Chapter 2
The Power-to-Gas Concept

This chapter gives an overview of the technological fundamentals of the Power-to-Gas concept. After a general introduction to the concept itself, efficiencies and synergy potentials of the Power-to-Gas technology are described. Furthermore, a very short introduction to similar concepts is given, as well as a view to the technological challenges and restrictions for integration of hydrogen into the natural gas grid. Due to the limited available space, only the main aspects are addressed with reference to further reading.

As described in Chap. 1, temporal and spatial fluctuations of the power generation by renewable energy sources demand both high-capacity distribution systems as well as intermittent storage possibilities. The Power-to-Gas concept approaches these demands by the conversion of the electrical power to a gaseous chemical storage medium, the energy-rich gases hydrogen (H_2) and methane (CH_4), respectively. The Power-to-Gas concept is depicted in Fig. 2.1 (Sterner 2009; Grond et al. 2013; Müller-Syring et al. 2013a; Deutsche Energieagentur 2013; Egner et al. 2012).

As shown in the upper left side of Fig. 2.1, renewable electricity is usually transferred to the power grid. The transport of electricity is limited on the one hand by the actual grid-side demand which may result in temporal excess energies. On the other hand, renewable energy production may be located in afield areas with limited transport capacities or completely autarkic structures. According to Fig. 2.1, the renewable electric power is then used in a water electrolysis plant to produce hydrogen and oxygen from water. Oxygen can be released to the atmosphere, or can be preferably used in industrial production processes, like the chemical or the metallurgical industry. But, the utilization of oxygen depends strongly on the local conditions, particularly the distance to the potential consumers and the consumer demand. The actual product is hydrogen which can be transported either in an own hydrogen distribution grid, as admixture in the natural gas grid, by truck or by train. Hydrogen can also be stored in appropriate facilities or together with natural gas in existing natural gas storage infrastructure.
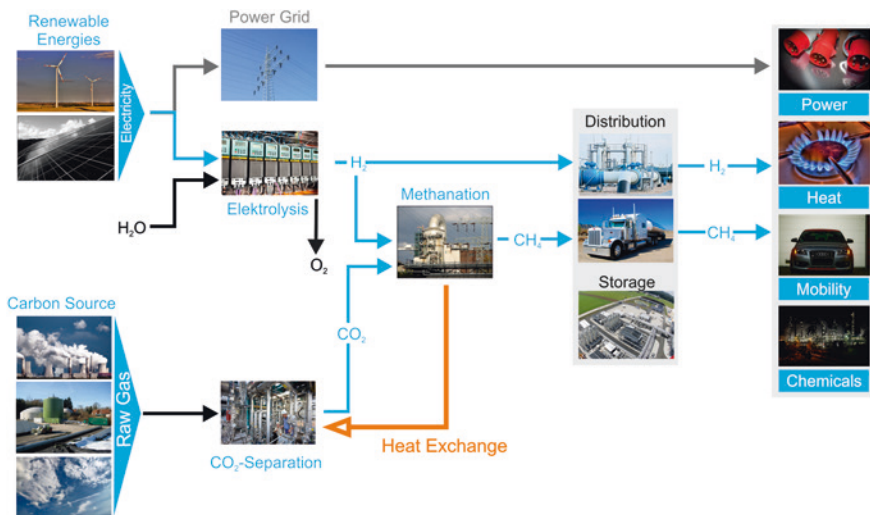
Fig. 2.1 The Power-to-Gas concept

Hydrogen is then re-transferred either to electric power, as fuel in the mobility sector, or as valuable feedstock for industry. Particularly, the chemical, petrochemical and metallurgical industries consume huge annual amounts of hydrogen (approximately 600 billion m^3/a) which are currently produced mainly by methane steam reforming.[1]

Thus, hydrogen is the first possible end-product of the Power-to-Gas process chain. But, the producible volume of hydrogen is limited by either missing hydrogen infrastructure (i.e. hydrogen grid, storage facilities, end-use technologies), or by a maximum allowable content in the natural gas grid.

