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Review of Power-to-Gas Projects in Europe

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Abstract

Core of the Power-to-Gas (PtG) concept is the utilization of renewable electricity to produce hydrogen via water electrolysis. This hydrogen can be used directly as final energy carrier or can be converted to e.g. methane, synthesis gas, liquid fuels, electricity or chemicals. To integrate PtG into energy systems technical demonstration and systems integration is of mayor importance. In total 128 PtG research and demonstration projects are realized or already finished in Europe to analyze these issues by May 2018. Key of the review is the identification and assessment of relevant projects regarding their field of application, applied processes and technologies for electrolysis, type of methanation, capacity, location and year of commissioning. So far, main application for PtX is the injection of hydrogen or methane into the natural gas grid for storing electricity from variable renewable energy sources. Producing fuels for transport is another important application of PtX. In future PtX gets more important for refineries to lower the carbon food print of the products.

Keywords: Power-to-Gas; Power-to-X; Hydrogen; Methanation; Electrolysis, R&D project, Review

1. Introduction

Power-to-X concepts mainly produce gaseous chemical energy carriers (Power-to-Gas; other used terms: power to gas, P2G, PtG) by using renewable or excess electricity. Core of all these conversion chains is hydrogen (Power-to-Hydrogen) from water electrolysis. This hydrogen can be used directly as a final energy carrier or converted to e.g. methane, synthesis gas, electricity, liquid fuels, or chemicals. Reasons to use PtX are diverse but all related to the

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integration of high shares of variable renewable energy sources (VRES) into different energy sectors. One of the main application is seasonal energy storage by converting VRES into easily storable chemical energy carries. At the same time, an additional flexible load can provide benefit to the electricity system being a corner stone for sector coupling. Furthermore, the production of electricity based fuels for transportation, households, small consumers or industry as well as the production chemicals for industry can be a main driver for PtX. Fig. 1 gives a schematic overview of possible PtX concepts, pathways and components. The usage of the produced gases and fuels, e.g. production of chemicals or usage in fuel cells is not in the scope of this work as well as Power-to-Heat.

