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Power-to-Gas: Electrolysis and methanation status review

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ABSTRACT

This review gives a worldwide overview on Power-to-Gas projects producing hydrogen or renewable substitute natural gas focusing projects in central Europe. It deepens and completes the content of previous reviews by including hitherto unreviewed projects and by combining project names with details such as plant location. It is based on data from 153 completed, recent and planned projects since 1988 which were evaluated with regards to plant allocation, installed power development, plant size, shares and amounts of hydrogen or substitute natural gas producing examinations and product utilization phases. Cost development for electrolysis and carbon dioxide methanation was analyzed and a projection until 2030 is given with an outlook to 2050.

The results show substantial cost reductions for electrolysis as well as for methanation during the recent years and a further price decline to less than 500 euro per kilowatt electric power input for both technologies until 2050 is estimated if cost projection follows the current trend. Most of the projects examined are located in Germany, Denmark, the United States of America and Canada. Following an exponential global trend to increase installed power, today's Power-to-Gas applications are operated at about 39 megawatt. Hydrogen and substitute natural gas were investigated on equal terms concerning the number of projects.

Declarations of interest

None.

1. Introduction

Power-to-Gas (PtG) as a sector coupling and energy storing technology has been discussed intensively in recent years with view to integrated future energy systems architecture [1–4], with technological focus [5,6], with regard to social acceptance [7], marketing [8,9] and political discussions [9,10]. Various pilot and demonstration projects which are described in this paper result from a rising interest in the technology. PtG is an option for converting energy from electricity into chemical bond energy, stored in a combustible gas. Using electric power, an electrolyzer splits water into its two components: oxygen on the one hand and hydrogen as combustible gas on the other. Hydrogen can be used directly or fed into a downstream methanation process. The choice of process pathway depends on the requirements of the embedding energy system such as hydrogen-tolerance of gas networks, gas buffering, mobility or heat applications.

Golling et al. [10] presented a roadmap for the implementation of PtG technology in Germany showing a way to short-term reductions in greenhouse gas emissions of −40% until 2020, -55% by 2030 and -80 to −95% in the long run. It takes into account international CO_2-trade, hydrogen infrastructure implementation, intersectoral planning of infrastructure and opening export markets for PtG technology. Similar roadmaps could be developed for other countries as well.

Despite its currently high costs and losses during conversion the technology is considered worthwhile because it is the most cost-efficient long-term storage option for power, assuming that gas power plants or combined heat and power plants exist to reconvert the renewable gas [11]. It also supports intersectoral decarbonization and the substitution of fossil energy carriers. Literature shows that with renewable power generation on the increase, long-term storage with PtG will become necessary and cost-efficient [4,12].

There is currently a variety of projects worldwide addressing different scopes in diverse fields of application. This work aims to give a brief global overview on PtG projects producing either hydrogen or methane in the context of energy transition from fossil to renewable sources. It depicts the situation in early 2019 as well as its temporal development in the past and gives an outlook on costs and trends up the year 2050. It updates, deepens and completes previous reviews by Wulf et al. [13,14], Bailera et al. [15], Blanco and Faaij [16], Buttler and Spliethoff [17], Lecker et al. [18] or Götz et al. [5] including hitherto

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Abbreviations

CAPEX	Capital expenditure
CO_2	Carbon dioxide
H_2	Hydrogen
kW	Kilowatt
LHV	Lower heating value
MW	Megawatt
PEM	Proton exchange membrane
PtG	Power-to-Gas
R^2	Coefficient of determination

unreviewed projects and by combining project names with details such as plant location.

2. Methods

2.1. Electrolysis and CO_2-methanation cost development - status quo and projection

Installation costs for different electrolyzer and methanation technologies were analyzed. In each case, they include capital expenditure (CAPEX) for the electrolyzer or the methanation plant but not additional system integration equipment like downstream compression, grid connection, installation or maintenance costs after a PtG plant was completed. Plant size of methanation is always referred to the electrical power input of an electrolyzer necessary to feed the methanation plant. This is valid for cost indication as well as for power description in the project database and avoids the pitfall of erroneous comparison of power related to electrical or chemical energy. Thus, costs for methanation are referred to electrical power of the electrolyzer but not containing the electrolyzer costs itself. This approach enables the comparison of PtG plants producing either hydrogen or methane from a power sector point of view. It is reasonable, since at least in large scale applications, methanation plants are assumed to mostly operate in combination with an electrolyzer.

The historical data for calculation of capital expenditures was generated from literature with regard to alkaline electrolysis [10,17,19–22], membrane (PEM) electrolysis [10,17,20,22], high-temperature electrolysis [10,17] and methanation parameters [10]. Predictions were given by Bertuccioli et al. [20], Buttler and Spliethoff [17] and Golling et al. [10]. An expert survey on cost predictions for electrolysis was executed. It involved ten participants covering power ranges from 20 kW_{el} to 50 MW_{el} without including high-temperature electrolysis. Manufacturer specifications and projections were given e.g. by H-tec, Hydrogenics and Siemens.

Investigated annual costs were arithmetically averaged over all data entries of one year. Then, trends for CAPEX in Euro per kilowatt (€/kW_{el}) for alkaline and membrane electrolysis (Fig. 1) as well as for biological and chemical CO_2-methanation (Fig. 2) were calculated via exponential approximation over average annual values.

2.2. Power-to-Gas project database

For the PtG project overview, a database of 153 projects in 22 countries was analyzed. It contains information on product use, grid injection, operating status, year of project start, commissioning and decommissioning, power input of the electrolyzer, hydrogen production, methanation technology, methane production and source of carbon dioxide. Project-information about location, products, gas grid injection electrical power and methanation type is processed in geospatial data as supplementary file to this work. Projects then were evaluated with regard to their target product gases. Further analysis focused on the choice of electrolyzer and methanation technology and on the choice of reactor technologies for methanation. Carbon sources were quantified for projects, in which methanation was implemented. The feed-in of either hydrogen or methane into the gas network was quantified. Installed capacity starting from 1993 was quantified and a projection is given. For the countries with highest PtG activity, the development of installed electrical power and of the number of projects is given covering the years from 2003 to 2020 differentiating between hydrogen and methane projects. Mean plant size is examined concerning the annual performance from 1993 until 2019 on the one hand and the development per country on the other. Product gas utilization phases were appraised and total gas production as well as mean efficiency in active projects were quantified. An excerpt of the data is listed in Table 1. A classification into active and inactive projects with and without biological or chemical-catalytical methanation was taken.

Values on plant capacity refer to the electrical power of the electrolyzer for methanation as well as for hydrogen projects. Not always, data sources give information, if only stack, or system power are specified (Table 1). To determine total gas output of all projects and

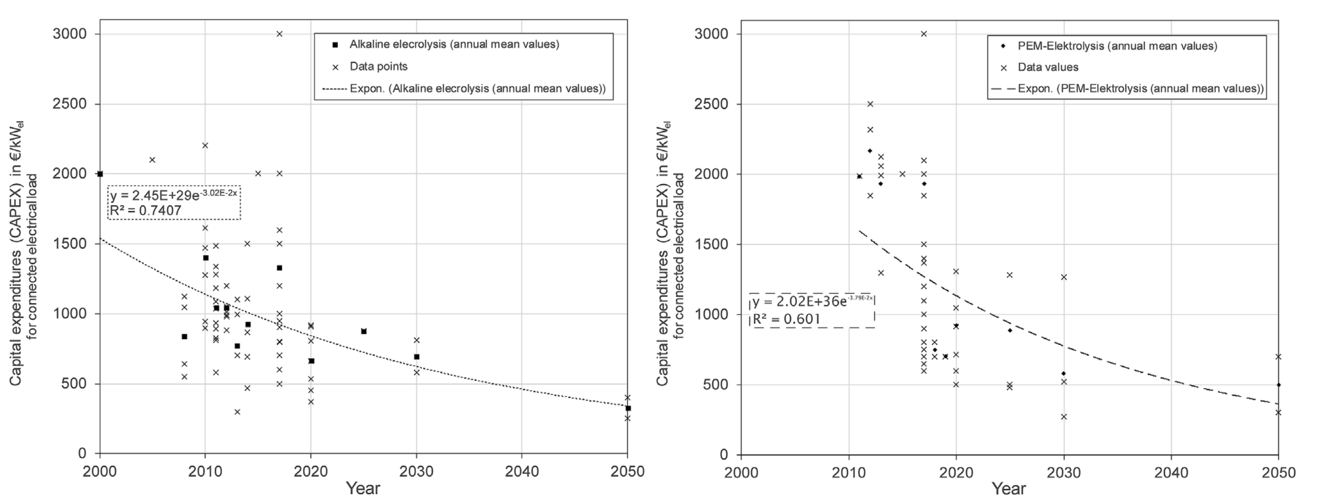

Fig. 1. Development and projection of capital expenditures for alkaline electrolysis (left side, data: [10,17,19–22]) and PEM-electrolysis (right side, data: [10,17,20,22]). X-values in exponential approximation formulae refer to the years as numeric value in axis of abscissas. Values beyond the year 2018 are projected data.