Therefore, the second, but optional process step within the Power-to-Gas process chain is methanation. Hydrogen and carbon dioxide (CO_2) synthesize to methane, either by a chemically or biologically catalyzed reaction. The produced methane is called synthetic or substitute natural gas (SNG). The by-product of this reaction is steam (H_2O). The necessary carbon dioxide can be derived from exhaust or process gases of industrial production processes or fossil power plants, biogas plants, or in principal also from the atmosphere or from sea water (Fig. 2.1). The latter options are certainly energy-intensive. Since pure carbon dioxide sources are only rarely available (Ausfelder and Bazzanella 2008), carbon capture plays a significant role in the Power-to-gas concept, both technically and economically.

The main advantage of methane as end-product of the Power-to-Gas process chain is its unlimited usability in the gas infrastructure. SNG bi-directionally links the power grid and the gas grid. Already existing transport and storage possibilities

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[1] The by-product of the reforming process is carbon dioxide. Methane steam reforming is the reverse reaction of methanation, see Chap. 4.

of the gas grid are used for the transfer of renewable electricity in the form of SNG. The huge gas storage facilities in Europe[2] enable the intermittent retention of renewable energy in the range of up to 1,000 TWh. Furthermore, the infrastructure for methane utilization also exists, and is completely technically mature. Beside the conversion into electricity in combined cycle plants, the utilization as fuel in mobility or as feedstock for industry, SNG can be also used for heating. The physical and chemical properties of SNG and natural gas are so similar that no technical changes in the end-use systems have to be undertaken. Almost no new investments in infrastructure for transport, storage and utilization are necessary. This is not only of an economic benefit, but also time saving with regard to permission by authorities, and beneficial for the general public acceptance which is commonly low for any infrastructure projects.

The conversion to the energy-rich gases hydrogen and methane, respectively, enables the transport of the renewable energy outside the power grid, and also the large scale, long-term storage of renewable energy. The chemical energy carriers can be reconverted to electricity, but a multitude of other utilization routes are possible which result in different efficiencies of the total system.

2.1 Efficiencies of Power-to-Gas Process Chains

Since any technical process is associated with energy losses, the high exergy[3] level of electric power is inevitably reduced by the conversion processes within the Power-to-Gas process chain. Therefore, it is preferential to avoid unnecessary conversion steps whenever possible. Electric power should be used as electric power provided that sufficient grid capacities are available. The use of electric power can also be accelerated by generating higher demands, for example by an increased electrification of industrial processes (Leiter et al. 2014). Nevertheless, both the demand management as well as the extension of the power grid are limited, and, therefore, storage of renewable energies is inevitably necessary when the shares of renewable energies are steadily increased in future.

Within the Power-to-Gas process chain, the first usable product is hydrogen. As already mentioned, the chemical, petrochemical and metallurgical industry demands significant volumes of hydrogen. But its utilization requires either a consumer nearby the electrolysis plant, or transport facilities which are poorly developed for hydrogen, at least at present. Furthermore, storage options for hydrogen would enable the buffering and decoupling from the demand side. Beside storage

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[2] There are about 134 subsurface gas storage facilities throughout Europe with an aggregate storage volume of 94 billion m^3 of natural gas.

[3] Exergy describes the part of energy which is convertible to its full extent in any other form of energy. Anergy is the part of the energy which is not convertible to exergy. The sum of exergy and anergy is the total energy. Electric power consists of 100 % exergy (Baehr 1996).

Table 2.1 Efficiencies for different Power-to-Gas process chains (Sterner et al. 2011)

Path	Efficiency (%)	Boundary conditions
Electricity to gas		
Electricity → Hydrogen	54–72	Including compression to 200 bar (underground storage working pres.)
Electricity → Methane (SNG)	49–64	
Electricity → Hydrogen	57–73	Including compression to 80 bar (feed in gas grid for transportation)
Electricity → Methane (SNG)	50–64	
Electricity → Hydrogen	64–77	Without compression
Electricity → Methane (SNG)	51–65	
Electricity to gas to electricity		
Electricity → Hydrogen → Electricity	34–44	Conversion to electricity: 60 %, compression to 80 bar
Electricity → Methane → Electricity	30–38	
Electricity to gas to combined heat and power (CHP)		
Electricity → Hydrogen → CHP	48–62	40 % electricity and 45 % heat, compression to 80 bar
Electricity → Methane → CHP	43–54	

in underground caverns, the natural gas grid is a potential buffer for hydrogen. The limitations and challenges of the latter option are described later in an own section.

