Chapter 9

Power-to-Gas—Concepts, Demonstration, and Prospects

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9.1 INTRODUCTION

The Power-to-Gas concept (other terms used: power to gas, P2G, PtG) uses renewable or excess electricity to produce hydrogen (Power-to-Hydrogen) via water electrolysis. This hydrogen can be used directly as a final energy carrier or converted to methane, synthesis gas, electricity, liquid fuels, or chemicals, for example. The reasons for using PtG are diverse (Tichler et al., 2014). The main purpose is to store energy long term by converting it to other easily storable energy carries, and at the same time reducing the load of the electricity grid by controlled operation (flexible demand). Furthermore, the production of renewable fuels for transportation, households, or industry, as well as for chemical production, can be a main driver for PtG. Not only are the motivations for PtG diverse, but also the choice of technologies. Fig. 9.1 gives a schematic overview of the necessary PtG pathways and components that have been discussed. In the following sections, the different components needed for gas production are discussed in more detail regarding their special needs for PtG (for example, different electrolysis technologies) their process design (for example, methanation) and the requirements for the transport and distribution of gases in the natural gas grid. The uses of the produced gases that are unrelated to energy, for example, in the production of chemicals, is not in the scope of this chapter.

The actual existing PtG projects in Europe are analyzed in Section 9.3 regarding their purpose and the technologies used. In Section 9.4, an overview of scenario studies for the deployment of PtG considering the development of future energy systems gives an estimation of the expected installed capacities for selected regions or countries.

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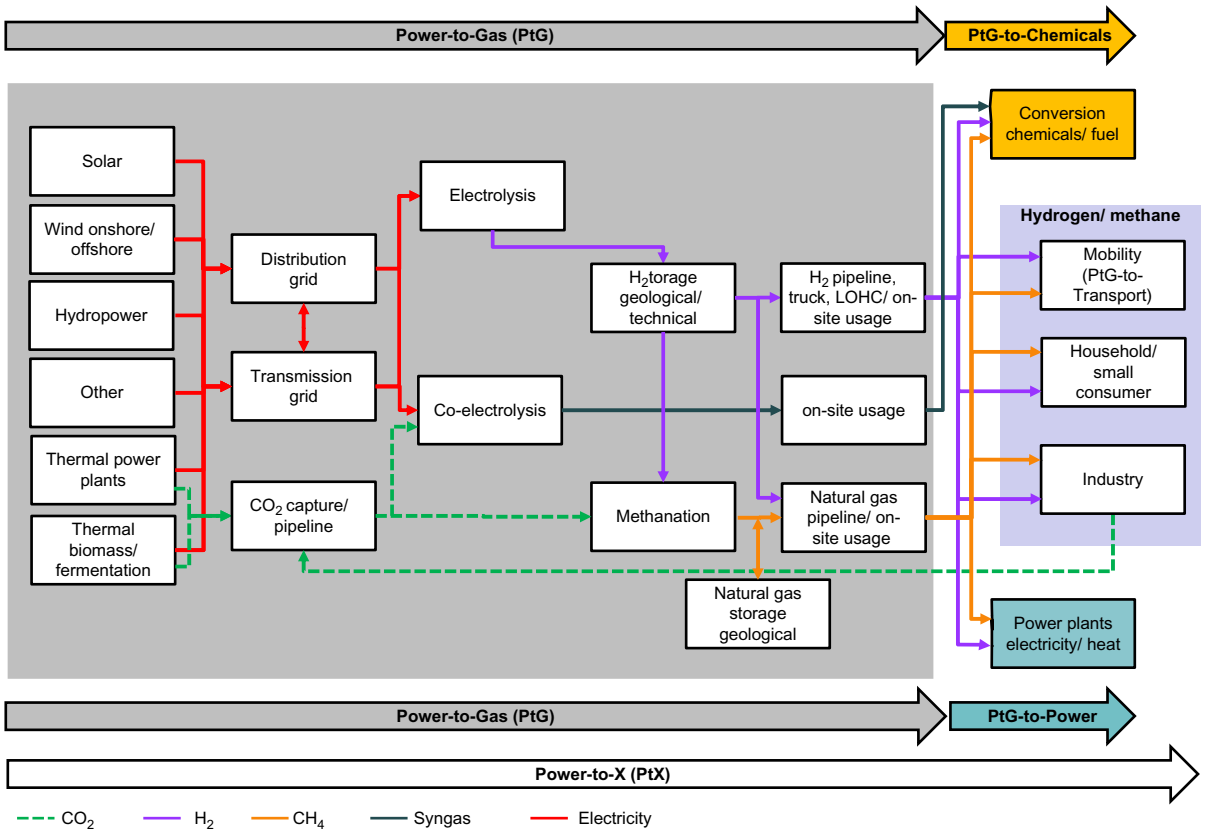


FIG. 9.1 Overview of Power-to-X concepts.

9.2 TECHNOLOGIES FOR POWER-TO-GAS

The main component of PtG systems is the gas production. This includes hydrogen production by electrolysis and its further processing to methane. Also, the electrolytic production of synthesis gas is an option. Transport and distribution of these gases is another important topic discussed here.

9.2.1 Hydrogen Production

Several concepts for electrolytic hydrogen production are already commercially available today. One option is alkaline water electrolysis. As PEM (polymer electrolyte membrane) electrolysis has a better part load behavior, this type of electrolysis became the first choice for PtG (Stenzel et al., 2016). However, for larger capacities, it has not reached a Technology Readiness Level of 9 yet, as the alkaline electrolyzer has done. Furthermore, a new type of electrolyzer, SOEC (solid oxide electrolyzer cell), which works under high-temperature conditions (700–800°C), is being explored for PtG applications. As hydrogen production by electrolysis is explained in more detail in another chapter, here only aspects are mentioned that are connected to the special requirements of PtG.

One important goal of PtG is to integrate fluctuating electricity generation from renewable energies (REN) into regional or national energy systems. Therefore, the main challenge for electrolysis within PtG is intermittent/dynamic operation. All three electrolyzers considered, PEM, alkaline electrolysis, and SOEC, are able to handle load changes. As alkaline and PEM electrolysis are more developed than SOEC, they are discussed here in more detail.

In general, PEM electrolysis can handle load changes better than alkaline electrolysis. Its minimum load lies between 0% and 10%, while alkaline electrolyzers only achieve 20%–40% (Smolinka et al., 2011). These values are defined due to the gas purities and subsequent safety concerns. Gas crossover takes places in every electrolyzer. While hydrogen occurrence at the anode, where oxygen is produced, causes no problems, oxygen at the cathode might be dangerous. An oxygen/hydrogen gas mixture with an oxygen content of >4 vol% is spontaneously combustible. Therefore, in technical applications, the maximum value of oxygen in hydrogen is set to 2 vol%. In alkaline electrolyzers hydrogen reaches the cathode by diffusion through the diaphragm or because it is dissolved in potassium hydroxide, which is mixed constantly. In PEM electrolyzers hydrogen diffuses through the membrane or is transported there dissolved in water. As these effects occur with a constant rate, independent from the actual hydrogen production, impurities increase with lower loads. Both electrolyzers are theoretically able to operate under overload conditions also. Since the performance range of the PEM is wider than for the alkaline electrolyzer, overload operation is normally only done with PEM electrolyzers. However, operating in overload leads to efficiency losses and stress for the materials (Tjarks et al., 2016).