2. Overview

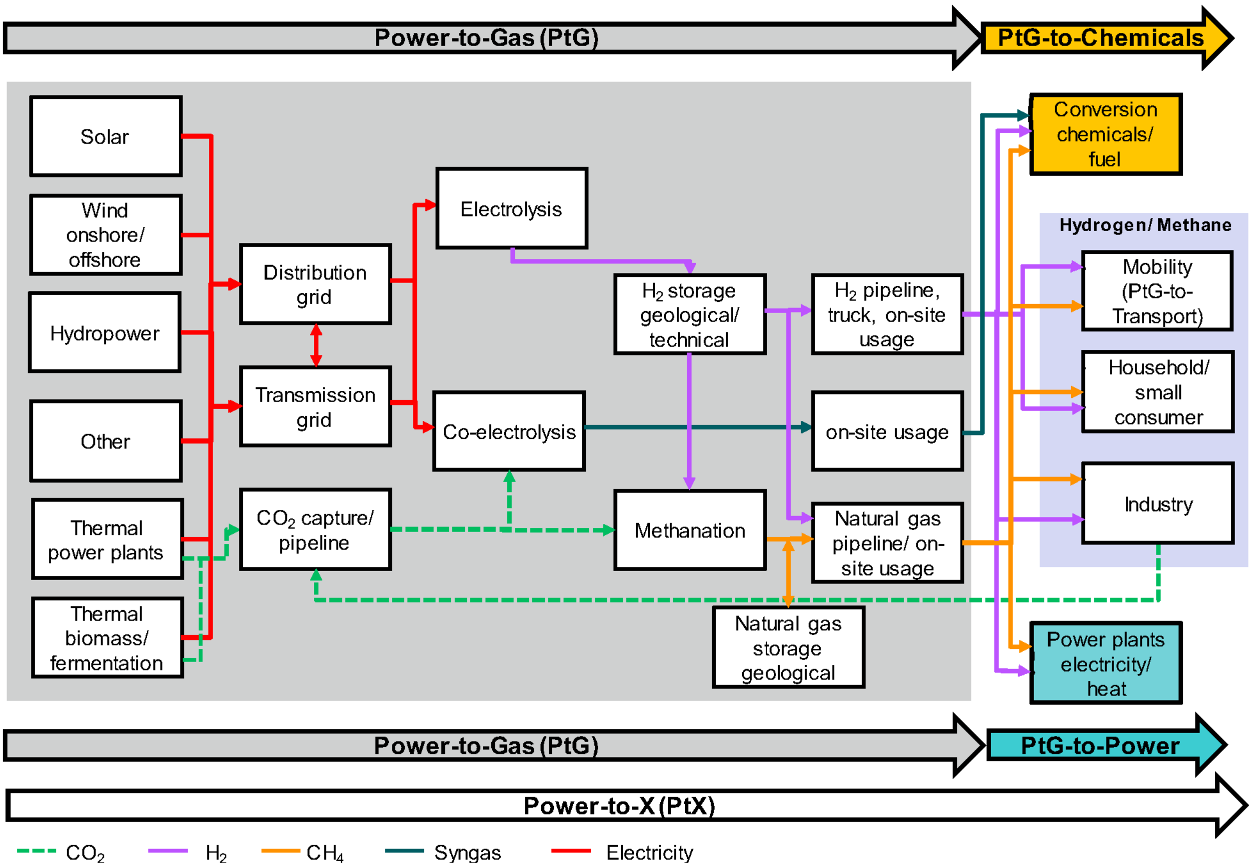

Fig. 1 Overview of Power-to-X concepts.

Overall in Europe 128 demo-projects regarding PtX have been, are or will be in operation (status as of end of 2017 ; including decommissioned and planned projects) to gain experience with systems integration of PtX components. All projects and characteristic systems parameters are listed in Table 1. The projects are clustered regarding their field of application: blending of hydrogen or methane into the natural gas grid, re-electrification with CHP, fuel production or industry applications. Some projects do not specify the usage of the produced gas because the focus of these projects lies on the system components. Out of the 128 projects, 27 are already finished while 38 are not commissioned yet. Consequently, 63 projects were in operation by end of May 2018.

Table 1. Overview of Power-to-Gas projects in Europe.

Acronym/ location/ name of the project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Processing H_2	Country	Source
Blending into the natural gas grid							
Ameland	PEM	8.3	2008[f]	6	-	The Netherlands	[1]