Methanation converts hydrogen to synthetic methane (SNG). The efficiency of the conversion is reported to be 70–85 % in case of the chemical path, greater than 95 % for the biological path (Grond et al. 2013). The main benefit of SNG is its unrestricted compatibility with the natural gas grid, and with the utilization options of natural gas.

The re-powering of methane to electricity in combined cycle plants closes the loop electric power—SNG—electric power. It opens the possibility to produce electric power in areas far away from the renewable power sources, connected by an already existing gas grid. However, the efficiency of this option is the lowest of all possibilities, see Table 2.1.

Slightly better conversion efficiencies can be achieved by producing electricity from hydrogen. Gas turbines, fuel cells or also reverse fuels cells can be utilized for that purpose. Fuel cells would also enable the utilization of hydrogen in the mobility sector, but fuel cell powered cars are technologically not mature, and an infrastructure for hydrogen distribution and storage does not yet exist in most regions.

Generally, the efficiencies for Power-to-Gas systems are increased when the released heat of the systems is used, for example in district heating or in industrial plants nearby (Table 2.1). The pressure level to which the product gases have to be pressurized, has an important influence on the total achievable efficiency. The pressure level mainly depends on the facilities to be used for transport and storage, and is therefore subject to the specific local conditions of a Power-to-Gas plant.

A ranking of the utilization paths according to Table 2.1 cannot be made only by considering the efficiencies alone. Systemic, economic and macroeconomic aspects have to be additionally taken into account, which is the subject of Chap. 5 of this book.

The conversion efficiencies can be improved by either technical progress in the single conversion steps, namely water electrolysis and methanation (see Chaps. 3 and 4 for details), or by synergies with industrial processes which are coupled with the Power-to-Gas plants. Both options are subject of current research activities, see for example (Karlsruher Institut für Technologie 2014; Schöß et al. 2014; Bergins 2014). Some information on synergy potentials is given in the following chapter.

2.2 Plants Sizes and Synergy Potentials

The plant size of a Power-to-Gas system may vary from a few 100 kW connected duty up to several 100 MW, or even in the GW range for autarkic systems. As a consequence, the set-up of the system has to be adjusted individually to the specific boundary conditions of a distinct application. These conditions influence the decision on the end product, hydrogen and methane,[4] respectively, the utilized carbon dioxide source,[5] the use of the potential byproducts, namely oxygen and released process heat, as well as the way the end product is distributed and stored.[6] However, the main purpose of a Power-to-Gas plant may vary: the utilization of (local) excess energies in renewable power production, power grid stabilization or substitution of transport capacities by the natural gas grid, conversion of renewable power for long-term storage, or even the operation of large scale, completely autarkic systems. Furthermore, the desired utilization of the end product influences the plant size and the mode of operation (i.e. pressure level, annual availability etc.). Therefore, future Power-to-Gas systems will consist of completely different plant set-ups, operation modes and plant sizes. Consequently, the Power-to-Gas technology has to be flexible, easily up-scalable and modular in order to allow an adjustment to the specific conditions. Particularly, the total investment and operation costs of a Power-to-Gas plant are influenced by a number of factors, and therefore, the cost for the end product, hydrogen or methane, is not only subject to the actual price of electricity. Indeed, the annual operation hours influence the product costs significantly more than the electricity costs (Kinger 2012). The total cost structure, as well as the technological setup, is also determined by the possibilities to utilize the byproducts (see also Chap. 5).

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[4] A comprehensive study has been performed recently by DVGW (Müller-Syring et al. 2013b). Four distinct locations for Power-to-Gas plants are examined, and specific Power-to-Gas plant concepts are determined.