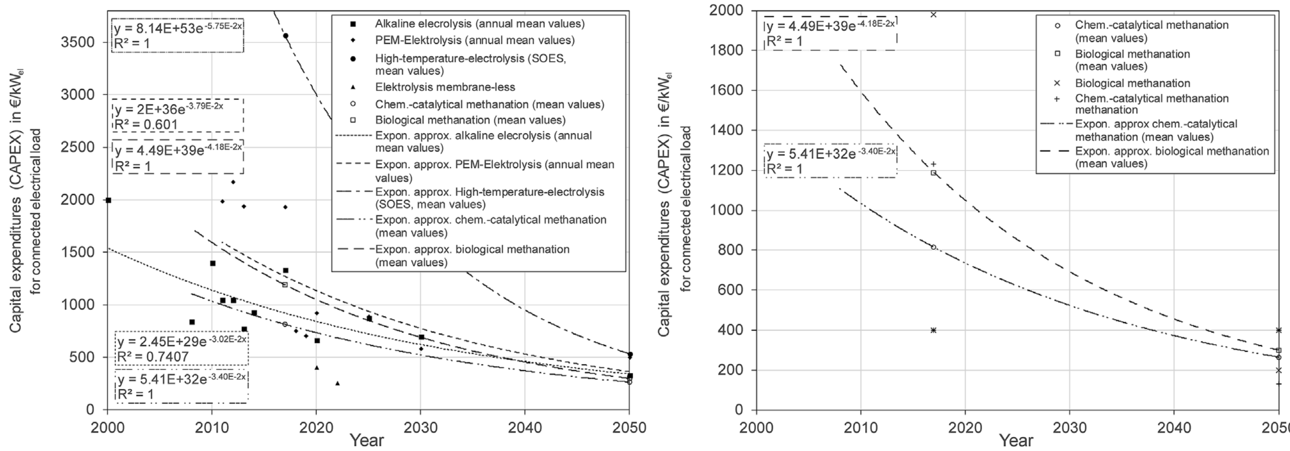

Fig. 2. CAPEX status quo and projection until 2050 for biological and chemical methanation in higher resolution focusing on methanation (right side, data: [10]). Mean values and exponential approximations of price development for electrolysis and methanation from 2000 to 2050 (left side, data: [10,17,19–22]). X-values in exponential approximation formulae refer to the years as numeric value in axis of abscissas. Values beyond the year 2018 are projected data. Connected electrical load for methanation refers to the electrolyzer power feeding the methanation plant with hydrogen.

resulting efficiencies, capacity is calculated by the lower heating value of the end-product gas (Table 2).

3. Results and discussion

3.1. Cost development for electrolysis and methanation between the years 2000 and 2050

Investment costs of all five technologies examined are expected to decrease further: According to Buttler et al. [17], Smolinka et al. [19], Bertuccioli et al. [20], Jensen et al. [21], Dahl et al. [22], Golling et al. [10] and our own survey data, average costs for alkaline electrolyzers will fall from about 1300 €/kW$_{el}$ in 2017 to below 500 €/kW$_{el}$ in 2050 with an exponential fit of the data (Fig. 1). The given exponential cost development approximation scatters with a coefficient of determination of $R^2 = 0.74$. One cause of the observed scatter and with-it uncertainty in cost projections, can be that data sources not always report clearly on costs referring to stack rather than system costs. Reliability of predictions until 2050 has to be questioned because unexpected changes can occur e.g. shifts in preference for feedstock or climate policy decisions which can interrupt energy system setups within decades. The price development shown in this work is based on current market development, predicting market launch of Power-to-Gas technology for the upcoming years. Predictions are always affected by uncertainties due to rapidly changing energy demand, policy development and supporting funds.

With even higher spread ($R^2 = 0.60$), data from the poll as well as from Buttler et al. [17], Bertuccioli et al. [20], Dahl et al. [22] and Golling et al. [10] shows, that specific costs for proton exchange membrane electrolyzers (PEM) are expected to fall from about 1900 €/kW$_{el}$ in 2017 to 500 €/kW$_{el}$ in 2050. The projection of the data by exponential fitting, as for alkaline electrolysis leads to values below 500 €/kW$_{el}$ This will result in cost reduction for both technologies of about 75% in the given time span. Fig. 1 illustrates data points from literature and from the survey as well as their annual mean value. For better transparency exponential approximation of the annual mean values of the two most important electrolysis technologies is given. High-temperature electrolysis will most likely reach a cost reduction of 85% from about 3570 €/kW$_{el}$ in 2017 to 535 €/kW$_{el}$ in 2050. Until 2030, costs are expected to fall to about 600 €/kW$_{el}$ for PEM and 700 €/kW$_{el}$ for alkaline electrolysis. The prediction from the exponential approximation, with above described high uncertainties, arrives at almost equal costs in the long run as shown in Figs. 1 and 2. In Fig. 2 (left side), annual approximations of all relevant electrolysis technologies are contrasted to demonstrate that today's spread in cost will lessen in the future which means that learning curves for membrane electrolyzers are expected to be steeper than for alkaline.

Recent expert studies on future cost and performance parameters of water electrolysis by Glenk and Reichelstein [194] or Schmidt et al. [195] support the values and figures processed here. They move within the same range, although scattering upwards is stronger especially for high-temperature electrolysis. Main reasons for cost decline may be increasing automation and production capacities plus further technological development for Power-to-Gas application electrolyzers [11].

Regarding CAPEX for CO_2-methanation in Power-to-Gas application, the data situation is uncertain. For chemical methanation Golling et al. [10] give mean values at about 800 €/kW$_{el}$ related to electrical power input feeding the methanation plant in 2017 and 130 to 400 €/kW$_{el}$ in 2050 which is a cost reduction of about 67%. For biological methanation, a cost reduction of 75% from about 1200 €/kW$_{el}$ related to electrical power input of the electrolyzer in 2017 to 300 €/kW$_{el}$ results from the data illustrated in Fig. 2 (right side) as exponential approximation of annual mean values. Until 2030, the cost of biological methanation is predicted to fall to about 700 €/kW$_{el}$ and that of chemical CO_2-methanation to about 500 €/kW$_{el}$. Cost reductions in this field may be mainly due to economy of scale, with technological development playing a part as well. Membrane-less electrolysis is a potentially disruptive technology as developed e.g. by AquaHydrex. Since it is not mature for application, it shall not be examined here further.

Due to privacy policies, the data situation regarding cost development for electrolyzers from industrial point of view is quite poor. There are, however, references which make it possible to quantify guide values at relatively high spread of basic data. Due to relatively low amounts of data points and high spread of data (± 66% from mean value for biological and ± 50% for chemical methanation), it is assumed here, that exponential approximation over annual mean values is reasonable. It also does not disregard outliers which would be the case using medians.