Acronym/ location/ name of the project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Processing H_2	Country	Source
Hybrid power plant Prenzlau[a]	Alkaline	500	2011	7	-	Germany	[2]
Morbach	Alkaline	25	2011[f]	7	-	Germany	[3]
H2-Researchcentre BTU	Alkaline	145	2012	6	-	Germany	[4]
Methanation at Eichhof							
1st	n.s.	25	2012[f]	6	cat. Methanation	Germany	[5]
2nd	PEM	50	2018	6	cat. Methanation	Germany	[6, 7]
Power to Gas at Eucolino	n.s.	108	2012[f]	6	cat. Methanation	Germany	[8]
Hybrid power plant Falkenhagen - STORE&GO Germany	Alkaline	2,000	2013	7	cat. Methanation	Germany	[9]
Audi e-gas	Alkaline	6,000	2013	7	cat. Methanation	Germany	[10]
Foulum	n.s.	250	2013[f]	6	bio. Methanation	Denmark	[11]
Viessmann microbial methanation	PEM	275	2013[f]	6	bio. Methanation	Germany	[12]
GRYHD[b]	PEM	n.s.	2014	6	-	France	[13]
Rozenburg	Alkaline	8.3	2014	6	cat. Methanation	The Netherlands	[14, 15]
Thüga demonstration plant	PEM	300	2014	7	-	Germany	[16]
RWE demonstration plant	PEM	150	2015	7	-	Germany	[17]
WindGas Hamburg	PEM	1,000	2015	7	-	Germany	[18]
Energiepark Mainz[c]	PEM	6,000	2015	7	-	Germany	[19]
Energy Storage – Hydrogen Injected into the Gas Grid via Electrolysis Field Test	PEM	5.5	2015	7	-	Denmark	[20]
Biogas upgrading	SOEC	~50	2016	5	cat. Methanation	Denmark	[21]
DemoSNG	PEM	~60	2015	6	cat. Methanation	Sweden	[22]
BioPower2Gas	PEM	1,200	2015	6	bio. Methanation	Germany	[23]
Energy park Pirmasens-Winzeln	Alkaline	2500	2016	7	bio. Methanation	Germany	[24]
Hybrid power plant Aarmatt - STORE&GO Switzerland	PEM	700	2015	7	bio. Methanation	Switzerland	[9]
BioCat Project/POWERSTEP	Alkaline	1,000	2016	7	bio. Methanation	Denmark	[25]
bioCONNECT	PEM	n.s.	2016	5	bio. Methanation	Germany	[26]
Ingrid – STORE&GO Italy	PEM	1,000	2016	7	cat. Methanation	Italy	[9]
Renovagas	Alkaline SPE	15	2016	6	bio. Methanation	Spain	[27]
Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion	SOEC	15	2017	5	cat. Methanation	Germany	[28]
Minerve	SOEC	n.s.	2017	5	n.s. Methanation	France	[29]
CO2-SNG	n.s.	n.s.	2018	6	cat. Methanation	Poland	[30]
HyDeploy	PEM	500	2019	7	-	United Kingdom	[31]
Wind to Gas	PEM	2400	2019	7	-	Germany	[32]
Jupiter 1000	Alkaline/ PEM	500+ 500	2018	7	cat. Methanation	France	[33]
HyStock	n.s.	1,000	2018	7	-	The Netherlands	[34, 35]
Swisspower Hybridkraftwerk	n.s.	2,000	2018	6	bio. Methanation	Switzerland	[36]
Symbio	n.s.	n.s.	~2018	6	bio. Methanation	Denmark	[37]
SYNFUEL	SOEC	n.s.	~2019	5	cat. Methanation	Denmark	[38]
Greenlab Skive	Alkaline	n.s.	~2020	6	cat. Methanation	Denmark	[39]
H2V Product							[40]
1st	Alkaline	100,000	2020	8	-	France	
2nd	Alkaline	600,000	2025	9	-	France	
Power-to-Gas Hungary	n.s.	10,000	projected	7-8	bio. Methanation	Hungary	[41]
Heat and power generation							
HARI	Alkaline	36	2004[f]	6	-	United	[42]