[5] Small Power-to-Gas plants (few 100 kW) may use carbon dioxide from biogas plants, and may also utilize biological methanation instead of chemical. For Power-to-Gas plants in the MW scale, industrial carbon dioxide sources are required, and preferably chemical methanation is used.

[6] The way the end product is distributed and stored is mainly a question of the existing infrastructure on site, and the desired utilization of the end product (Müller-Syring et al. 2013b).

In terms of the byproducts of a Power-to-Gas system, the utilization of released reaction heat from the methanation, as well as of oxygen from the electrolysis has to be considered. The methanation reaction is exothermic, and therefore a surplus of heat is generated in the Power-to-Gas process chain. The released heat can be utilized, for example, for the carbon capture process supplying the necessary carbon dioxide for methanation. In case of carbon capture by chemical absorption with amine based solutions, the main energy demand arises from the regeneration of the rich solutions which is done by heating of the scrubbing liquids. An example for the heat integration is given in Chap. 4. It is shown, that the heat surplus of methanation exceeds by far the demand of carbon capture, and therefore can be used additionally for power generation, for example.

The utilization of the byproduct oxygen is coupled to an industrial user, like the chemical or the metallurgical industry. Special power plant concepts, like the oxy-fuel technology, would also need oxygen in significant amounts. Different authors made studies of the implementation of a Power-to-Gas plant in an industrial environment (Schöß et al. 2014; Bergins 2014). It is shown that numerous synergies can be generated. Whereas Bergins (2014) focus on the synergetic coupling with a steel plant, its oxygen demand and the possibility to utilize excess heats, and pronounces the economy of scale for such installations, Schöß et al. (2014) proposes the use of process gases from the steel industry as carbon source. All these concepts are suitable for Power-to-Gas plants on a larger scale (MW). Schöß et al. (2014) simulates an electrolyzer duty of 53.9 MW and a methane production of 4,507 m^3/h.

Figure 2.2 depicts a future vision of a large-scale, autarkic Power-to-Gas system (Frühwirth 2014). An offshore wind park supplies its renewable electricity production
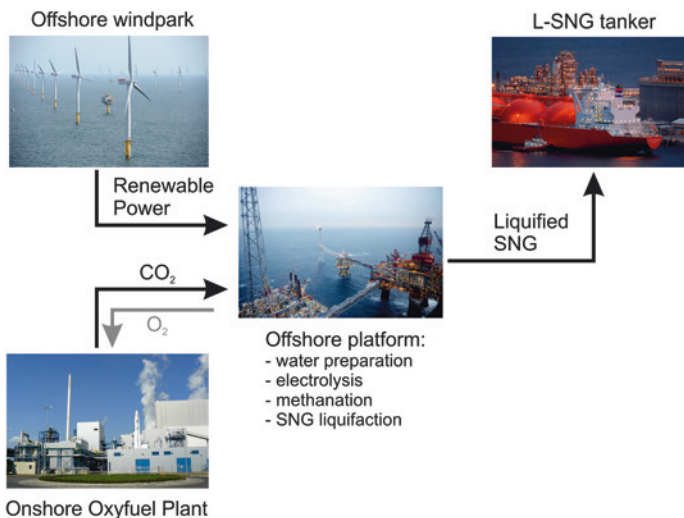

Fig. 2.2 Future vision of an autarkic Power-to-Gas system for the offshore production of liquefied SNG (pictures by courtesy of Statoil, *source* http://fotoweb.statoil.com/fotoweb/Default.fwx)

to an offshore platform nearby. At this platform, an appropriate electrolyzer unit converts the electric power to hydrogen, which is subsequently synthesized to methane. The water for electrolysis is derived from the methanation as well as from evaporated sea water. The necessary evaporation heat is covered by the released reaction heat of methanation. The carbon dioxide is produced in an onshore oxyfuel plant, and pumped through a pipeline to the platform. In return, oxygen from the electrolysis is transferred to the oxyfuel plant. For this reason, the air separation unit at the oxyfuel plant can be saved. Furthermore, the oxyfuel plant can be operated continuously, and it provides the necessary base load in the power grid. Finally, the produced SNG is liquefied to Liquefied Synthetic Natural Gas (L-SNG) at the platform, and is shipped by LNG tankers.