Setting costs of considered electrolysis and methanation technologies in relation to each other, it becomes evident, that projections point towards an alignment of costs in future. It has to be stated here, that cost for methanation exclude electrolysis costs even if they refer to the connected electrical power of an electrolyzer necessary as described above. All costs will then range between about 300 and 500 €/kW$_{el}$. This means, that the hydrogen production unit and the methanation unit will in future probably be responsible for costs at roughly equal shares if cost basis for both technologies is the same as described in the methodology. To reach this situation, electrolyzers which today make

Table 1
Power-to-Gas project list alphabetically arranged by country code and city of location with main literature and references. The column *'project start'* marks the year of commissioning. If this is not known, the year of project or planning phase start is used. *'Power'* marks the connected electrical load of the electrolyzer. '*n.r.*' stands for 'no record' and marks positions without any available figures. Non-relevant entries are marked with '-'. Country codes are used as AR: Argentinia, AT: Austria, CA: Canada, CK: Cook Islands, CH: Switzerland, DK: Denmark, DE: Germany, ES: Spain, FIN: Finland, FR: France, GR: Greece, GB: Great Britain, GL: Greenland, ISL: Iceland, JPN: Japan, NO: Norway, NL: Netherlands, NL-DE: Dutch-German collaboration, SE: Sweden, TR: Turkey, US: United States of America. Power indications for methanation projects refer to the connected power of an electrolyzer feeding the methanation unit with hydrogen.

Project name	Location		Product	Grid inject.	Proj. start	Power	Metha-nation	Literature, Reference
	Country	*City*	*H_2/CH_4*	*yes/no*	*Year*	*in MW_{el}*	*biol./chem.*	
Hychico Hydrogen Plant	AR	Comodoro Rivadavia	H_2	no	2008	0.700	–	[24,25]
w2h	AT	Auersthal	H_2	yes	2014	0.100	–	[26]
Underground Sun Storage	AT	Pilsbach	H_2	yes	2015	0.600	–	[27,28]
Biological biogas upgrading in a trickle-bed reactor	AT	Tulln/Donau	CH_4	no	2016	n.r.	biol.	[29,30]
HARP System Bella Coola	CA	Bella Coola	H_2	no	2010	0.320	–	[31–34]
Power-to-Gas (for energy storage purposes)	CA	Ontario	H_2	yes	2014	0.005	–	[35–37]
Laboratory Plant HRI	CA	Quebec	H_2	no	2001	0.005	–	[34]
Ramea Wind-Hydrogen-Diesel (WHD) Project	CA	Ramea	H_2	no	2012	0.162	–	[34,38–40]
Wind-Hydrogen Village PEI	CA	Tignish	H_2	no	2009	0.300	–	[34,41]
IRENE System	CA	Victoria	H_2	no	2007	0.006	–	[34,42]
CHIC	CH	Brugg/Aargau	H_2	no	2011	0.300	–	[13,43]
Erstes Energieautarkes Haus der Welt	CH	Brütten	H_2	no	2016	0.015	–	[44]
n.r. (MicrobEnergy GmbH)	CH	Dietikon	CH_4	yes	2019	n.r.	biol.	[45]
SolarFuel-Alpha 5th site	CH	Rapperswil	CH_4	no	2015	0.025	chem.	[46]
Store&Go-Project, Hybridwerk Aarmatt	CH	Solothurn/Zuchwil	CH_4	yes	2018	0.350	biol.	[47,48]
RENERG2	CH	Villigen	CH_4	n.r.	2015	0.100	chem.	[15]
COSYMA	CH	Zürich/Werdhölzli	CH_4	yes	2017	n.r.	chem.	[49,50]
Hydrogen Island Aitutaki	CK	Aitutaki	H_2	no	n.r.	0.055	–	[34]
BioPower2Gas	DE	Allendorf (Eder)	CH_4	yes	2015	0.300	biol.	[45,51]
BioPower2Gas-Erweiterung	DE	Allendorf (Eder)	CH_4	yes	2016	n.r.	biol.	[45,51]
Smart Grid Solar	DE	Arzberg	H_2	no	2016	0.075	–	[52]
Exytron Zero-Emission-Wohnpark	DE	Alzey	CH_4	no	2016	0.063	chem.	[52]
Methanisierung am Eichhof, SolarFuel-Alpha 4th site	DE	Bad Hersfeld	CH_4	no	2012	0.025	chem.	[46,52–54]
Direktmethanisierung von Biogas	DE	Bad Hersfeld	CH_4	yes	2017	0.050	chem.	[55]
H2BER Multi-Energie-Tankstelle	DE	Berlin	H_2	no	2014	0.500	–	[52,56]
PtG Berlin-Schöneberg	DE	Berlin	H_2	yes	2014	0.007	–	[56,57]
H2 Forschungszentrum Cottbus	DE	Cottbus	H_2	no	2012	0.145	–	[52]
GICON-Großtechnikum	DE	Cottbus	CH_4	no	2015	n.r.	biol.	[52,58]
Biocatalytic methanation	DE	Cottbus	CH_4	no	2013	n.r.	biol.	[59,60]
PtG-Emden	DE	Emden	CH_4	yes	2015	0.312	biol.	[54]
PtG-Etzel	DE	Etzel	H_2	yes	2013	6.000	–	[54,61]
WindGas Falkenhagen	DE	Falkenhagen	CH_4	yes	2015	2.000	biol.	[62,63]
PtG-Fehndorf	DE	Fehndorf/Wesuwe	H_2	yes	2019	2.000	–	[64]
Thüga Strom zu Gas Plattform	DE	Frankfurt	H_2	yes	2014	0.300	–	[65]
H_2Move	DE	Freiburg	H_2	no	2012	0.040	–	[66,67]
Biologische Methanisierung in Rieselbettreaktoren	DE	Garching	CH_4	no	2016	n.r.	biol.	[68–70]
RH_2-WKA	DE	Grapzow	H_2	yes	2013	1.000	–	[71]
H_2-Tankstelle HafenCity	DE	Hamburg	H_2	no	2013	0.960	–	[54]
WindGas Hamburg	DE	Hamburg	H_2	yes	2015	1.000	–	[52,72,73]
Power-2-Hydrogen-Tankstelle	DE	Hamburg	H_2	no	2015	0.180	–	[54,74]
HyFLEET:CUTE	DE	Hamburg	H_2	no	2003	0.400	–	[13]
Demonstrationsanlage Hanau	DE	Hanau	H_2	no	2015	0.030	–	[75]
WindGas Haβfurt	DE	Haβfurt	H_2	yes	2016	1.250	–	[34,52,54,76–80]
H_2Herten	DE	Herten	H_2	no	2013	0.160	–	[81]
Einsatz der biologischen Methanisierung […]	DE	Hohenheim	CH_4	no	2016	n.r.	biol.	[82]
designetz Pilotanlage Ibbenbüren	DE	Ibbenbüren	H_2	yes	2013	0.150	–	[83]
ORBIT 2nd site	DE	Ibbenbüren	CH_4	yes	2020	0.001	biol.	n.r.
PHOEBUS	DE	Jülich	H_2	no	1993	0.026	–	[34]
DemoSNG (2nd site)	DE	Karlsruhe	CH_4	yes	2014	0.006	chem.	[84]
HELMETH	DE	Karlsruhe	CH_4	yes	2015	0.008	chem.	[85–88]
Forschungsanlage der DVGW-Forsch.-stelle am EBI	DE	Karlsruhe	CH_4	no	2014	n.r.	chem.	[89]
Laborreaktor am Fraunhofer IWES	DE	Kassel	CH_4	no	2016	n.r.	k.A.	[90]
H_2ORIZON	DE	Lampoldshausen	H_2	no	2017	1.000	–	[81,91,92]
bioCONNECT	DE	Lemgo	CH_4	yes	2016	n.r.	k.A.	[52]
HYPOS: Megalyseur	DE	Leuna	H_2	yes	2019	2.000	–	[57,93]
Energiepark Mainz	DE	Mainz	H_2	yes	2014	6.000	–	[54,94,95]
SolarFuel-Alpha 3rd site	DE	Morbach	CH_4	no	2011	0.025	chem.	[46,52,53,96]
Solar-Wasserstoff-Projekt	DE	Neunburg vorm Wald	H_2	no	1996	0.300	–	[97]
CO_2RRECT	DE	Niederauβem	CH_4	yes	2013	0.100	chem.	[54,98]
NSWPH	DE	North Sea	H_2	n.r.	2035	< 30 GW	n.r.	[99,100]
INFINITY I	DE	Pfaffenhofen a. d. Ilm	CH_4	yes	2020	1.000	biol.	[101]
Energiepark Pirmasens-Winzeln	DE	Pirmasens	CH_4	yes	2015	2.500	biol.	[102–104]
Forschungsanlage am Technikum des PFI	DE	Pirmasens	CH_4	no	2013	n.r.	biol.	[105,106]
Hybridkraftwerk Prenzlau	DE	Prenzlau	H_2	yes	2011	0.600	–	[107]
ORBIT 1st site	DE	Regensburg	CH_4	no	2018	n.r.	biol.	n.r.
Stromlückenfüller	DE	Reußenköge	H_2	yes	2015	0.200	–	[108]