Acronym/ location/ name of the project	Type of Electrolyzer	Capacity kW	Commis sioning	TRL	Processing H_2	Country	Source
						Kingdom	
Utsira	Alkaline	50	2004[f]	6	-	Norway	[43]
Vestenskov	n.s.	n.s.	2006[f]	6	-	Denmark	[44]
RES2H2 Pozo Izquierdo	Alkaline	100	2007[f]	6	-	Spain	[45]
Hídrolica	PEM	30	2007[f]	6	-	Spain	[46]
HYRES	PEM	4.5	2008[f]	6	-	Greece	[47]
Abalone Energie	Alkaline	n.s.	2009[f]	6	-	France	[48]
H2KT	Alkaline	100	2010	6	-	Denmark	[49]
Myrthe	PEM	210	2013	6	-	France	[50]
RH2-WKA Grapzow	Alkaline	1,000	2013	7	-	Germany	[51]
La Croix Valmer	PEM	n.s.	2014	7	-	France	[52]
Spring Bank Farm[b]	Alkaline SPE	4.8	2014	6	-	United Kingdom	[53]
El Tubo	Alkaline SPE	2.4	2015	6	-	Spain	[53]
Exytron demonstration project	Alkaline	21	2015	7	cat. Methanation	Germany	[54]
Zero-Emission-Wohnpark	Alkaline	62.5	2017	7-8	cat. Methanation	Germany	[55]
Stromlückenfüller							[56]
Test	PEM	20	2015	6		Germany	
Pilot phase	PEM	200	projected	7		Germany	
Hybrid plant	PEM	1,000	projected	7		Germany	
Power-to-Gas Haßfurt	PEM	1,250	2016	7		Germany	[57]
Smart Grid Solar	PEM	75	2016	6		Germany	[58]
Power-to-Flex	Alkaline	n.s.	2018	6-7	bio. Methanation, Methanol	Germany/ The Netherlands	[59]
HYPOS LocalHy	Alkaline	250	2018	7	-	Germany	[60]
Haeolus[b]	PEM	2,000	2020	8	-	Norway	[61]
Fuels							
HyFLEET:CUTE Hamburg	Alkaline	400	2003[f]	6	-	Germany	[62]
HyFLEET:CUTE Amsterdam	Alkaline	400	2003[f]	6	-	The Netherlands	[62]
HyFLEET:CUTE Barcelona	Alkaline	400	2003[f]	6	-	Spain	[62]
HyFLEET:CUTE Stockholm	Alkaline	400	2003[f]	6	-	Sweden	[62]
ECTOS	Alkaline	300	2003[f]	6	-	Iceland	[63]
PURE	Alkaline	18	2005[f]	6	-	United Kingdom	[64]
RES2H2 Keratea	Alkaline	25	2005[f]	6	-	Greece	[65]
Chic Aargau	Alkaline	300	2011[f]	7	-	Switzerland	[66]
George Olah Plant							
1.	Alkaline	~1,700	2011	7	Methanol	Iceland	[67]
2.	Alkaline	~5,200	2014	7	Methanol	Iceland	[67]
Hydrogen refuelling station HafenCity	Alkaline	600	2012	7	-	Germany	[68]
Solar hydrogen filling station Freiburg	PEM	30	2012	7	-	Germany	[69]
Herten hydrogen centre of excellence	Alkaline	280	2013	7	-	Germany	[70]
Hydrogen filling station Stuttgart	Alkaline	400	2013	7	-	Germany	[71]
Sunfire Research project	SOEC	10	2014[f]	5	Fischer-Tropsch	Germany	[72]
Sunfire Power-to-Liquids	SOEC	150	2014	5	Fischer-Tropsch	Germany	[73]
Multi-energy fueling station H2BER[d]	Alkaline	500	2014	7	-	Germany	[74]
Power to Gas Biogasbooster[e]	n.s.	10	2014	6	bio. Methanation	Germany	[75]
M1 Wind Hydrogen Refuelling station	PEM	100	2015	7	-	United Kingdom	[76]
Wind2Hydrogen	PEM	100	2015	6	-	Austria	[77]
Power-2-Hydrogen-Tankstelle	PEM	185	2015	7	-	Germany	[78]
H2 Aberdeen: Hydrogen Bus Project	Alkaline	1,000	2015	7	-	United Kingdom	[79]
Rapperswil	Alkaline	25	2015	6	cat. Methanation	Switzerland	[80]
Levenmouth Community Energy Project[g]	Alkaline/ PEM	2x60 + 250	2016	7	-	United Kingdom	[81]
Don Quichote	PEM	~130	2016	6	-	Belgium	[82]
HyFive London 1	PEM	100	2016	7	-	United Kingdom	[76, 83]
HyFive London 2	PEM	100	2016	7	-	United Kingdom	