Load changes affect temperature and pressure levels in the electrolyzer, and subsequently, its efficiency. Each electrolyzer has an optimal operation temperature. With lower loads, less heat is produced and the optimal temperature may not be reached. In contrast, under overload conditions, additional cooling is needed. A change of pressure has contradictory effects on the efficiency. A higher pressure level lowers the stack efficiency of the electrolyzer while it otherwise lowers the energy demand for gas drying and compression after the hydrogen production. In particular, for pressurized alkaline electrolyzers, lower pressure leads to lower system efficiencies. In those electrolyzers inherent to the system, a compression of the hydrogen up to 30 bar is done, which is more efficient than an external compressor. These electrolyzers are, however, more affected by stops of the system. If not enough electricity for the minimum load is provided by the fluctuating energy sources, the electrolyzer needs to be shut down completely after a short time, including a depressurization. Then the electrolyzer has to be flushed to prevent unwanted reactions of the remaining hydrogen. In conclusion, a stop leads to hydrogen losses as well as a loss in the pressure level, and subsequently to efficiency losses (Bourasseau and Guinot, 2016; Tjarks et al., 2016).

For small loads, additionally, the specific efficiency decreases significantly. The balance of the plant, for example, the pumps and cooling, has a constant energy demand independent of the hydrogen production. For loads lower than 30%, this leads to a significantly higher energy demand per kg hydrogen (Bourasseau and Guinot, 2016). In general, not only the electrolyzer itself, but also the process control, power rectifier, and the balance of the plant need to be designed for load changes.

Next to efficiency losses, a faster degradation of the materials used for the electrolyzer can be anticipated. At the moment, no studies are available that quantify the degradation and explain the reasons. However, with fluctuations of electricity input, the electrical as well as the mechanical parts of an electrolyzer system come under higher stress in comparison to constant load operation (Bourasseau and Guinot, 2016).

The amount of experience with the degradation of SOEC is even less than for the other electrolyzers. However, SOEC has been tested to check that it can work under fluctuating load conditions (Bourasseau and Guinot, 2016). Like the other electrolyzers, the SOEC is affected by fluctuating conditions with temperature and pressure changes. As the maintenance of a high temperature is of utmost importance, a cooldown due to a cessation of operation would lead to a long downtime and high energy losses. In total, SOEC has reached a TRL level of 5 at the moment.

The specific investments (per kW electrical input) for electrolyzers vary considerably. Values for alkaline and PEM electrolyzers range between 900 and 4200 €/kW for the year 2010–12 and are expected to decrease to between 250 and 900 €/kW in 2030 (Bertuccioli et al., 2014; Kasten et al., 2016). This big difference may be explained by the different technologies analyzed. At the

moment, PEM electrolyzers are still more expensive than alkaline electrolyzers. For the year 2030, however, both might be in the same range (Bertuccioli et al., 2014). Other factors for the uncertainty are upscaling and learning effects. Even though the electrolysis cells cost the same in small and big electrolyzers, the balance of the plant (e.g., power supply, system control, gas drying) achieves cost reductions due to upscaling. The future costs therefore depend on the scenario chosen for the electrolyzer sizes and the absolute installed capacity. Specific gas production costs not only depend on the investments, but also strongly on the purchase costs for the needed electricity and the full load hours of the system. This affects also the other parts of PtG systems, such as methanation.

9.2.2 Methane Production

Besides hydrogen production, another special process for PtG is the methanation described by the Sabatier reaction (Eq. 9.1). If methanation is part of the PtG system, carbon dioxide has to be separated from industry processes, power plants, or biogas plants if they are to be carbon neutral.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{9.1}$$

Two different concepts are available, so far. Most common is the catalytic methanation at higher temperatures (starting at 250–300°C) (Otten et al., 2016). Additionally, biological methanation is an option.

9.2.2.1 Catalytic

The above-mentioned Sabatier reaction is most commonly conducted as a thermochemical catalytic reaction. The highest conversion rate of this reaction is reached at low temperatures. However, to also ensure a reasonable reaction rate, a catalyst is needed. Today, mainly nickel catalysts (other metals like ruthenium are possible (Younas et al., 2016; Meylan et al., 2016)) with aluminum oxide as carrier material (also silica, zeolites, or metals under research (Lehner et al., 2014)) are applied. They require at least 300°C to work (Grond and Holstein, 2014). This reaction is highly exothermic ($\Delta H = -252.9\,\text{kJ/mol}$). The catalyst, however, starts sintering above 550°C (Younas et al., 2016). Thus, the main challenge of reactor design is temperature control. The pressure level varies between 1 and 200 bar (Benjaminsson et al., 2013; Götz et al., 2014; Leonzio, 2016). Next to temperature control, maximization of the conversion rate to synthetic natural gas (SNG) is the main goal for reactor design.

Therefore, different types of reactors are used or are under research. Fixed-bed reactors are state of the art for methanation (Götz et al., 2014). To control the temperature, several reactors (between two and five) are connected in series with cooling of the flow in between (adiabatic design) (TRL 7). As an alternative, directly cooled fixed-bed reactors, that is, tube bundle and plate reactors, are being tested as prototypes for an isothermal design (TRL 6) (Rönsch et al.,

2016). These reactors reach a sufficient conversion to SNG in just one reactor stage. However, they are more expensive than adiabatic reactors and the waste heat reaches lower temperatures, which makes further usage difficult (Specht et al., 2016; Benjaminsson et al., 2013). Currently, fluidized bed reactors are at the prototype stage, too (TRL 6) (Rönsch et al., 2016). They have a simple design and enable good heat removal. On the other hand, they also show faster attrition and incomplete carbon dioxide conversion caused by bubbling (Götz et al., 2016). Another possibility is three-phase reactors, either as fluidized bed or bubble columns, which are being investigated at lab scale at the moment (TRL 4) (Rönsch et al., 2016; Götz et al., 2014). An even less explored design is structured reactors with honeycombs or microchannels as well as sorption enhanced reaction (TRL 3) (Götz et al., 2016).

At the moment, the efficiency of fixed-bed reactors lies between 70% and 85% and is highly dependent on the use of the waste heat (Grond et al., 2013; Götz et al., 2014). Depending on the system integration of catalytic methanation, the heat might be used for biogas upgrading by an amine scrubber (Specht et al., 2016). Due to the sensitivity of the catalyst to impurities, the carbon dioxide needs to be cleaned from sulfur compounds, especially when coming from biogas upgrading. In theory, the use of desulfurized biogas is also possible. Because of a larger volume flow, this leads to a higher reactor volume and thus to higher investments. The produced SNG has a purity of approximately 92%. Depending on the requirements of the local natural gas grid, membrane processing of the SNG might be necessary before feeding it into the grid (Specht et al., 2016).

The dynamic and part load behavior of catalytic methanation is another important aspect in the design of PtG systems. The minimum load of adiabatic fixed-bed reactors is approximately 40% of the nominal load, while isothermal reactors reach lower values. More advanced systems, such as three-phase methanation even achieve values between 10% and 20% (Götz et al., 2016). Fast load changes and subsequent temperature changes in the methanation are no problem for the catalyst (Specht et al., 2016). However, state of the art catalysts have only a maximum lifetime of 24,000 h (Grond and Holstein, 2014). Furthermore, after a period of downtime, the reactor needs several days for restart (Grond et al., 2013), and before shutting the reactor down it needs to be flushed with hydrogen or some other inert gas (Götz et al., 2016).

The specific investments (per kW methane capacity[1]) for catalytic methanation are also hard to define. For 2030, the expected range lies between 200 and 600 €/kW (Kasten et al., 2016).

According to Götz et al. (2016), for average size reactors, three-phase or fluidized-bed reactors, and for large-scale plants (>100 MW), fixed-bed reactors are most favorable from a technical point of view.