(*continued on next page*)

Table 1 (*continued*)

Project name	Location		Product	Grid inject.	Proj. start	Power	Metha-nation	Literature, Reference
	Country	*City*	*H_2/CH_4*	*yes/no*	*Year*	*in MW_{el}*	*biol./chem.*	
EXYTRON Demonstrationsanlage	DE	Rostock	CH_4	no	2015	0.021	chem.	[52,109]
GrInHy	DE	Salzgitter	H_2	no	2017	0.150	–	[85,110,111]
PtG am Eucolino	DE	Schwandorf	CH_4	no	2013	0.108	biol.	[112,113]
Mikrobielle Methanisierung	DE	Schwandorf	CH_4	yes	2015	0.275	biol.	[54,114]
HYPOS: localhy	DE	Sonneberg	H_2	yes	2015	0.075	–	[57,115]
Komplexlabor FH Stralsund	DE	Stralsund	H_2	no	2015	0.020	–	[34,54,116–118]
Biogasbooster	DE	Straubing	CH_4	no	2015	n.r.	biol.	[52]
Wasserstofftankstelle Stuttgart Talstraβe	DE	Stuttgart	H_2	no	2015	0.400	–	[54]
SolarFuel-Alpha 1st site	DE	Stuttgart	CH_4	no	2009	0.025	chem.	[46,53]
P2G-Elektrolyse zur AEL-Erforschung	DE	Stuttgart	H_2	no	2014	0.370	–	[54]
REG-Technikum	DE	Stuttgart	CH_4	no	2012	0.250	chem.	[54,96]
n.r. (MicroPyros GmbH)	DE	Weilheim-Schongau	CH_4	yes	2018	0.250	biol.	[119]
SolarFuel-Alpha 2nd site	DE	Werlte	CH_4	yes	2010	0.025	chem.	[46,52]
e-Gas-Anlage Werlte	DE	Werlte	CH_4	yes	2013	6.000	chem.	[120]
PtG-Anlage Grenzach-Whylen	DE	Whylen	H_2	no	2018	1.000	–	[121]
n.r. (Amprion, OGE)	DE	northern NRW/NI	n.r.	yes	2030	50–100	n.r.	[122]
Agerbæk/Helle-Project	DK	Agerbæk and Helle	H_2	yes	2015	0.006	–	[123]
El-Opgraderet Biogas	DK	Foulum	CH_4	yes	2013	0.040	chem.	[15,124]
P2G-Foulum Project	DK	Foulum	CH_4	no	2013	0.025	biol.	[125]
MeGa-stoRE 2	DK	Heden	CH_4	yes	2018	0.250	chem.	[126]
HyBalance	DK	Hobro	H_2	no	2018	1.250	–	[127]
BioCat Project	DK	Kopenhagen/Avedore	CH_4	yes	2016	1.000	biol.	[128]
MeGa-stoRE 1	DK	Lemvig	CH_4	yes	2013	n.r.	chem.	[15,126]
SYMBIO	DK	Lyngby	CH_4	no	2014	n.r.	biol.	[15,129]
SYNFUEL	DK	Lyngby	CH_4	n.r.	2019	n.r.	chem.	[13,130]
Towards the Methane Society, Phase 1	DK	Midtjylland-Region	CH_4	yes	2011	n.r.	chem.	[131]
Nakskov Industrial & Energy Park Lolland	DK	Nakskov	H_2	no	2007	0.005	–	[34,132]
MeGa-stoRE Com 1	DK	n.r.	CH_4	yes	2035	10.000	chem.	[126]
MeGa-stoRE Com 2	DK	n.r.	CH_4	yes	2050	10.000	chem.	[126]
HyFLEET:CUTE	ES	Barcelona	H_2	no	2003	0.400	–	[13]
RENOVGAS Project	ES	Jerez de la Frontera	CH_4	yes	2015	0.015	chem.	[15,133]
RES2H2 Spanish site	ES	Pozo Izquierdo, Gran Canaria	H_2	no	2007	0.055	–	[34,53,134]
El Tubo	ES	Sevilla	H_2	no	n.r.	0.002	–	[89,135]
Sotavento experimental wind farm	ES	Sotavento	H_2	no	2005	0.288	–	[136]
Hidrolica	ES	Tahivilla	H_2	no	2008	0.041	–	[34]
Biocatalytic methanation of hydrogen and carbon dioxide in a fixed bed bioreactor	FIN	Helsinki	CH_4	no	2016	n.r.	biol.	[137]
PVFCSYS Sophia Antipolis	FR	Antibes	H_2	no	2000	0.004	–	[34]
HyCube MYRTE	FR	Corsica	H_2	no	2012	0.050	–	[112]
GRHYD	FR	Dunkerque	H_2	yes	2013	n.r.	–	[138]
Jupiter 1000	FR	Fos-sur-Mer	CH_4	yes	2018	1.000	n.r.	[139]
H2V59 & H2V76	FR	Loon-Plage & St. Jean de Folleville	H_2	yes	2022	610.00	–	[140,141]
MINERVE	FR	Minerve	CH_4	n.r.	2017	n.r.	chem.	[13,142]
PUSHY OSSHY	FR	n.r.	H_2	n.r.	2013	0.060	–	[13,142]
PUSHY LASHY	FR	n.r.	H_2	n.r.	2015	0.065	–	[142]
RES2H2 Greek site	GR	Keratea	H_2	no	2005	0.025	–	[34,134,143–145]
Stand-alone power system	GR	Xanthi	H_2	no	2008	0.004	–	[34,146]
HydrogenBusProject	GB	Aberdeen	H_2	no	2015	1.000	–	[13]
CymruH_2Wales project	GB	Baglan near Swansea	CH_4	yes	2008	0.049	n.r.	[34,147]
PURE	GB	Baltasound	H_2	no	2005	n.r.	–	[34,148,149]
Smart Power Farm	GB	Cheshire	H_2	yes	2016	0.005	–	[150,151]
HyDeploy	GB	Newcastle-u-Lime	H_2	yes	2019	0.500	–	[152,153]
HaRi	GB	Longhborough	H_2	no	2008	0.034	–	[154,155]
HyFive London 1	GB	London	H_2	no	2016	0.100	–	[13,156]
HyFive London 2	GB	London	H_2	no	2016	0.100	–	[13,156]
HyFive London 3	GB	London	H_2	no	2017	0.100	–	[13,156]
Levenmouth Community Energy Project	GB	Methil	H_2	no	2020	0.310	–	[157]
H2KT	GL	Nuuk	H_2	no	2010	0.098	–	[34,158]
n.r. (Electrochaea GmbH)	HU	tbd.	CH_4	yes	n.r.	10.000	biol.	[159,160]
ECTOS	ISL	Reykjavik	H_2	n.r.	2007	0.300	–	[13,161]
PVFCSYS Agrate	IT	Agrate	H_2	no	2004	0.003	–	[34]
H2 from the Sun	IT	Brunate	H_2	no	2008	0.011	–	[34,162]
SAPHYS Project	IT	Rome	H_2	no	1997	0.005	–	[163]
Ingrid FCH JU project	IT	Troia/Puglia	H_2	no	2014	1.000	–	[112,164,165]
Continuous CH_4 Production from H_2 and CO_2 […]	JPN	Higashi-Hiroshima	CH_4	no	1988	n.r.	biol.	[166]
Hydrogen Energy Storage System	JPN	Takasago	H_2	no	2005	0.028	–	[34]
Continuous methane fermentation […]	JPN	Tsukuba	CH_4	no	2004	n.r.	biol.	[167]
Grimstad Renewable Energy Park	NO	Grimstad	H_2	no	2000	0.050	–	[34,168]
Laboratory Plant IFE Kjeller	NO	Kjeller	H_2	no	2003	0.002	–	[34]
Utsira	NO	Utsira Island	H_2	no	2004	0.048	–	[169,170]