Acronym/ location/ name of the project	**Type of Electrolyzer**	**Capacity kW**	**Commis sioning**	**TRL**	**Processing H_2**	**Country**	**Source**
HyFive London 3	PEM	100	2017	7	-	United Kingdom	
H2Mobility - Karlsruhe	SOEC	9.4	2017	5	-	Germany	[84]
FaHyance	Alkaline	57	2017	7	-	France	[85]
BIGH2IT	PEM	1,500	2018	7	-	United Kingdom	[86]
Flagship project: Power-to-Gas Baden-Württemberg	Alkaline	1,000 + 300	2018	7	-	Germany	[87]
MefCO2	PEM	1,000	2018	6	Methanol	Germany	[67, 88]
HyBalance	PEM	1,200	2018	7	-	Denmark	[89]
H2energy	PEM	200	2018	7	-	Switzerland	[90]
Wasserstofftankstelle Kirchheim	n.s.	~30	2018	7	-	Germany	[91]
Infinity 1	PEM	n.s.	2020	7	bio. Methanation	Germany	[92, 93]
Hydrogen for industry							
Sotavento	Alkaline	300	2007[f]	6	-	Spain	[94, 95]
CO2RRECT	n.s.	300	2013[f]	7	-	Germany	[96]
Osshy Pushy	Alkaline	60	2013	6	-	France	[97]
Lashy Pushy	Alkaline	65	n.s.	6	-	France	[97]
Hanau	PEM	35	2015	7	-	Germany	[98]
H&R Ölwerke Schindler	PEM	5,000	2017	7	-	Germany	[99, 100]
H2Orizon[a]	PEM	1,000	2018	7	-	Germany	[101, 102]
GrInHy	SOEC	150	2018	6	-	Germany	[103]
Energy valley	PEM	12,000	2018	7	-	The Netherlands	[104]
HYPOS Megalyseur	PEM	2,000	2019	7	-	Germany	[105]
ALIGN-CCUS	Alkaline	~65	2019	6	DME	Germany	[106]
REFHYNE	PEM	1,000	2020	8	-	Germany	[107]
Fredericia	Alkaline	n.s.	~2020	8	-	Denmark	[39]
H2Future	PEM	6,000	2021	7	-	Austria	[108]
BASF/bse	n.s.	n.s.	projected	7	Methanol	Germany	[109]
PtG for the refining process Lingen	n.s.	6,000-15,000	projected	8	-	Germany	[110]
Usage of gas not specified							
ITHER	Alkaline/ PEM	63+7	2010[f]	6	-	Spain	[94]
SEE	PEM	6	2011[f]	6	-	Germany	[111]
PtG 250	Alkaline	250	2012	6	cat. Methanation	Germany	[112]
Hydrogen Centre	Alkaline/ PEM	55 + 12+~1	2012	6	-	United Kingdom	[113, 114]
MeGa-stoRE							[115, 116]
1	Alkaline	6	2014[f]	6	bio. Methanation	Denmark	
2	Alkaline	60	2016	6	bio. Methanation	Denmark	
ESI Platform	PEM	100	2016	6	cat. Methanation	Switzerland	[117]
Underground Sun Storage[h]	Alkaline	600	2016	6	-	Austria	[118]
HPEM2Gas	PEM	180	2018	6	-	Germany	[119]
Demo4Grid	Alkaline	4,000	2019	7	-	Austria	[120]
HYPOS rSOC	SOEC	n.s.	projected	5	-	Germany	[121]

Note: TRL - Technology Readiness Level; n.s.: not specified; PEM: polymer electrolyte membrane; SOEC: solid oxide electrolysis cell; SPE: solid polymeric electrolyte

[a]: H_2 also for mobility and CHP; [b]: H_2 also for mobility; [c]: H_2 also for mobility and industry; [d]: H_2 also for CHP, industry and natural gas grid; [e]: CH_4 also for natural gas grid; [f]: plant decommissioned; [g]: H_2 also for natural gas grid and re-electrification; [h]: Main objective: underground storage of H_2

3. Analysis

The number of countries engaging in PtX demonstration is quite high. So far, 16 countries have demonstration projects (Fig. 2) in Europe. In 2003 the first projects started. In those years the name PtG or PtX was not yet established and the projects had their focus on the usage of hydrogen rather than storing and using renewable electricity, e.g. HyFLEET:CUTE [62]. After 2011, the number of projects increased rapidly and found its maximum so far in 2015 with 16 projects (Fig. 5). In 2017, only seven projects launched their operation of plants, while for 2018 another 18 projects are scheduled to start. On the one hand this might reflect an increasing interest and on the other hand not all projects scheduled for commissioning in 2017 could meet their target and had to postpone the date of commissioning [101]. Probably not all projects planned for 2018 and following years will start in time or start at all as only a letter of intent exists and wait on approval of funding and/or operation license [91, 121].