1. Based on the lower heating value.

9.2.2.2 Biologic

Instead of the thermochemical catalytic process described above, the Sabatier reaction can also be conducted by metabolic processes of methanogenic archaea, chemoautotrophic microorganisms. This is a common process that is part of the production of biogas in anaerobic digesters. Therefore, different methods of implementing this reaction into biological reactors are possible. First, into a biogas digester or the post digester hydrogen is added to increase the methane yield. In this way, the methane concentration in the biogas can be elevated from 50% to 75% (Benjaminsson et al., 2013; Götz et al., 2014; Krassowski and Jochum, 2016). A higher hydrogen partial pressure in the digester, however, inhibits the degradation of biomass. Thus, the addition of hydrogen is limited (Benjaminsson et al., 2013).

As a second option, the methanation can also take place in a separate reactor with microorganisms, into which pure carbon dioxide or raw biogas is fed. Similar to the biogas digester, the microorganisms need thermophilic conditions (around 65°C). Archaea, which work under mesophilic (33–45°C) or hyperthermophilic (65–85°C) conditions, are used (Krassowski and Jochum, 2016). At higher temperatures, the solubility of hydrogen in water decreases, though (Benjaminsson et al., 2013). The gases (hydrogen and carbon dioxide) need to be solved into water to be processed by microorganisms. The pH value must stay between 6.8 and 7.2, which needs to be monitored closely as the carbon dioxide decreases it. An effective method for pH value control still needs to be developed (Götz et al., 2016). Furthermore, strictly anaerobic conditions are necessary as oxygen kills the microorganisms. Because the microorganisms are more resistant to impurities than the nickel catalyst in thermochemical methanation, the biological methanation can be fed with raw biogas and hydrogen without any pretreatment. Before SNG can be fed into the gas grid, however, it needs to be cleaned, for example, of sulfur components. In test reactors, higher methane yields were achieved with pure carbon dioxide in comparison to biogas (Krassowski and Jochum, 2016). Furthermore, the methanation reactor can be smaller if pure carbon dioxide is used. After methanation, only 85%–95% of the produced gas is methane (Götz et al., 2014; Krassowski and Jochum, 2016). The rest consists of hydrogen and carbon dioxide, which is sent back to the methanation process after cleaning. Due to unfinished reactions of the starting materials, the conversion efficiency of hydrogen to methane is lowered. Furthermore, 18% of the added hydrogen is transferred into heat and not methane (Benjaminsson et al., 2013). For this process, different types of reactors are under development. Most common for this application is a continuously stirred tank reactor. This type, however, needs additional energy to mix everything. At a certain size of the reactor, a homogeneous mixing becomes complicated (Götz et al., 2014). Alternative reactor designs are a trickle-bed reactor and reactors with hollow fiber membranes (Benjaminsson et al., 2013). Both designs avoid stirring by pumping the different media through the reactors.

The most important challenge at the moment for biological methanation is the supply of gaseous hydrogen to the microorganisms due to the low solubility of hydrogen in water (Götz et al., 2016). On the bright side, a first test showed that archaea are robust against sudden temperature, pressure, and load changes (Götz et al., 2014; Krassowski and Jochum, 2016). Even a start after a longer period of downtime is possible without problems (Grond and Holstein, 2014). Further research is needed to investigate the dynamic behavior. It can be assumed, however, that the process control system will be the limiting factor and not the process itself (Götz et al., 2016). Compared to thermochemical methanation, biological methanation happens at a lower rate due to the lower temperature, gas liquid mass transfer resistances, and backmixing (Götz et al., 2016). This leads to bigger reactor volumes when a similar volume flow should be reached. At the moment, biological methanation is still at the pilot and demonstration scale, leading to TRL between 6 and 7.

The investment required for biological methanation are, for smaller plants ($\sim$5 MW_{SNG}), in the same range as for catalytic methanation. Scaling effects, however, are clearly more distinct for catalytic methanation (Bär et al., 2015; Benjaminsson et al., 2013).

According to Götz et al. (2016), for small reactor sizes, biological methanation is technically most favorable.

9.2.3 Synthesis Gas Production

Besides hydrogen and methane, other synthesis gases with different H_2:CO ratios play an important role in PtG. As input to several subsequent production processes for fuels or chemicals they are the starting point for sector coupling, especially to the transport sector and the chemical industry. Today most of the syngas is produced from fossil fuels, either by steam reforming or partial oxidation with all their environmental constraints. The electrolytic production route consists of hydrogen production in an electrolyzer from water and subsequent reaction of parts of this hydrogen with carbon dioxide in a water-gas shift reactor to produce carbon monoxide. Hydrogen and carbon monoxide are then mixed in the desired ratio. For H_2:CO ratios lower than 3:1, the mature Fischer-Tropsch process converts syngas into liquid hydrocarbons.

The coupling of low-temperature water electrolysis and high-temperature gas-phase conversion, however, is challenging as both require different reaction conditions. In this context, the already mentioned solid oxide cells are gaining renewed interest due to steam and carbon dioxide reduction at high temperatures. In a so-called coelectrolysis process, a high-temperature CO_2-reduction reaction and steam electrolysis are combined in one simultaneous process step instead of subsequently coupling these two distinct reactions in separate reactors. As possible syngases, H_2:CO ratios from 1:1 to 3:1 are accessible (Foit et al., 2016), thus providing feed material for several fuels or chemical products, such as alcohols (1:1), diesel and kerosene (>1:1), ethanol and methanol (2:1),

or even methane (3:1). At present, research focuses on the ability of the operating parameters, such as temperature, current density, and material, to steer the required distribution of the H_2:CO ratios to reach an extensive understanding of this complex process.

Conventional fossil fuel-based syngas production often comes with undesired degrading reactants, such as sulfuric components or soot (Speight, 2015). The coelectrolysis, however, starts with pure input flows of deionized water from cooling water and carbon dioxide of sufficiently high concentrations, for example, from industrial point sources, leading to almost pure products. The starting point of current research work is the expertise in well-known solid oxide fuel cells. The typical process temperatures from 750 to 1000°C, using an oxygen-ion conducting ceramic electrolyte, show thermodynamic advantages. Additionally, the kinetics of the electrode reactions is much faster, meaning there is no need for expensive noble metal catalysts. At the steam electrode, usually a Ni/8 yttrium oxide stabilized zirconium oxide (YSZ) cermet is used for the water and carbon dioxide reduction. 8YSZ is used for the electrolyte and an electronically conducting metal oxide is used as oxygen evolution electrode (Ebbesen and Mogensen, 2009). However, there is still a great need for further fundamental research, as especially under coelectrolysis conditions, at high current densities, considerable degradation rates have been reported. Possible reasons are impurities in the gas and air flows, delamination of the air electrode due to pores building at the grain boundary, or coarsening on nickel particles (Foit et al., 2016). The TRL is therefore not higher than 3. These challenges must be overcome first before coelectrolysis will play a major role in future PtG scenarios.

9.2.4 Blending of Hydrogen Into the Natural Gas Grid

Hydrogen produced by water electrolysis can be blended at a defined share directly to the natural gas grid, or, after the conversion to methane by methanation, be added to the natural gas system nearly without any restrictions. After adding hydrogen or methane to the natural gas grid, the full scale of the natural gas supply and application system can be used. Therefore, PtG enables the use of REN or excess electricity in gas-fired power plants, industrial applications, or final consumer technologies, such as heating systems or gas stoves. Worldwide there are demonstration projects ongoing to analyze the impact of adding hydrogen to the natural gas grid and to analyze the interaction of this cross-sectional solution for the use of renewable electricity and its storage (see Section 9.3).