(*continued on next page*)

Table 1 (*continued*)

Project name	Location		Product	Grid inject.	Proj. start	Power	Metha-nation	Literature, Reference
	Country	*City*	*H2/CH4*	*yes/no*	*Year*	*in MWel*	*biol./chem.*	
Ameland	NL	Ameland Island	H_2	yes	2008	0.009	–	[13,171]
HyFLEET:CUTE	NL	Amsterdam	H_2	no	2003	0.400	–	[13]
Energy Valley Delfzijl	NL	Delfzijl	CH_4	yes	2020	12.000	n.r.	[172]
P2G Project	NL	Rozenburg	CH_4	yes	2013	0.008	chem.	[112,173]
W2P2G	NL	Wijster	CH_4	yes	2014	0.400	chem.	[174–176]
Power-to-Flex	NL-DE	n.r.	CH_4	n.r.	2018	n.r.	biol.	[13,177]
DemoSNG (1st site)	SE	Stockholm	CH_4	yes	2014	0.006	chem.	[13,84,178–181]
HyFLEET:CUTE	SE	Stockholm	H_2	no	2003	0.400	–	[13]
Hydrogen Island Bozcaada	TR	Bozcaada	H_2	no	2011	0.055	–	[34,182–184]
HyDePark	TR	Gebze	H_2	no	2008	0.007	–	[34,185]
Wind2H2	US	Boulder	H_2	no	2010	0.033	–	[186]
High-Performance Biogas Upgrading […]	US	Durham	CH_4	no	2017	n.r.	biol.	[187]
SoCalGas-NREL	US	Golden/Colorado	CH_4	yes	2017	0.250	biol.	[188]
Methane production from synthesis gas […]	US	Fayetteville	CH_4	no	1991	n.r.	biol.	[189,190]
SoCalGas-UCI	US	Irvine/California	H_2	n.r.	2016	0.007	–	[191]
CO_2-Recycling via reaction with hydrogen	US	Reno	CH_4	yes	2009	0.005	chem.	[15]
RSOC-Anlage Boeing	US	San Diego	H_2	no	2016	0.150	–	[192]
DTE Energy Hydrogen Technology Park	US	Southfield/Michigan	H_2	no	2004	0.160	–	[193]

Table 2
Status quo of active projects in 2019: Efficiency of the conversion from power to gas in projects producing hydrogen or methane (including biological and chemical methanation) and number of projects feeding in their products. Installed electrical load of methanation projects is related to the electrolysis power necessary to feed the methanation unit.

	Hydrogen-Projects	Methanation-Projects
Feed-in projects	21	36
No. of active projects in 2019	56	38
Installed production capacity	6205 m^3/h 18.6 $MW_{ch,LHV-H2}$	590 m^3/h 6 $MW_{ch,LHV-CH4}$
Installed electrical load	24.1 MW_{el}	14.5 MW_{el}
Efficiency electricity-to-gas	**77%**	**41%**

hydrogen production more expensive than methanation, will decrease in costs by about 75% (both, alkaline and PEM). For biological methanation, which today is supposedly more expensive than chemical methanation, the same cost reduction is estimated whereas chemical methanation will get cheaper by 67%, so both will reach costs of about 300 €/kW_{el}.

3.2. Power-to-Gas projects: development and projection

For the time span from 1993 to 2050, 153 completed, recent and planned projects in 22 countries were found. They show a variety of applications from early research and development level up to pilot and industrial scale power conversion plants in diverse fields of application. Project location and basic data can be retrieved as supplemented geospatial data. Fig. 3 illustrates analyzed projects on a global scale.

3.2.1. Plant allocation, product gas and electrolyzer technology

About 57% of all projects have or had their focus on hydrogen production, storage and use. The rest is or was investigating, additionally or solely, into CO_2-methanation. Half of the methanation projects covered biological methanation issues and the other half dealt with chemical methanation ones (Fig. 4). Regarding global project allocation, it is obvious that most of them are located in central Europe and especially in Germany, Denmark and the Netherlands. This was to be expected as the idea of large scale Power-to-Gas for energy system transition was first published in Germany [2]. Regarding installed capacity (electrical power of electrolyzers), Germany holds highest shares with a total of nearly 40 Megawatt (MW_{el}) followed by Denmark with well over 20 MW_{el}. Planning for the future, the Netherlands will increase their capacity until 2022 up to 12 MW_{el}. In Hungary, a 10 MW_{el} project is planned (Fig. 5).

In terms of electrolyzer technology, half of the projects investigated apply PEM electrolyzers, the other half alkaline ones. Only few projects tested high temperature or solid oxide electrolysis. Some few also investigated into two technologies at the same time or used hydrogen originating from other sources like gas bottles.

3.2.2. Methanation reactor types, carbon sources and gas grid feed-in

Most groups working with chemical methanation do not give detailed information on reactor type. As characterization, fixed-bed and Sabatier are stated most often, followed by bubbling fluidized bed, fluidized bed, multi-channel, honeycomb and packed bed. For biological methanation more detailed information is given: Of all the projects on biological methanation listed in the database, about 46% examined trickle-bed reactors while about 36% investigated on continuously stirred tank reactors (CSTR). One test was done in-situ of a biogas fermenter and another of a sewage gas fermenter.

Fifteen current projects use biogas or sewage gas from wastewater treatment plants as their carbon source for CO_2-methanation. Projects above lab or technical center scale mainly use bottled gas (13 projects). Other carbon sources investigated are bioethanol/alcoholic fermentation plants (two projects), syngas from biomass gasifiers, closed circle processes, fossil power plants, capture from biomass combustion and direct capture from air. Since not all data concerning carbon sources is accessible for every project, these values should be understood as benchmarks.

Nearly half of the projects (45%) inject their product gases into the gas network. About 35% of them feed in hydrogen, 65% methane. Amongst all hydrogen-projects feed-in share is clearly lower than amongst methanation projects. Here about 60% of the projects feed their gas directly into the gas network. This could be due to the fact that in all countries gas grid feed-in restrictions for hydrogen are higher than those for (bio-) methane.