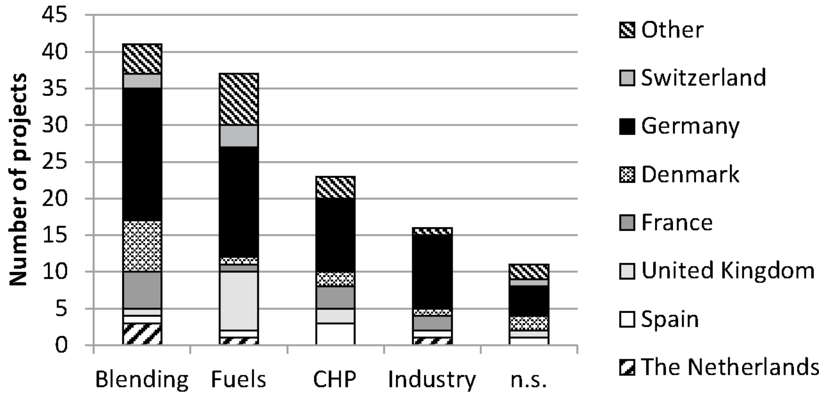

Fig. 2 Spatial distribution of Power-to-X technologies regarding field of application (n.s. – not specified)

Germany has the highest share in realized demonstration projects (Fig. 2). In the early years, however, other countries were more interested in this concept in particular Spain with 28 % of the projects (i.e. five projects). As mentioned before 16 different countries were involved so far. However, in 2017 only three countries (Germany, France and United Kingdom) commissioned new electrolyzers. Regarding the field of application of these projects, some countries concentrate on special fields. For example, Denmark has a clear focus on blending hydrogen or synthetic methane, into the natural gas grid. In contrast, the United Kingdom concentrates on using hydrogen as a transportation fuel. Spain set priority to re-electrification with CHP, while Germany fosters projects in all fields. The availability of

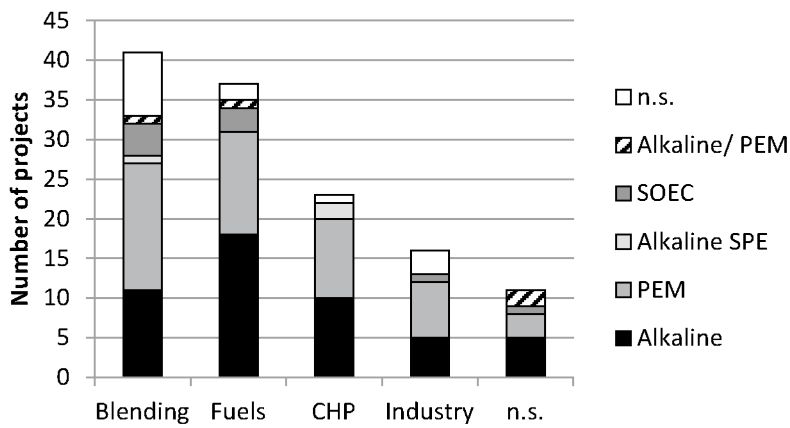

Fig. 3 Electrolyzer technologies in Power-to-X regarding field of application (n.s. – not specified)

accessible information depends on written language of project documentation and a bias towards projects in German-speaking and English-speaking countries cannot be excluded, as they are easier trackable.

The share of projects blending the produced hydrogen or methane into the natural gas grid (32 % of all projects, Fig. 3) is highest. For the project category "blending of gas" all electrolyzer technologies are applied. Even electrolyzer technologies with lower TRL like solid oxide electrolyzers (SOEC) and alkaline solid polymeric membrane (SPE) electrolyzers [53] are part of demonstration projects. This type of application focuses on using cheap or excess renewable electricity. PEM electrolyzers are the most used technology in this field of application, in particular, because of their dynamic behavior. The category "fuels" focuses more on steady supply of fuels. Therefore, alkaline electrolyzers are more prominent in this field of application.