The results of one of the most comprehensive studies on the restrictions of hydrogen blending to the natural gas grid was published in Müller-Syring et al. (2013). On the basis of a detailed analysis on the impacts of hydrogen blended to natural gas, the authors of the study summarize that the existing natural gas infrastructure is suitable for up to 10 vol% of hydrogen blending. This statement is only valid if the combustion parameters of the gas blend fulfill the prevailing

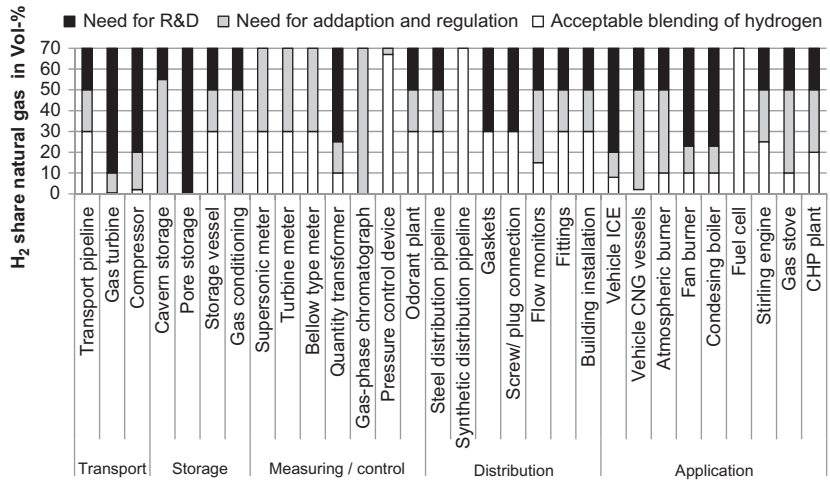


FIG. 9.2 Margin of hydrogen shares in natural blends for selected parts of the natural gas system. *(Source: Müller-Syring, G., Henel, M., Köppel, W., Mlaker, E., Sterner, M., Höcher, T., 2013. Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz. DVGW-PRojekt G1-07-10. DVGW, Bonn. Own illustration.)*

rules and standards for gas quality. Fig. 9.2 points out the hydrogen compatibility for important components of natural gas transport and distribution, gas storage, measuring technologies, and final consumer technologies.

The authors of the study identified a need for research on natural gas and hydrogen blends in geological storage (especially pore-space storage), on gas turbines and changing combustion behavior of the blends and high-pressure vessels for CNG (Compressed Natural Gas) vehicles. Currently, the share of hydrogen in natural gas for the operation of gas turbines is limited to 1–5 vol %, depending on manufacture requirements. Higher hydrogen concentrations cause an increase in the rate of spread for the flame that may lead to thermal stress in the components of the combustor and therefore to damage. In addition, flame instabilities can occur, which can also cause damage depending on the hydrogen share of the blend. For pressure vessels in compressed natural gas (CNG) vehicles and the corresponding components of the filling stations, further research must be done for the assessment of the stability of the currently used steel tanks under alternating pressure conditions.

The suitability of geological pore-space storage for natural gas/hydrogen blends is still subject to fundamental research. Needs for additional knowledge are seen concerning the microbiological aspects (formation of iron sulfite through microorganisms) as well as the integrity of the geological overburden. In industrial natural gas applications, not the hydrogen share itself is the problem but the quality of the blend, for instance in ceramic or glass producing industries. A changing composition of the gas blend makes the application of

additional measuring equipment necessary (e.g., Wobbe index measuring or process chromatographs). However, the authors of the study see fewer problems in final consumption technologies, such as heating appliances and gas engines.

The study of Müller-Syring et al. (2013) indicates that blending hydrogen to natural gas pipelines results in a reduction of the transport capacity. As one example calculation, for a pipeline diameter of DN 1000, a length of 250 km, and a capacity of 1 million Nm^3/h, blending 10 vol% of hydrogen to natural gas leads to a reduction in transport capacity of between 5% and 6% (according to the gas quality high- or low-grade gas). To reach the same transport capacities for a blended gas, the volume flow and the pressure level must be increased. The result is an increase of the compressor capacity of 25% when blending 10 vol% of hydrogen.

9.3 POWER-TO-GAS IN EUROPE

To integrate PtG into the energy system, in addition to the development of the single components, the system integration is of major importance. This can only be investigated by demonstration projects. In total in Europe 106 PtG projects have been conducted (January 2017). In the following, the projects are discussed in terms of their field of application, the processes used, and other important parameters (Table 9.1). While Bailera et al. (2017) focus only on projects that include methanation, here also Power-to-Hydrogen and PtG-to-Chemicals projects are included. The analysis is based on several previous review studies or projects (Bailera et al., 2017; Götz et al., 2016; Dena, 2017; Vartiainen, 2016; Iskov and Rasmussen, 2013; European Powertogas, 2017; Stenzel et al., 2016; DVGW, 2015). Furthermore, a great number of primary sources is used to fill knowledge gaps.

In total 15 different European countries have executed or are projecting PtG projects. The earliest projects started in 2003. For the following seven years, only a small number of projects were commissioned (between one and three, see also Fig. 9.6). Since 2011 the number of commissioned projects has increased rapidly and reached its maximum in 2015 with 19 projects. In 2017, eight projects will launch their plants. Also, for the years to come, several projects will start. The number of projected projects (seven), however, has to be regarded cautiously. Some of them sound very ambitious, for example, Power-to-Gas Hungary (Fründt and Pentz, 2016), while other notices of intent are already several years old, for example, Wijster (DNHK, 2014).

Even though Germany has realized the largest number of projects today and will continue to do so (47 have been executed or are projected, 44%), it had only one project in the early years (2003 – 10). In those days, Spain realized 28% of the projects (five projects). Also, Greece, Denmark, The Netherlands, and United Kingdom each realized two projects. Regarding the field of application of these projects, the distribution for Germany and 'other' countries correlate with the overall distribution, see Fig. 9.3. Spain, France, Denmark, and United

TABLE 9.1 Overview of Power-to-Gas projects in Europe

Acronym/ Location/Name of the Project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Methanation	Country	Source
Blending into natural gas grid							
Ameland	PEM	8.3	2008[a]	6		The Netherlands	(Kippers et al., 2011)
Hybrid power plant Prenzlau[b]	Alkaline	500	2011	7		Germany	(Enertrag, 2015)
Morbach	Alkaline	25	2011[a]	7		Germany	(Energielandschaft Morbach, 2015)
H2-Research centre BTU	Alkaline	145	2012	6		Germany	(Dena, 2012a)
Methanation at Eichhof							
1st	n.s.	25	2012[a]	6	Catalytic	Germany	(Krautkremer, 2017)
2nd	n.s.	50	2017	6	Catalytic	Germany	(Schröer and Krautkremer, 2016)
Power to Gas at Eucolino	n.s.	108	2012[a]	6	Catalytic	Germany	(Dena, 2012b)

Hybrid power plant Falkenhagen—STORE&GO Germany	Alkaline	2000	2013	7	Catalytic (u.c.)	Germany	(DVGW, 2016)
Audi e-gas	Alkaline	6000	2013	7	Catalytic	Germany	(Köbler, 2013)
Foulum	n.s.	250	2013[a]	6	Biological	Denmark	(Byman et al., 2013)
Viessmann microbial methanation	PEM	275	2013[a]	6	Biological	Germany	(Viessmann, 2015)
GRYHD[c]	PEM	n.s.	2014	6		France	(FCB, 2012)
Rozenburg	Alkaline	8.3	2014	6	Catalytic	The Netherlands	(Stedin Netbeheer, 2014; Vlap et al., 2015)
Thüga demonstration plant	PEM	300	2014	7		Germany	(Thüga, 2014)
RWE demonstration plant	PEM	150	2015	7		Germany	(RWE, 2015)
WindGas Hamburg	PEM	1000	2015	7		Germany	(Uniper, 2016)
Energiepark Mainz[d]	PEM	6000	2015	7		Germany	(Energiepark Mainz, 2016)
Energy storage—hydrogen injected into the gas grid via electrolysis field test	PEM	5.5	2015	7		Denmark	(Bruun et al., 2014)