3.2.3. Capacity, plant size and project development

Starting from the early 1990s, installed capacity in PtG projects has continuously increased appearing to follow an exponential trend until 2020 (Fig. 6, left side) The projections given in this figure are derived from data on facilities planned already today. The data shows a breakthrough between 2012 and 2015 when numbers and sizes of active facilities grew intensely. With big plants planned already today for the upcoming decades e.g. in France [140,141], Hungary [159,160] or

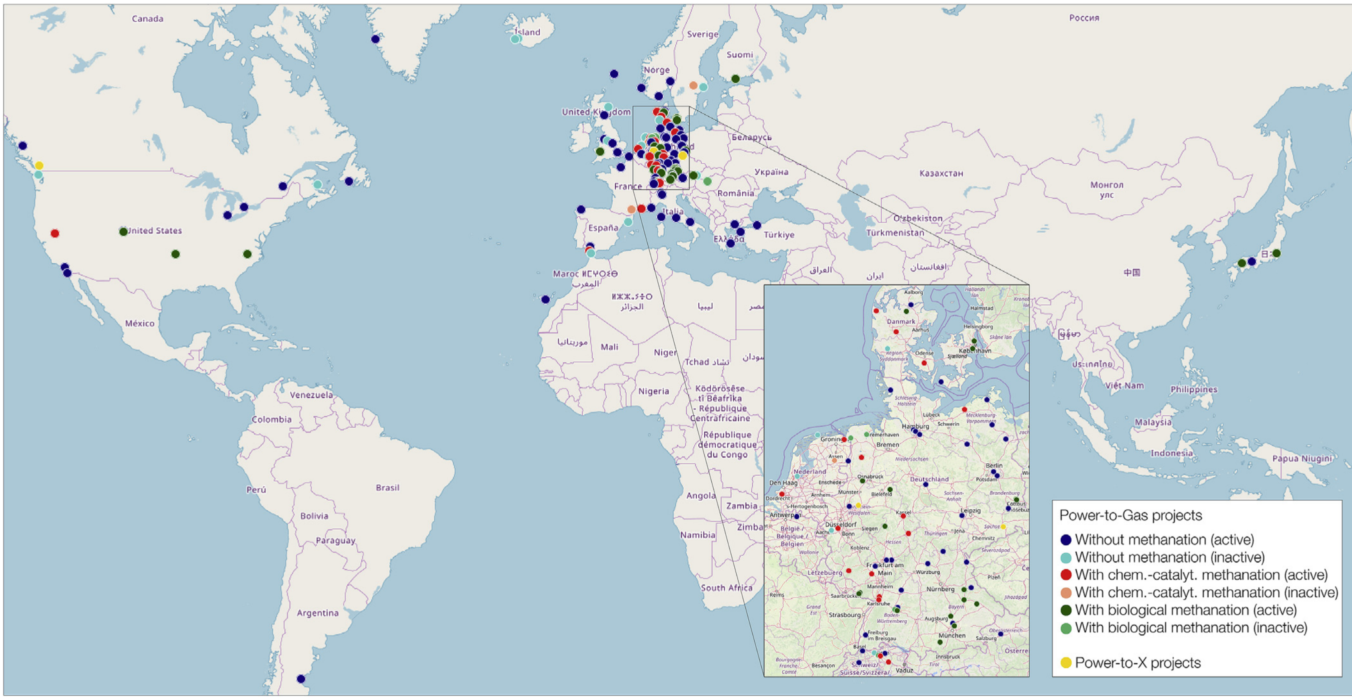

Fig. 3. PtG project allocation differentiated according to the target products hydrogen and methane as well as activity/inactivity. Dark green: PtG with biological CO_2-methanation active. Light green: PtG with biological CO_2-methanation inactive. Red: PtG with chemical CO_2-methanation, active. Orange: PtG with chem. CO_2-methanation, inactive. Dark blue: PtG without methanation, active. Light blue: PtG without methanation, inactive. Yellow: Power-to-X. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the North Sea [99,196], the exponential trend could continue, but blurring for this projection is high, as more projects could follow in upcoming years as illustrated on right hand side in Fig. 6. This means that presumably, the projections on installed PtG capacity will probably substantially increase as new facilities with higher capacity are announced (Table 3).

Until early 2019, the main part of PtG power installed, is located in Germany (30.7 MW_{el}) followed by Denmark (2.53 MW_{el}), Canada and the United States of America (both about 0.45 MW_{el}). Other countries as the Netherlands, France or Hungary are already planning to increase their capacity until 2020 and further on. Fig. 7 shows the annual development of installed PtG-capacity (electrolysis power in hydrogen and methanation projects). In early 2019, as many as 95 examined projects are active globally with an electrical power of 38.6 MW_{el}. 58% of them or 56 projects with a total capacity of 24.1 MW_{el}, produce hydrogen. The rest, 38 projects with a total capacity of 14.5 MW_{el}, produce methane.

Average plant size has been increasing over the years, experiencing a kind of disruptive growth from 118 kW_{el} to 390 kW_{el} between the years 2012 and 2015 (Fig. 8) as described above for the number of plants. With an average electrical power of about 380 kW_{el} per facility, methanation projects are about 12% smaller than projects producing hydrogen (430 kW_{el} per facility). In early 2019, the total average plant size for both product groups is 407 kW_{el} per plant.

Mean plant size projection over all hydrogen- and methanation projects until 2050 is 0.7 MW_{el} while chemical methanation plants are the biggest (mean value 1.56 MW_{el}). Due to a high number of smaller projects, mean plant size for hydrogen-projects is 0.45 MW_{el}, whereas biological methanation plants are in middle range with 0.61 MW_{el}. As future projects cannot be reliably reported here, this can only be a benchmark which will presumably get outnumbered in future. Fig. 9 shows the boxplot of installed electrical power per plant in sum per

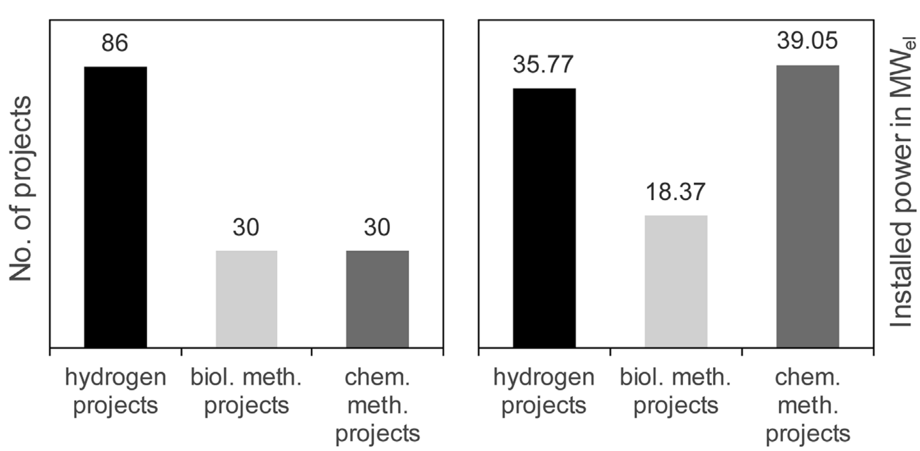

Fig. 4. Number of projects (left side) and total of installed electrical power in MW_{el} (right side) of PtG-projects with regard to their products either hydrogen or methane from chemical or biological methanation. This figure includes active and inactive e.g. completed or planned projects.

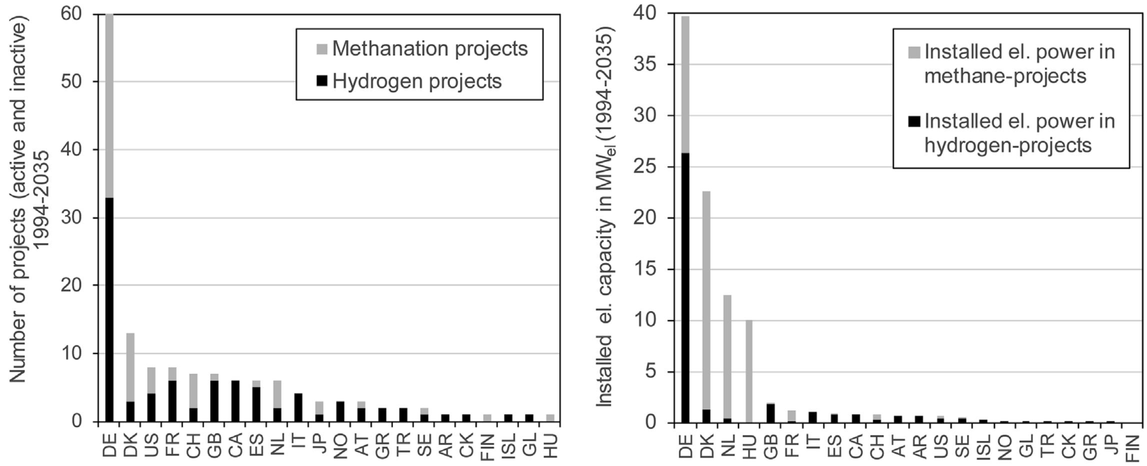

Fig. 5. Power-to-Gas project allocation and number of methane- and hydrogen-projects per country (left side). Installed electrolyzer capacity per country divided by projects with and without methanation. The figure includes active and inactive projects to emphasize total national interest in Power-to-Gas applications over the years.

country for both, methanation and hydrogen projects in the data set.