Projects using PEM and alkaline electrolyzers are equally represented (Fig. 4). Industrial applications tend towards PEM electrolyzer but currently the number of projects is too small to identify a viable conclusion.

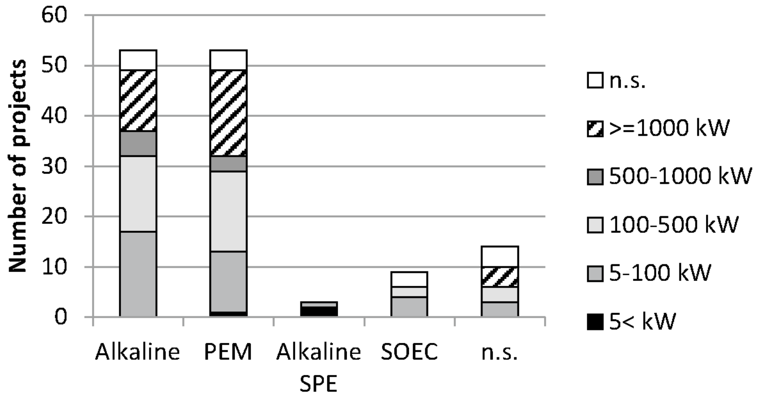

Fig. 4 Electrolyzer technologies in Power-to-X projects classified by their capacity (n.s. – not specified)

The chronology of PtG demonstration projects shows that in the beginning all projects used alkaline electrolyzer (Fig. 5). The first PEM electrolyzer was commissioned in 2007 and novel electrolyzer technologies were not introduced before 2014. Since then, in particular the PEM electrolyzer became more prominent. However, projects with alkaline electrolyzers are still part of demonstration projects as it is a mature technology. The historical trend

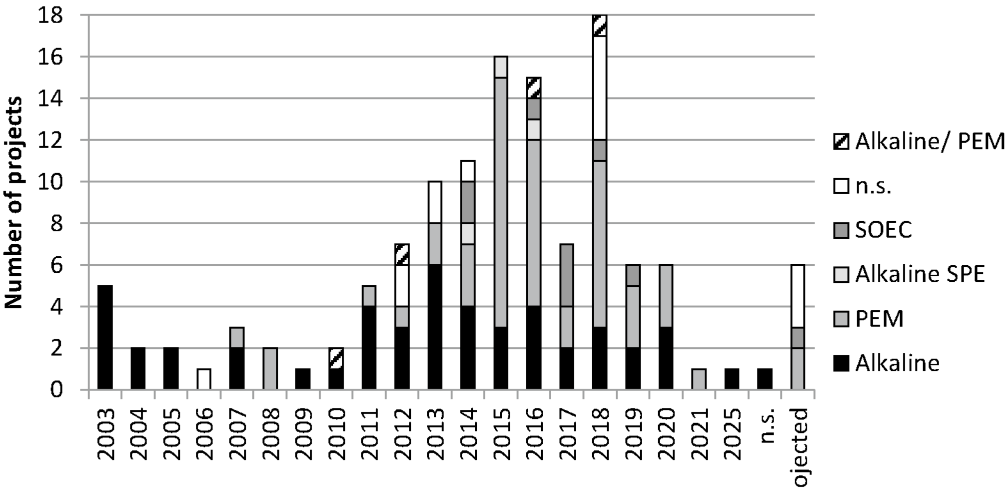

Fig. 5 Temporal development of further processing of hydrogen in Power-to-X

(Table 1) of projects for the category "Use in industry" shows that in particular refineries become more and more interested in PtG to produce green hydrogen for their processes. For the next years, seven new projects are announced, while only five were executed over the last years. The historical trend shows a clear trend towards bigger electrolyzers. For 2018, already eight projects with an electrolysis capacity higher than 1 MW are announced. As Fig. 4[1] already indicates most of them will be PEM electrolyzers. In general, PEM as well as alkaline electrolyzers are able to cover the full range of capacity. PEM electrolyzers are more often used for higher capacities and alkaline for lower. This is probably due to the chronology of projects with the trends towards PEM and higher hydrogen production capacities. Alkaline SPE electrolyzers are only used in very small plants indicating a very early stage of technical development. SOEC are still at lower TRL levels and thus farer from commercialization. Those electrolyzers, however, need a certain capacity (> 5 kW) to develop their full potential.