Continued

TABLE 9.1 Overview of Power-to-Gas projects in Europe—cont'd

Acronym/ Location/Name of the Project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Methanation	Country	Source
Biogas upgrading	SOEC	~50	2016	5	Catalytic	Denmark	(Hansen, 2017)
DemoSNG	PEM	~60	2015	6	Catalytic	Sweden	(Graf, 2014)
BioPower2Gas	PEM	1200	2015	6	Biological	Germany	(IdE, 2015)
Power-to-Gas-pilot plant Allendorf	n.s.	1100	2015	6	Biological	Germany	(Viessmann, 2015)
Energy park Pirmasens-Winzeln	Alkaline	20,500	2016	7	Biological	Germany	(PFI Germany, 2017)
Hybrid power plant Aarmatt—STORE&GO Switzerland	PEM	700	2015	7	Biological	Switzerland	(DVGW, 2016)
BioCat Project/ POWERSTEP	Alkaline	1000	2016	7	Biological	Denmark	(Forstmeier, 2016)
bioCONNECT	PEM	n.s.	2016	5	Biological	Germany	(HS-OWL, 2015)
Ingrid—STORE&GO Italy	PEM	1.000	2016	7	Catalytic	Italy	(DVGW, 2016)
Renovagas	Alkaline SPE	15	2016	6	Biological	Spain	(Rubio et al., 2016)

Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion	SOEC	15	2017	5	Catalytic	Germany	(Founti, 2016)
Minerve	SOEC	n.s.	2017	5	n.s.	France	(AFUL, 2017)
CO2-SNG	n.s.	n.s.	2017	6	Catalytic	Poland	(BIOMA, 2015)
HyDeploy	PEM	500	2018	7		United Kingdom	(Markillie, 2016)
Jupiter 1000	Alkaline/ PEM	500+ 500	2018	7	Catalytic	France	(GRTgas, 2016)
Symbio	n.s.	n.s.	~2018	6	Biological	Denmark	(DTU, 2013)
SYNFUEL	SOEC	n.s.	~2019	5	Catalytic	Denmark	(Hendriksen, 2015)
Power-to-Gas Hungary	n.s.	10,000	projected	7–8	Biological	Hungary	(Fründt and Pentz, 2016)
Wijster	n.s.	n.s.	projected	7	Catalytic	The Netherlands	(DNHK, 2014)
Heat and power generation							
HARI	Alkaline	36	2004[a]	6		United Kingdom	(Gammon et al., 2006)
Utsira	Alkaline	50	2004[a]	6		Norway	(Statoil, 2004)
Vestenskov	n.s.	n.s.	2006[a]	6		Denmark	(DAC&CITIES, 2009)

Continued

TABLE 9.1 Overview of Power-to-Gas projects in Europe—cont'd

Acronym/ Location/Name of the Project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Methanation	Country	Source
RES2H2 Pozo Izquierdo	Alkaline	100	2007[a]	6		Spain	(Argumosa and Cambreleng, 2009)
Hídrolica	PEM	30	2007[a]	6		Spain	(Andalusian Energy Agency, 2011)
HYRES	PEM	4.5	2008	6		Greece	(Voutetakis, 2015)
Abalone Energie	Alkaline	n.s.	2009	6		France	(Hydrogenics, 2010)
H_2KT	Alkaline	100	2010	6		Denmark	(Nielsen, 2010)
Myrthe	PEM	210	2013	6		France	(FCB, 2014)
RH2-WKA Grapzow	Alkaline	1.000	2013	7		Germany	(WIND-WASSERSTOFF-projekt, 2016)
La Croix Valmer	PEM	n.s.	2014	7		France	(Areva, 2015)
Spring Bank Farm[c]	Alkaline SPE	4.8	2014	6		United Kingdom	(Acta, 2016)
El Tubo	Alkaline SPE	2.4	2015	6		Spain	(Acta, 2016)

Exytron demonstration project	Alkaline	21	2015	7	Catalytic	Germany	(Dena, 2016a)
Zero-Emission-Wohnpark	Alkaline	62.5	2017	7–8	Catalytic	Germany	(Dena, 2016b)
Stromlückenfüller							(Rentzing, 2016)
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	(Stadwerk Haßfurt, 2015)
Smart Grid Solar	PEM	75	2016	6		Germany	(Gossens, 2016)
Power-to-Flex	n.s.	n.s.	2018	6–7	Biological	Germany/ The Netherlands	(Power to Flex, 2016)
HYPOS LocalHy	Alkaline	250	2018	7		Germany	(HYPOS, 2015a)
Fuels							
HyFLEET:CUTE Hamburg	Alkaline	400	2003[a]	6		Germany	(HyFLEET:CUTE, 2009)
HyFLEET:CUTE Amsterdam	Alkaline	400	2003[a]	6		The Netherlands	(HyFLEET:CUTE, 2009)
HyFLEET:CUTE Barcelona	Alkaline	400	2003[a]	6		Spain	(HyFLEET:CUTE, 2009)

Continued

TABLE 9.1 Overview of Power-to-Gas projects in Europe—cont'd

Acronym/ Location/Name of the Project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Methanation	Country	Source
HyFLEET:CUTE Stockholm	Alkaline	400	2003[a]	6		Sweden	(HyFLEET:CUTE, 2009)
ECTOS	Alkaline	300	2003[a]	6		Iceland	(Icelandic New Energy, 2013)
PURE	Alkaline	18	2005[a]	6		United Kingdom	(Lumsden, 2011)
RES2H2 Keratea	Alkaline	25	2005[a]	6		Greece	(Varkaraki, 2009)
Chic Aargau	Alkaline	300	2011[a]	7		Switzerland	(PostAuto, 2012)
George Olah Plant							
1.	Alkaline	~1700	2011	7	[h]	Iceland	(Steffansson, 2015)
2.	Alkaline	~5200	2014	7	[h]	Iceland	(Steffansson, 2015)
Hydrogen refueling station HafenCity	Alkaline	600	2012	7		Germany	(Wulf et al., 2011)
Solar hydrogen filling station Freiburg	PEM	30	2012	7		Germany	(Fraunhofer ISE, 2012)
Herten hydrogen center of excellence	Alkaline	280	2013	7		Germany	(Brautmeier, 2015)

Hydrogen filling station Stuttgart	Alkaline	400	2013	7		Germany	(EnBW, 2017)
Sunfire Research project	SOEC	10	2014[a]	5	Fischer-Tropsch	Germany	(BMBF, 2015)
Sunfire Power-to-Liquids	SOEC	150	2014	5	Fischer-Tropsch	Germany	(Jendrischik and Aldag, 2014)
Multienergy fueling station H_2BER[e]	Alkaline	500	2014	7		Germany	(Total, 2014)
Power to Gas Biogasbooster[f]	n.s.	10	2014	6	Biological	Germany	(Dena, 2015)
M1 Wind Hydrogen Refueling station	PEM	100	2015	7		United Kingdom	(Pearce, 2015)
Wind2Hydrogen	PEM	100	2015	6		Austria	(OMV, 2015)
Power-2-Hydrogen-Tankstelle	PEM	185	2015	7		Germany	(Falk, 2016)
H2 Aberdeen: Hydrogen Bus Project	Alkaline	1000	2015	7		United Kingdom	(Aberdeen City Promotions, 2016)
Rapperswil	Alkaline	25	2015	6	Catalytic	Switzerland	(IET, 2017)
Levenmouth Community Energy Project[g]	Alkaline/ PEM	$2 \times 60 + 250$	2016	7		United Kingdom	(Todd, 2016)