3.2.4. Product gas utilization

In 57 out of 143 projects, the product gas is fed in or is planned to be fed into the natural gas grid and reconverted into electricity or heat or to be used as fuel from there on (Table 1).

Product use was further differentiated into local storage and reconversion without gas grid feed-in, fuel production, industrial or substantial use, oxygen and off-heat utilization and research applications (Fig. 10). About 45% of the projects feed in, and 55% store their products locally. Both kinds of product treatment reconvert the gas after buffering. Overall 88% of the projects reconvert their products after either feed into the gas grid or local store.

After reconversion, biofuel production is the most common product utilization phase with application in 29% (36 projects) of all projects. Off-heat gets used in only about 10% of the plants. Use of the products e.g. in industrial processes (4%, 5 projects) and oxygen use (2.4%, 3 projects) only play subordinate roles in application. Only 13 projects are solely research facilities. This shows, that nearly all of them are designed as technical centers or pilot plants for near-to medium term market application.

The increase in installed power consequently affects the gas output proportionally (Fig. 11). In early 2019, a production capacity for about 6205 m^3/h of hydrogen is installed which, with respect to the lower heating value of hydrogen, is equal to a power of 18.6 $MW_{ch,\ LHV\text{-}H2}$. For methane it is about 590 m^3/h or about 6 $MW_{ch,\ LHV\text{-}CH4}$.

Mean efficiency calculated from energy content in product gas referred with respect to the lower heating value and installed electrical loads is listed in Table 2. Hydrogen systems with 77% efficiency, referred to the lower heating value, range near the middle of theoretical efficiency given by Sterner and Stadler [11] at 54–84%. Methanation projects appear with less efficiency of 41% compared to theoretical values of 49–79%. This could be due to the fact that less than ten percent of the projects include off-heat usage in their scope (Fig. 10). In addition, it is likely that nominal parameters which this analysis refers to, are seldom reached in real operation. Often, they are given without power consumption of balance of plants and, for example, refer to installed electrical power as installed stack power of the electrolyzer. This indicates that auxiliary systems like up- and downstream water and gas treatment, compression or cooling as well as standby power

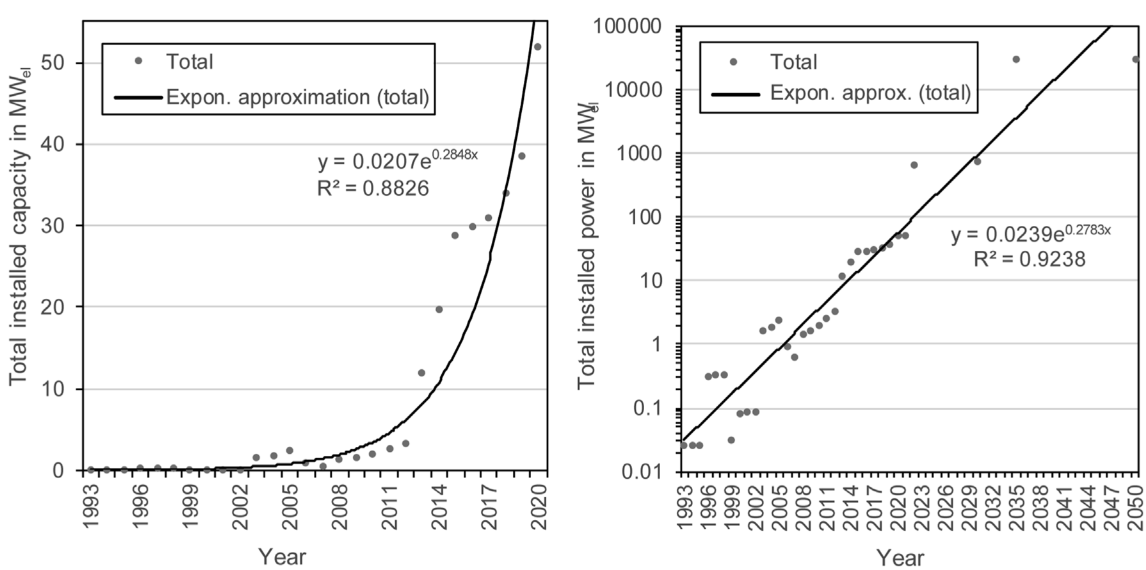

Fig. 6. Global mid-term trend in total installed electrical power of electrolyzers in methanation and hydrogen projects for the years 1993–2020 (left side) and long-term trend for the years 1993–2050 (right side). Values beyond the year 2018 are projected data. Methanation projects without electrolyzer are excluded in this approach.

Table 3
PtG-Projects not included in this evaluation but in supplementary geospatial data.

Project name	Location		Product	Grid inject.	Proj. start	Power	Metha-nation	Literature, Reference
	Country	*City*	*H_2/CH_4*	*yes/no*	*Year*	*in MW_{el}*	*biol./chem.*	
Klimafreundliches Wohnen in Augsburg	DE	Augsburg	CH_4	no	2019	n.r.	chem.	[198,199]
Wasserstoff-Sauerstoff-Projekt	DE	Barth	H_2	no	2003	0.045	–	[200]
Graforce Hydro demonstration plant	DE	Berlin	H_2	no	2018	0.041	–	[201,202]
Forschungsanlage TU Clausthal	DE	Clausthal-Zellerfeld	CH_4	n.r.	2017	n.r.	chem.	[203]
Blue Hamster	DE	Dernbach (Westerwald)	H_2	no	2014	0.002	–	[204,205]
Energieverbund Freiburg	DE	Freiburg	H_2	yes	2017	0.120	–	[54,206]
Solarhaus	DE	Freiburg	H_2	no	1994	0.002	–	[34,207]
SSE	DE	Freiburg	CH_4	no	2011	0.006	chem.	[14,208–210]
Raststätte Fürholzen West	DE	Fürholzen (A9)	H_2	no	2017	0.200	–	[211]
Smart Grid Labor	DE	Hamburg	CH_4	no	2015	n.r.	biol.	[212]
Solartankstelle Isenbüttel	DE	Isenbüttel	H_2	no	2005	0.012	–	[213]
Tankstelle Erlachseeweg 10	DE	Karlsruhe	H_2	no	2017	0.009	–	[14,214]
SOPHIA	DE	Köln	H_2	no	2014	0.003	–	[215]
HyWindBalance	DE	Oldenburg	H_2	no	2006	0.006	–	[216,217]
Stromlückenfüller	DE	Reußenköge	H_2	yes	2017	0.400	–	[218,219]
HYSOLAR	DE	Stuttgart	H_2	no	1987	0.010	–	[118,220]
Forschungsanlage TH Wildau	DE	Wildau	H_2	no	2010	0.007	–	[221,222]
Energiepark Ostfalia	DE	Wolfenbüttel	H_2	no	2009	0.006	–	[223,224]
BioCat Roslev ApS	DK	Roslev	CH_4	yes	tbd.	8.000	biol.	[225]
HyCAUNAIS Project	FR	Saint-Florentin	CH_4	yes	n.r.	2.000	biol.	[225]

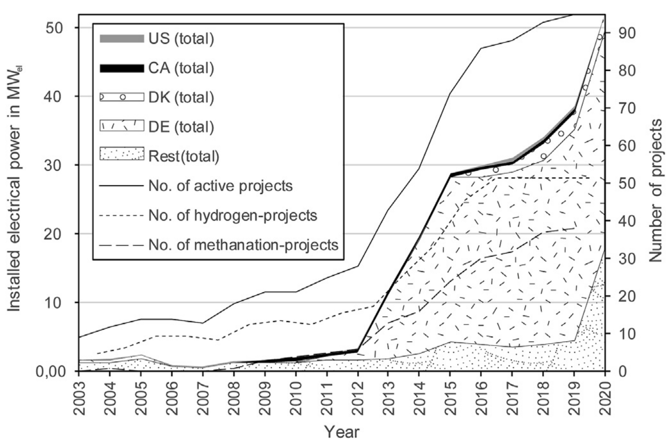

Fig. 7. Annual development of installed electrical power in PtG-projects split up in detail for the four main stakeholder countries Germany (DE), Denmark (DK), United States of America (US) and Canada (CA).