As described in the introduction, PtX also includes the conversion of hydrogen to other fuels and chemicals, for instance methanol, dimethyl ether (DME), long-chain hydrocarbons and most prominently methane. For methanation, two different processes are applied. Since 2011 catalytic methanation is in operation, see Fig. 6. An additional way to produce methane is the biological processing from hydrogen and carbon dioxide. Both processes will be improved in several demonstration projects over the next years. There is no preference for one technology yet. Other fuel production technologies are used only seldom.

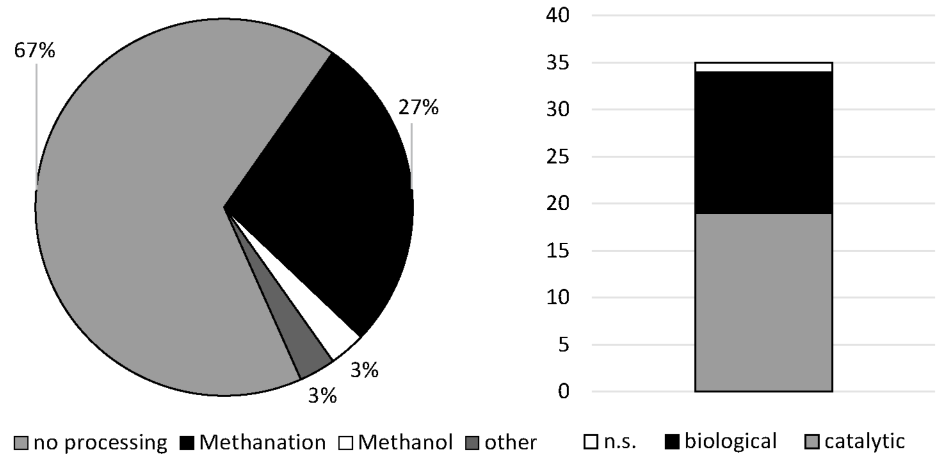

Fig. 6 Share of further processing of hydrogen in Power-to-X

Sorting the type of product by countries (Table 1), it becomes obvious that Denmark has a strong preference for methanation in particular based on biological processes. Also in Switzerland, some kind of methanation is included in two-thirds of all PtX projects. Demonstration projects in the United Kingdom focus on hydrogen production without any processing, while in Germany nearly all possible PtX pathways are demonstrated.

4. Conclusion and Outlook

The concept of PtX and its demonstration is rapidly developing over the last 15 years in Europe. 128 demonstration projects in operation or planning are identified by this review (status of May 2018). . In 2018, additional 18 projects are scheduled to be commissioned. The leading country in this development is Germany with 56 projects over all years. In general, the topic PtX is diversifying by different technologies, more countries and more types of final products of the processes. Not only PEM and alkaline electrolyzers are tested but also SOECs and new designs like alkaline SPE. The same is true for the processing to final products. Next to biological and catalytical methanation also production of methanol, DME and long-chain hydrocarbons fuels are developed and demonstrated. Key application for PtX still is the injection of hydrogen or methane into the natural gas grid for storing renewable electricity. Producing fuels for transportation, however, is another important application of PtX. In future PtX also gets more important for refineries to lower the carbon footprint of products. At the same time demonstration projects relying on

[1] As four projects use two different types of electrolyzers for this analysis, 132 projects are taken into account and not 128.

established technologies, i.e. PEM or alkaline electrolyzer, methanation or methanol production, are getting larger in their electrolyzer capacity. It is still open if all planned projects will be realized and if in the end, the technology can reach the goal for being economically viable in existing energy markets.

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