This concept is a kind of "big picture" for the Power-to-Gas technology. It is, of course, far from realization, but it demonstrates future possibilities of a gas "exploration" which is completely on a renewable basis. At the moment a feasibility study of this concept is been worked on (Frühwirth 2014) which should show how mass and energy balances of all parts of such a system fit together. If this concept seems to be feasible, a lot of synergy potential exists.

2.3 Similar Concepts

Power-to-Gas is not the only possibility of converting renewable energy to chemical storage media. Beside the gases hydrogen and methane, other chemical energy carriers, like methanol, formic acid or fuels can be produced. These utilization routes are summarized under the term "Power-to-Liquids", or sometimes also "Power-to-Fuels" (Bilfinger Industrial Technologies 2014). The hydrogen derived from water electrolysis is catalytically converted with CO_2 to methanol, or via Fischer-Tropsch-synthesis to fuels. The basic technological setup is the same as for methanation used in the Power-to-Gas concept. Power-to-Liquids supplies liquid energy carriers which can be easily transported by tankers (road, train, ship), and which are not depending on an appropriate gas grid. As with the products of a Power-to-Gas system, methanol and fuels have an already established utilization, for example in the mobility sector or in the chemical industry. It is discussed that Power-to-Liquid systems are more suitable for larger scale plants whereas Power-to-Gas systems can cover also smaller scales (Leiter et al. 2014). Since Fischer-Tropsch synthesis is not very selective, some additional efforts for the refining of the products result.

Another, very interesting and quite promising concept is introduced under the term "Power-to-Chemistry®". The term is a registered trademark of Evonik Industries (Markowz 2014). Other than in the Power-to-Gas or Power-to-Liquid concept, renewable electricity is not converted to hydrogen in an electrolyzer. An arc furnace is used to convert methane to acetylene and hydrogen according to following fundamental, simplified equation:

$$2CH_4 \rightarrow C_2H_2 + 3H_2 \quad \Delta H_R^0 = +376.8\,\text{kJ/mol} \tag{2.1}$$
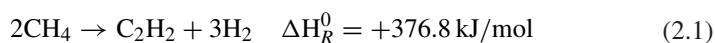
A byproduct of this reaction is ethylene (C_2H_4). A single arc furnace has a power consumption of 10 MWh_{el}, and can be operated highly dynamic with start-up times lower than 1 min. The conversion efficiency is also quite high, 1 MWh_{el} is converted to 0.9 MWh_{th} (Markowz 2013). Load flexibility can be achieved by the parallel connection of a number of arc furnaces. Acetylene was an important intermediate in the chemical industry until the late 1960s, and is nowadays substituted by ethylene and propylene produced in steam crackers. All process routes for the utilization of acetylene are known and still available. Another benefit is the conversion of a C1 hydrocarbon (CH_4) to a C2 hydrocarbon, the "byproduct" hydrogen is also a valuable base chemical. Finally, no carbon dioxide source is required, and thus also the carbon capture costs are saved. But, the concept does not disburden the electricity grid, since the electric power has to be transferred from the renewable source to the chemical site. Additionally, the renewable power is mainly converted to a chemical intermediate, and thus the multiple utilization routes of the Power-to-Gas concept (Fig. 2.1) are not available.

2.4 Integration in the Natural Gas Grid

The products of the chemical conversion in a Power-to-Gas plant, hydrogen and SNG (methane), respectively, have to be preferentially[7] transported by the natural gas grid, and stored in the grid as well as the connected large-scale storage facilities. Therefore, the impacts of the injection of hydrogen or SNG have to be evaluated. Furthermore, the requirements for the injected gas composition and gas volume, as well as any restrictions for the product gas injection have to be considered.