Continued

TABLE 9.1 Overview of Power-to-Gas projects in Europe—cont'd

Acronym/ Location/Name of the Project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Methanation	Country	Source
HyFive London 1	PEM	100	2016	7		United Kingdom	(HyFive, 2016; Pearce, 2015)
HyFive London 2	PEM	100	2016	7		United Kingdom	
HyFive London 3	PEM	100	2017	7		United Kingdom	
Flagship project: Power-to-Gas Baden-Württemberg	Alkaline	1000+300	2017	7		Germany	(Del Regno and Vartmann, 2016)
MefCO2	PEM	1000	2018	6	[h]	Germany	(Spire, 2016; Steffansson, 2015)
Kitzingen	n.s.	4400–14,000	projected	7	n.s.	Germany	(Dieter, 2014)
Hydrogen for industry							
Sotavento	Alkaline	300	2007[a]	6		Spain	(Correas and Aso, 2010; Sotavento Galicia, 2017)
CO2RRECT	n.s.	300	2013[a]	7		Germany	(Rieks, 2011)
Osshy Pushy	Alkaline	60	2013	6		France	(Afhypac, 2014)
Lashy Pushy	Alkaline	65	n.s.	6		France	(Afhypac, 2014)

Hanau	PEM	35	2015	7		Germany	(Focht, 2015)
H_2Orizon[b]	PEM	1000	2017	7		Germany	(Andersen, 2016b, a)
GrInHy	SOEC	150	2018	6		Germany	(GrinHy, 2016)
Delfzijl	n.s.	12,000	projected	7		The Netherlands	(Port of Hamburg, 2016)
Usage of gas not specified							
ITHER	Alkaline/ PEM	63+7	2010[a]	6		Spain	(Correas and Aso, 2010)
SEE	PEM	6	2011[a]	6		Germany	(Fraunhofer ISE, 2014)
PtG 250	Alkaline	250	2012	6	Catalytic	Germany	(Zuberbühler, 2011)
Hydrogen Centre	Alkaline/ PEM	55+12+∼1	2012	6		United Kingdom	(University of South Wales, 2017; Armata, 2013)
MeGa-stoRE							(Tornberg, 2015; Møller et al., 2015)
1	Alkaline	6	2014[a]	6	Biological	Denmark	
2	Alkaline	60	2016	6	Biological	Denmark	
ESI Platform	PEM	100	2016	6	Catalytic	Switzerland	(Büchi and Schmidt, 2015)

Continued

TABLE 9.1 Overview of Power-to-Gas projects in Europe—cont'd

Acronym/ Location/Name of the Project	Type of Electrolyzer	Capacity kW	Commissioning	TRL	Methanation	Country	Source
Underground Sun Storage[i]	Alkaline	600	2016	6		Austria	(Bauer, 2016)
HYPOS rSOC	SOEC	n.s.	projected	5		Germany	(HYPOS, 2015b)

Note: *TRL: Technology Readiness Level; u.c.: under construction; n.s.: not specified; PEM: polymer electrolyte membrane; SOEC: solid oxide electrolysis cell; SPE: solid polymeric electrolyte.*
[a]*Plant decommissioned.*
[b]*H_2 also for mobility and CHP.*
[c]*H_2 also for mobility.*
[d]*H_2 also for mobility and industry.*
[e]*H_2 also for CHP, industry, and natural gas grid.*
[f]*CH_4 also for natural gas grid.*
[g]*H_2 also for natural gas grid and re-electrification.*
[h]*Methanol production.*
[i]*Main objective: underground storage of H_2.*

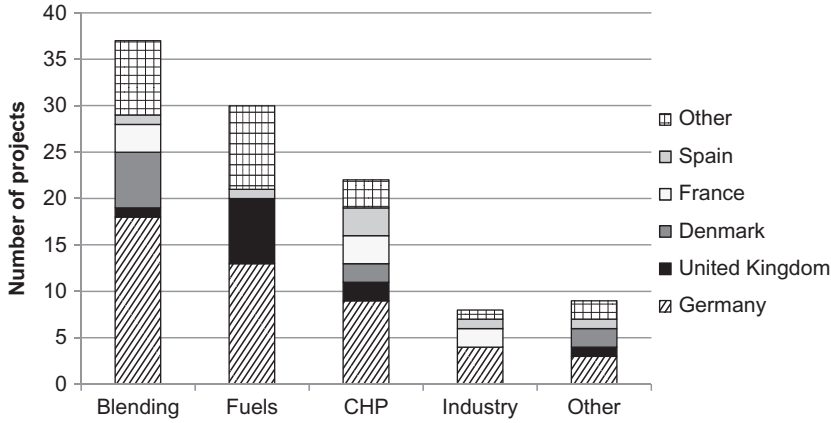
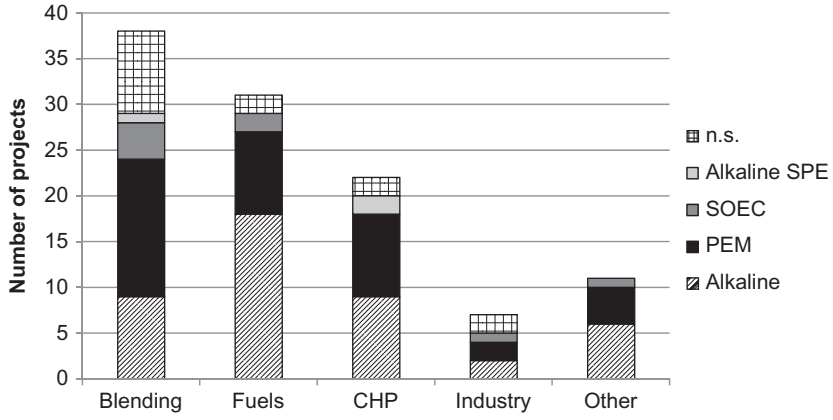


FIG. 9.3 Spatial distribution of Power-to-Gas technologies regarding field of application.

Kingdom, however, focus on certain fields of application. The United Kingdom, for example, conducts PtG mainly for fuel production ('Fuels'), while this field is not covered in Denmark and France. On the other hand, Denmark has a focus on blending hydrogen or methane into the natural gas grid (Blending), and France as well as Spain have a focus on electricity and heat production (CHP).

In the 106 projects, different types of electrolyzers are used. In addition to the alkaline, PEM, and SOEC electrolyzers described above (Section 9.2.1), a new technology has been developed, the so-called alkaline solid polymeric membrane (SPE) electrolyzer (Acta, 2016). It combines an alkaline with a PEM electrolyzer by using a solid membrane and an alkaline environment in one of the electrodes. By avoiding expensive metals for the electrodes, it should be cheaper than a PEM electrolyzer but better in part load behavior than an alkaline electrolyzer. In most of the projects, alkaline electrolyzers are used (41%) because the technology is more mature. The temporal development of the use of electrolyzers shows that the first projects were all operated with an alkaline electrolyzer. The first PEM electrolyzer was used in 2007 and other kinds of electrolyzers were not introduced before 2014. Even though, since 2014, the majority of the projects are no longer operated with alkaline electrolyzers, they are still an important technology for PtG.

