrogen Island Bozcaada	TR
Hydrogen mini grid system Yorkshire (Rotherham)	UK
Hydrogen village Burgenland	AT
Hydrogen Wind Farm Sotavento	ES
HyFLEET:CUTE, Amesterdam	NL
HyFLEET:CUTE, Hamburg	DE
Hygreen	FR
HYLINK, Totara Valley	NZ

(continued on next page)

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Demo name	Location (country code)
HyNor Lillestrøm, Akershus Energy Park	NO
HYPOS (Leipzig)	DE
HySolar test bed Riyadh (R&D)	SA
HYSOLAR, Stuttgart	DE
HyWindBalance, Oldenburg	DE
INGRID	IT
IRENE System	CA
ITHER	ES
Jupiter 1000	FR
Kidman Park in Adelaide depot	AU
Laboratory Plant HRI Quebec	CA
Laboratory Plant Stralsund	DE
Laboratory System at IFE Kjeller	NO
Lam Takhong Wind Hydrogen Hybrid Project- EGAT	TH
LastEISys (R&D)	DE
MEDLYS, Medium temperature water electrolysis (R&D)	DK
MEFCO2	DE
MeGa-stoRE	DK
MeGa-stoRE Optimising and Upscaling	DK
METHYCENTRE	FR
MicrobEnergy GmbH, Schwandorf	DE
MicroPyros	DE
Minerve, Nantes	FR
MYRTE	FR
NEDO kofu city, Yamanashi Prefecture	JP
NEMO	FI
New zealand Matiu/Somes Island	NZ
NEXPEL (R&D)	NO
OptFuel	AT
P2G plant Erdgas Schwaben	DE
P2G-Biocat	DK
PHOEBUS	DE
Pilot & Demo PtM HSR	CH
Port-Jérôme	FR
PostBus Hydrogen bus, Brugg, aargau CHIC	CH
Power to flex	DE
Primolyzer (R&D)	DK
PROCON (R&D)	DK
PtG-Elektrolyse im MW-Maßstab (R&D)	DE
PURE Project, Unst	UK
PVFCSYS Agrate	IT
PVFCSYS Sophia Antipolis	FR
RABH2	UK
Raglan Nickel mine	CA
Ramea Wind-Hydrogen-Diesel Project	CA
Rapperswil	CH
Reduction and Reuse of CO2: Renewable Fuels for Electricity Production- ZHAW	CH
REFHYNE	DE
REFLEX	IT
Regenerativer Energipark Ostfalia/hybrid renewable energy park (HREP)	DE
RegEnKibo, Kirchheimbolanden	DE
Regio Energie Solothurn/Aarmat hybrid plant	CH
RENOVAGAS	ES
RES2H2 Gran Canaria	ES
RESelyser (R&D)	EU
Reussenköge	DE
RH2 WKA	DE
Rostock, Exytron Demonstrationsanlage	DE

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Demo name	Location (country code)
Rozenburg	NL
RWE PtG plant Ibbenbüren	DE
Samsø	DK
SAPHYS, ENEA	IT
Schatz Solar Hydrogen Project	US
SEE/Storage of electric energy	DE
Sir Samuel building Griffith Center, Brisbane, Australia	AU
Small Scale Renewable Power System DRI (Desert Research Institute)	US
SoCalGas/Southern California Gas	US
Solar-H2 Taleghan	IR
SPHYNX, R&D	FR
Stand-alone power system, Neo Olvio of Xanthi	GR
STORE And GO, Troia Italy	IT
Sunfire PtL demo "Fuel1"	DE
SWB Project, Neuburg vorm Wald	DE
SYNFUEL	DK
Tauron CO2-SNG	PL
The Hydrogen house	US
The Hydrogen office	UK
THEUS H2 Energy Storage, Takasago	JP
Thüga PtG plant Frankfurt/Main	DE
Tohoku pilot plant in 2003	JP
Towards the Methane Society	DK
Utsira Island	NO
Vestenskov/Nakskov Industrial and Environmental Park, Lolland	DK
WELTEMP, Water electrolysis at elevated temperature	EU
Wind2H2 Project NREL	US
Wind2Hydrogen, HyCentA	AT
Wind-H2 stand-alone system ENEA	IT
Wind-H2 Village Prince Edward Island	CA

Appendix 2. List of indicators

Indicator	% Av. data
Total number of demos	100%
Type of application	99%
Nb of demos completed	73%
Nb of ongoing demos	73%
Nb of demos vs start date	99%
Duration of demo	62%
Nb of demos including services	84%
Alkaline capacity MW	85%
PEM capacity MW	79%
SOEC capacity MW	85%
Nb of Alkaline demos	86%
Nb of PEM demos	86%
Nb of SOEC demos	86%
On-grid supply	76%
Off-grid supply	76%
On-grid + RES supply	76%
Nb of demos with wind supply	63%
Nb of demos with solar supply	60%
Instal led wind capacity (MW)	63%

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Indicator	% Av. data
Instal led solar capacity (MW)	60%
Supply scheme: Al l -in	63%
Supply scheme: Excess RES	63%
Demos incl. Storage option	74%
Shares of CHG storage	69%
Shares of MH storage	69%
Shares of CHG + MH storage	69%
Shares of CNG/CH4 storage	69%
Shares of Salt cavern storage	69%
Baseload H2 production	31%
Flexible H2 production	31%
Demos with tech. Obj. only	81%
Demos incl. Econ. Obj.	81%
Operation validation obj	83%
Efficiency obj	83%
Upscaling obj	83%
Pathway focus obj	83%
Regulatory obj	83%
Lobbying obj	83%
H2 production cost obj	81%
Nb of demos with upscaling plan	70%
Nb of demos connected to other demos	78%
Nb of demos connected to a roadmap	71%
TRL	36%
MRL	29%

% Av. data provides information about the percentage of demonstrations for which data was available and so the indicator was filled in.

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