The case of SNG as end product of the Power-to-Gas process chain is less critical than hydrogen, because natural gas consists to a large extent of methane.[8] Therefore, a practically unlimited injection of SNG into the gas grid is possible. Since methanation is an equilibrium reaction, parts of the educt gases, hydrogen and carbon dioxide, are not converted to methane. Furthermore, the product gas mixture emerging from the methanation reactor contains significant amounts of steam, the main byproduct of the methanation reaction. Therefore, a product gas upgrade is necessary in order to meet the requirements for the injection of the produced SNG into the gas grid. Product gas upgrade processes and the specifications for the SNG composition are given in Sect. 4.2 and Table 4.7.

The injection of hydrogen into the natural gas grid raises a number of questions which have been investigated in some recent studies (Müller-Syring et al.

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[7] A gas grid for hydrogen only exists in a few, spatially limited regions. Therefore, hydrogen should be injected to the existing and well established natural gas grid.

[8] Natural gas qualities are categorized in H- and L-gas (see also Table 2.2). H-gas contains >96 vol.% CH_4, L-gas >88 vol.% CH_4 (Müller-Syring et al. 2013b).

Table 2.2 Specification of gas properties according to different regulations [extended from (Müller-Syring et al. 2013b)]

Parameter	Unit	DVGW G 260 (Weißdruck May 2008)	ÖVGW G31	EASEE-gas	DIN 51624
Wobbe index	kWh/m^3		13.3–15.7		
L—gas		10.5–13.0		–	–
H—gas		12.8–15.7		13.6–15.8	–
Heating value	kWh/m^3	8.4–13.1	10.7–12.8	–	–
Relative density	–	0.55–0.75	0.55–0.66	0.555–0.75	0.555–0.7
Methane number	–	DIN 51624	–	–	70
Hydrogen content	vol.%	≤5	≤4	–	2

2012, 2013b; Melaina et al. 2013; Florisson 2010; Müller-Syring and Henel 2014; Haeseldonckx and D'haeseleer 2007). In detail, following problems have to be considered:

- The influence on the gas characteristics, like Wobbe[9]-index and heating value: the basis for this evaluation is the existing regulations for the natural gas grid, and the required properties of the transported gases, see Table 2.2. With increasing amounts of hydrogen, both Wobbe-index and heating values are reduced. The tolerable percentage of hydrogen strongly depends on the properties of the natural gas quality in the grid. An admixture of 5 % up to 15 % of hydrogen is possible (Müller-Syring et al. 2013b).
- The impacts on the gas infrastructure: piping, controls, fittings, valves, gaskets and the metering systems. Both, steel and plastic piping materials are usually capable of handling admixtures of hydrogen up to 30 % and more. Leakage rates will increase, but are still economically and ecologically tolerable (Müller-Syring et al. 2013b; Florisson 2010). Particularly, the metering systems have to be adjusted for hydrogen admixtures.
- The transport capacities: the volumetric heating value of hydrogen is three times lower than that of methane. Therefore, with the same volume flow of hydrogen, three times lower energy transport is achieved. An admixture of 10 vol.% hydrogen results in a 5–6 % decrease of the transport capacity (Müller-Syring et al. 2013b). But the full transport capacities of gas pipelines are exploited only for a few days per year. Nevertheless, for the transportation of the same energy amounts, a higher volume has to be transported which results in higher pressure losses, and consequently in increased compressor powers. Also, the capability of the installed compressors for the transportation of hydrogen/methane mixtures has to be evaluated.

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[9] The Wobbe-index is the ratio of the heating value and the square root of the relative density of the gas. The relative density is the ratio of the gas density to the density of air under standard conditions. The burner power remains constant with same Wobbe-indices despite different heating values (Müller-Syring et al. 2013b).

- The impacts on end user infrastructure: domestic appliances, like heating systems for houses or apartments, can usually operate hydrogen admixtures of up to 20 %, eventually the adaption of the burner nozzles is necessary due to the higher flame velocities (Müller-Syring et al. 2012).

  Gas turbines are more sensitive to hydrogen. Most of the manufacturers limit the hydrogen content to 1 or 2 vol.%, but laboratory tests show the possibility of admixtures up to 14 % (Müller-Syring et al. 2012). Similar considerations are valid for gas motors.