The different characteristics of the electrolyzers influence the choice of electrolyzers for the different fields of application discussed. Fig. 9.4[2] shows that, at least for alkaline and PEM electrolysis, clear preferences are apparent. When the main goal is fuel production, alkaline electrolyzers are clearly favored. Fueled vehicles rely on a steady supply of fuel. For a mostly constant hydrogen production, alkaline electrolyzers are preferred still. When blending hydrogen or methane into the natural gas grid, the supply does not need to be that steady and more PEM than alkaline electrolyzers are used to buffer electricity from fluctuating renewable energy sources because PEM electrolyzers

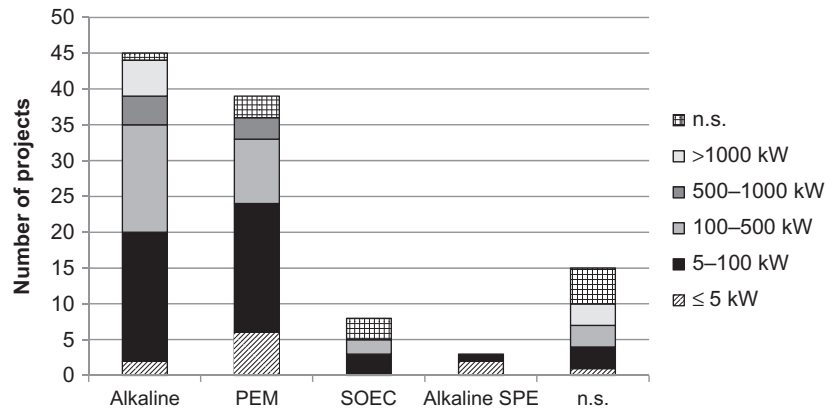


Note: n.s.: electrolyser technology not specified

FIG. 9.4 Electrolyzer technologies in Power-to-Gas regarding field of application.

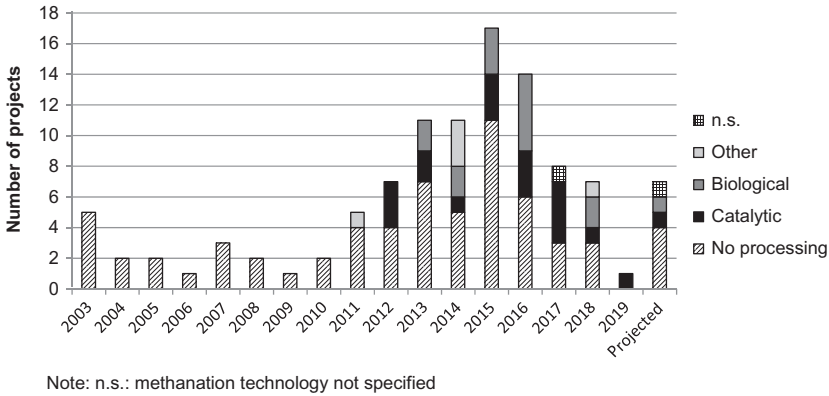
show a better dynamic behavior. This is also true when the hydrogen is used for electricity and heat generation. In those systems, often an alternative heat or electricity source is installed. Thus, the system can act more flexibly. Because the number of SOEC and alkaline SPE electrolyzers remains small, no clear trend can be identified yet.

Next to the field of application, the capacity (total input power) of the electrolyzer is an interesting parameter to categorize the projects. In this analysis, the size of the electrolyzers is grouped into five classes, see Fig. 9.5. Most of the electrolyzers have a capacity between 5 and 100 kW (36%) and are alkaline electrolyzers. In the smallest class (<5 kW), mostly PEM electrolyzers are used



Note: n.s.: capacity not specified

FIG. 9.5 Electrolyzer technologies in Power-to-Gas regarding their capacity.



Note: n.s.: methanation technology not specified

FIG. 9.6 Temporal development of methanation in Power-to-Gas.

for more research-oriented projects. SOEC electrolyzers are not realized in such a small capacity. On the other extreme, the largest electrolyzers (>1000 kW) are only found among the alkaline electrolyzers and in some projects in which the technology is not specified.

Another important application within PtG is the processing of hydrogen to methane or other chemicals. In the 106 projects, hydrogen is directly used in 65 of them (61%). In 2011, the first processing of hydrogen to methanol (in Fig. 9.6 subsumed under 'other' together with the Fischer-Tropsch process) was conducted in the George Olah Plant in Iceland (Steffansson, 2015). In the subsequent years, processing of hydrogen, and mostly methanation, became more and more popular. Even though, catalytic methanation is more mature, almost as many projects with biological methanation (15 projects) are being operated as with catalytic methanation (19 projects). Both started roughly at the same time 2012/13. Since 2016 even more PtG projects are processing hydrogen further to other chemicals than using it directly. Sorting the kind of product by country, it becomes obvious that Denmark is very interested in methanation (70% of all projects include methanation). In particular, there is focus on biological methanation. Only Germany has more projects investigating biological methanation.

9.4 PtG IN ENERGY SUPPLY SCENARIOS

In current energy scenarios, storage options, such as PtG, are the subject of analysis. Nearly all scenarios with a focus on energy storage assume a future trend toward increasing storage capacity in conjunction with more REN in the electricity generation. The quantification of the required storage capacity in the scenarios depends on many assumptions and is subject to current research work.

A survey of energy scenarios for the world, the EU, and the national examples France, Sweden, and Germany investigates the range of calculated

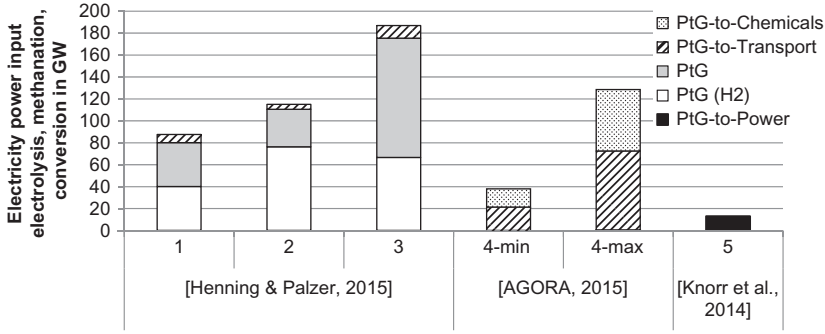


FIG. 9.7 Comparison of PtX capacities in different energy supply scenarios for Germany, year 2050, own assumptions (AGORA, 2015; Henning and Palzer, 2015; Knorr et al., 2014).

storage capacities with a special focus on the seasonal storage option by PtG. Important impacts on the results identified are in particular the share of REN in electricity generation, the composition of the conventional power plant mix, grid constraints, electricity export/import, storage costs, and carbon dioxide emission caps.

The IEA scenario study "Energy technology perspective (ETP)" (IEA, 2014) is accepted worldwide and is a reference for many national energy scenarios. The focus is on the application of established as well as new energy technologies and their future potential for climate protection. The 2014 version has a spotlight on electricity storage. For the 2DS scenario (ambitious scenario with a maximum global warming of 2°C worldwide resulting in high shares of REN worldwide and decarbonization in electricity generation in 2050), the trends for daily storage capacity are calculated. The installed capacity will reach over 300 GW in the regions of China, India, United States, and EU in 2050. This is more than four times the installed capacity of daily storage in 2011 for these regions. PtG is described as a technical option that can significantly increase the level of REN integration in the energy system by connecting the power system to the natural gas system, thus making use of the already existing storage potential of the natural gas infrastructure. However, the capacity of PtG applications in the scenarios is not quantified.