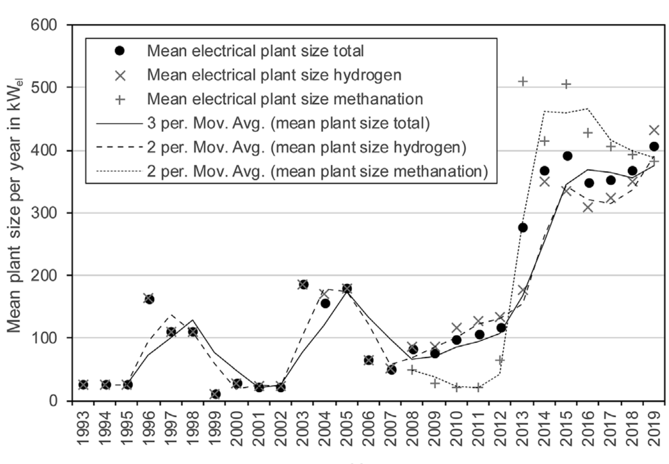

Fig. 8. Mean plant size (total, H_2-projects, CH_4-projects and their floating means for the years 1993–2018.

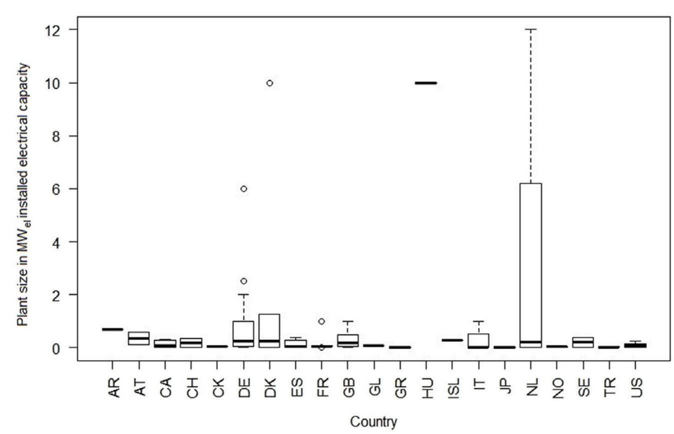

Fig. 9. Range of electrical power in which PtG plants are installed in the different countries. The boxplot shows the median of installed electrical power of a plant until 2022 combined in hydrogen and methanation projects, upper and lower quartiles, maximum values and outliers in plant size.

consumption or partial load operation significantly affect overall efficiency.

For the 67 projects which gave their data concerning 1988 to 2018, the average time needed for planning and constructing was about 1.5 years with a lifetime of mostly 1–3 years, although in some cases up to 10 years.

4. Conclusion

This analysis is restricted to electrolysis and methanation technologies. Exponential development of the technology concerning cost on one hand and installed capacity on the other indicate, that market implementation of Power-to-Gas is under way. Mean plant size and number of projects worldwide are rising. Even if today many projects are pilot plants with lifetimes of 1–3 years and still need funding, large-scale implementation is in planning in the mid and long term e.g. in north-west of Germany with 50–100 MW_{el} [122], about 610 MW_{el} in Hauts-de-France and Normandie [140,141] and up to 30 GW_{el} in the North Sea [99,196,197] and a growing number of projects is designed to be in operation for up to 10 years. Since our database constantly

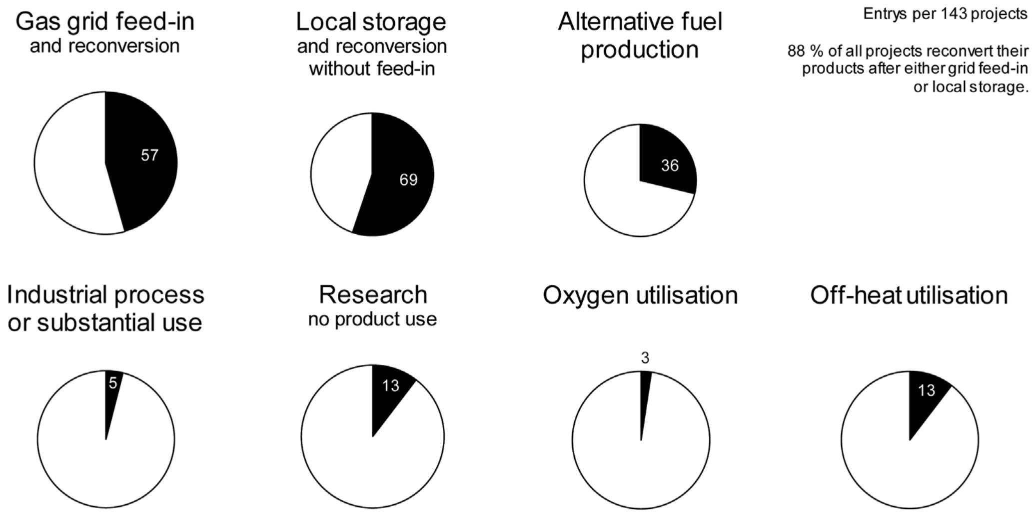

Fig. 10. Product gas utilization phases in the different projects. Numbers given show shares of total 143 projects which revealed their data concerning this matter. Due to overlap in utilization phases, the numbers given here add up to more than 143 projects.

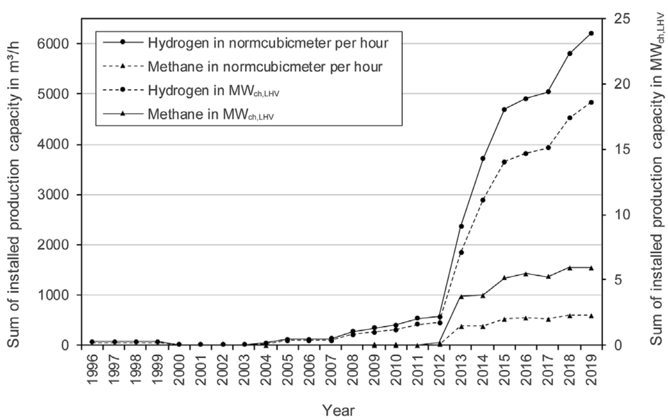

Fig. 11. Hydrogen and methane production capacity development between the years 1996 and 2019 in norm-cubic meter per hour and related to the lower heating value LHV (LHV_{H2} = 2.995 kWh/m^3, LHV_{CH4} = 9.986 kWh/m^3).

grows, the German projects listed in Table 3 have not been included in this evaluation but should be added in upcoming reviews as well as additional worldwide projects.

It was shown that capital expenditures for various electrolysis technologies as well as for methanation technologies are estimated to fall to about 500 €/kW$_{el}$ in the long term. At present, the global focus of research and application of PtG technology lies in Europe, but the United States of America seem to catch up. Worldwide, projects with methanation appear to have about the same significance as projects without methanation. The same is true for the distinction between membrane and alkaline electrolysis or chemical and biological methanation. Carbon sources for methanation are various while only about half of the projects feed or fed in their product gases into the natural gas infrastructure. Other fields of utilization are first and foremost alternative fuel production, then pure research applications and industrial processes or substantial use. Concerning efficiency, methanation projects show higher potential for improvement than pure hydrogen producing projects.

In the use of the by-products oxygen and heat, a large potential for improvement becomes obvious. If heat gets used within the process or decoupled into nearby heatsinks, substitution potentials for fossil energy carriers can be leveraged to rise efficiency. To improve economic efficiency, it would be beneficial to use all products of the plant: hydrogen or methane, heat and oxygen. Only few projects address this topic which, especially for methanation could contribute to rise efficiency.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rser.2019.06.030.

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