A European study supported by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) (FCH-JU, 2015) of the year 2015 analyzes the development of the European electric power system and the need for the installation of energy storage options. For daily storage (PtG-to-Power), the analysis provides scenario results for installed capacities in Germany, Spain, and Sweden. For PtG options (using excess electricity in the electricity, heat, and transport sectors) the installed electrolyzer capacity is calculated for Germany as an example. In the high-renewables scenario (85% share of REN in electricity generation in 2050), the calculated electrolyzer capacity is between 115 GW for no grid constraints and 170 GW for essential constraints in the transport and distribution grid. The European potential for electrolyzer capacity in 2050 of the

high-renewables scenario is stated as hundreds of GWs for the full integration of excess electricity. The calculated capacities in this study are very high because a full use of REN excess electricity is assumed and no curtailment or flexibility of demand is taken into account. The demand for storage differs significantly among the analyzed countries. In contrast to Germany and Spain, Sweden has large reservoir hydro capacities, which can integrate REN and eliminate the need for daily and seasonal storage options. There is no economic demand for REN integration in Sweden, even in the high-REN scenario.

The French study (ADEME, 2015) investigates scenarios for the French electricity sector and its possible pathway to a 100% REN share in a time horizon to 2050. The applied model optimizes the generation mix and the design of the electric grid and takes into account regional effects on a one-hour time resolution for a whole year. In this study only PtG-to-Power is analyzed as seasonal storage. For a share of 80% REN in the generation mix (46.5% wind, 14.3% hydro, 12.5% PV and 6.7% biomass and others) the optimization results show no need for the installation of the seasonal storage option PtG. The installed capacity for hourly and daily storage options (mainly pumped hydro storage is assumed) is calculated to be 15 GW in the scenario year 2050 for France. Flexible generation, grid improvement, and flexibility in electricity demand reduce the need for additional storage options. For the scenario with a 95% and 100% share of REN in French electricity generation in 2050 (increased share of PV and wind onshore, wind offshore/offshore floating), the optimization results show a need for installed capacity of 9 and 17 GW, respectively, for PtG-to-Power options. The need for long-term seasonal storage options therefore is strongly connected to the share of REN generation in the electricity system.

For Germany, the largest electricity consumer in the EU with ambitious goals regarding REN electricity generation, a large set of scenario calculations exist with a focus on storage demand. Some of the scenarios take into account PtX for the integration of REN in the sectors of electricity, heat, or transport. A detailed look at three different studies is used for a comparison of the prospects of PtX applications in the German energy system. The selection of these scenarios is based on suitability for the comparison by detailed information about the share of REN electricity and mode of PtX applications.

(A) Henning and Palzer (2015)
The study analyzes the development of the current German energy system through 2050 to comply with the goals of the German "Energiewende." On the basis of nine scenarios (among other assumptions different shares of REN in electricity generation) cost-optimized transformation paths are indicated. The scenarios take into account PtX for electricity, heat, and transport.

(B) AGORA (2014)
The study investigates the need for daily and seasonal storage by means of cost optimization for the transformation of the current German energy systems toward a sustainable one in light of the "Energiewende" concept.

The different scenarios assume different REN shares in electricity generation for Germany and Europe. For the year 2050, a share of 60% (Europe) and 90% (Germany) could be reached.

(C) Knorr et al. (2014)
The study analyzes an electricity supply system in Germany that completely relies on REN. The question that this study seeks to answer is whether the security of the electricity supply can be guaranteed at any time of the year. The analysis has a strong focus on the electricity system but takes into account the demand for heat and transport with respect to its flexibilities.

The calculated PtG capacities in five scenarios of the three German studies are summarized in Table 9.2. The selected set of scenarios for the German energy system in the year 2050 indicates a large spectrum of results in terms of installed PtX capacities and their mode and coupling to different sectors.

In the three selected scenarios with 80%, 85%, and 90% carbon dioxide reduction, Henning and Palzer (2015) assume an installed PtG capacity between ~90 and 180 GW for the year 2050. The high capacities arise from the need for guaranteed energy supply with high shares of REN in conjunction with very low carbon dioxide emissions. In the most ambitious scenario, #3, PtG is the dominant option due to the substitution of fossil natural gas in domestic and transport applications. Power-to-Hydrogen delivers transportation fuel and additional blend to natural gas.

The study AGORA (2014) gives a spectrum of installed capacities due to different assumptions about flexible generation, curtailment, transportation, and distribution grid enhancement and flexible demand. The PtG-to-Transport option is seen in the study as more cost effective in comparison to PtG-to-Power. The minimum capacity for the latter option is at a very low level, below 1 GW installed capacity.

The study by Knorr et al. (2014), with its focus on the electricity system, calculates 13 GW for PtG-to-Power options for a guaranteed electricity supply by 100% REN generation. Seasonal storage by PtG-to-Power is seen to be in competition with fast responding decentralized biomass power plants and flexible demand in this scenario.

A more detailed look at the scenario assumptions reveals differences in the share of REN in electricity generation, REN installed capacities, and carbon dioxide reduction goals. Especially the costs and application of flexible generation and demand is one of the assumptions that determines the results.

High shares of REN electricity generation lead in all scenarios to a large amount of excess electricity. All of the analyzed scenarios show a potential for PtG in transport or chemical applications. The selected PtG option depends on the assumed cost structure of the entire energy conversion chain, as well as the costs of competitive options, such as flexibility of generation or demand.

TABLE 9.2 Comparison of Selected Scenario Assumptions (AGORA, 2015; Henning and Palzer, 2015; Knorr et al., 2014)

# (Referring Fig. 9.7)	1	2	3	4-min	4-max	5
Source	Henning and Palzer (2015)			AGORA (2015)		Knorr et al. (2014)
Assumed REN share in electricity generation	Not specified	Germany: 85%	Not specified	Germany: 90% Europe: 60%		Germany: 100% Europe: 100%
Assumed PV and wind generation capacity in GW	293	367	536	279		260
Application of PtX	Power, gas, fuel	Power, gas, liquid, transport	Power, gas, liquid, transport	Power, fuel, chemicals		Power
Other assumptions	80% CO_2 reduction; see scenario #2	85% CO_2 reduction, ambitious goals for energy efficiency in buildings, alternative drive trains in transportation, phase out of coal power plants till 2040	90% CO_2 reduction, high excess electricity, see scenario #2;	Minimum potential of flexible generation, flexible demand, curtailment, grid enhancement, resulting in low capacities of PtX	Maximum potential of flexible generation, flexible demand, curtailment, grid enhancement, resulting in high capacities of PtX	fast responding decentralized power plants and demand side management

The comparison of studies conducted here shows no clear trend on cost effectiveness because the scenario assumptions are not comparable and influence the results in an essential way.

9.5 OUTLOOK

In the previous sections it was revealed that the technologies for PtG, as well as the applications, are diversified. If production of fuels and chemicals is the main goal of PtG, then alkaline electrolyzers are preferred. If, in contrast, the use of excess electricity and ancillary services for the electricity grid are the focus of the project, then PEM electrolyzers are, despite their higher costs, used more often. Furthermore, new electrolyzers (SOEC, SPE) are under development to increase the efficiency. To avoid the limitations on hydrogen that can be fed into the natural gas grid, another focus is on the production of other gases, for example, by methanation and coelectrolysis. The technologies for that are quite different. However, up to now, all technologies have, under certain requirements, a right to exist.

Looking into the future and the integration of PtX into energy systems, the international energy scenario analyses reveal the potential application of PtX options in scenarios for energy systems with high (>80%–85%) REN penetration. The quantification of capacities, however, depends strongly on local requirements of the generation, grid, and demand. All scenarios highlight the use of PtG to significantly increase the interactions between the gas, power, and transport sectors, as well the option to support uses unrelated to energy, such as chemicals and other products.

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