- The impacts in the automotive sector: the methane number (see also Table 2.2) is reduced by the admixture of hydrogen, 10 % hydrogen results in a decrease of 5–7 units. An exceedance of the knocking limit may be the consequence. But, the limitation of the hydrogen content to 2 vol.% of DIN 51624 is much more critical. The background of this limit is the lack of knowledge how the steel storage tanks, both in the cars and the filling stations, can tolerate higher hydrogen contents in a long-term view (Müller-Syring et al. 2013b).

- The impacts on underground gas storage facilities: for the storage of natural gas, salt caverns and depleted gas reservoirs are currently operated. Particularly, for porous subsurface reservoirs some fundamental questions are still open, for example microbiological reactions in the reservoir, de-mixing processes or the general impacts on the geochemical conditions. Those questions are addressed in a research project, currently carried out by a consortium of industry and universities in Austria.[10]

The maximum percentage of hydrogen is also limited by the natural gas flow at the distinct location where it is injected into the grid. Those grid sections with low annual turn-over of gas are less suitable for the introduction of hydrogen (Müller-Syring et al. 2013b).

Currently, it is recommended to limit the concentration of hydrogen in the natural gas grid to 2 vol.% in case natural gas filling stations are connected to the gas grid, and 10 vol.% H_2, in case no natural gas filling station, no gas turbine or gas motor are connected to the natural gas grid (Müller-Syring and Henel 2014).

References

Ausfelder F, Bazzanella A (2008) Verwertung und Speicherung von CO_2. Dechema, Frankfurt/Main

Baehr HD (1996) Thermodynamik, 9th edn. Springer, Berlin, p 134

Bergins C (2014) Energiewende umsetzen mit dem Großanlagenbau. Presentation at ProcessNet-Fachgruppe "Energieverfahrenstechnik", Karlsruhe, Hitachi Power Europe, 18, February 2014

Bilfinger Industrial Technologies (2014) Power-to-liquids. http://www.sunfire.de/wp-content/uploads/BILit_FactSheet_POWER-TO-LIQUIDS_EMS_en.pdf. Accessed 25 May 2014

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[10] http://www.underground-sun-storage.at/en.html. Accessed 22 May 2014.

Deutsche Energieagentur (2013) Strategieplattform Power-to-Gas. Thesenpapier: Technik und Technologieentwicklung. http://www.powertogas.info/fileadmin/user_upload/downloads/Positionen_Thesen/PowertoGas_Thesenpapier_Technik.pdf. Accessed 7 May 2014

Egner S, Krätschmer W, Faulstich M (2012) Perspektiven der Energiewende. In: Lorber K et al. (eds) DepoTech 2012, Tagungsband zur 11. DepoTech Konferenz, Leoben, pp 49–56

Florisson O (2010) Naturally preparing for the hydrogen economy by using the existing natural gas system as catalyst. Final publishable activity report, N.V. Nederlandse Gasunie

Frühwirth V (2014) Feasibility study of a large scale power-to-gas system. Master thesis, Montanuniversität Leoben (in preparation)

Grond L, Schulze P, Holstein S (2013) Systems analyses power to gas: deliverable 1: technology review. DNV KEMA energy & sustainability, Groningen

Haeseldonckx D, D'haeseleer W (2007) The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure. EHEC2005 32(10–11):1381–1386

Karlsruher Institut für Technologie (ed) (2014) Power-to-Gas: Wind und Sonne in Erdgas speichern. http://www.kit.edu/downloads/pi/KIT_PI_2014_044_Power-to-Gas_-_Wind_und_Sonne_in_Erdgas_speichern_.pdf. Accessed 23 May 2014

Kinger G (2012) Green energy conversion and storage (Geco). Endbericht for FFG project 829943, Wien

Leiter W, Schüth F, Wagemann K (2014) Diskussionspapier: Überschussstrom nutzbar machen. Dechema, Frankfurt. http://dechema.wordpress.com/2014/01/31/ueberschussstrom_1/. Accessed 15 May 2014

Markowz G (2013) Power-to-Chemistry® Ein alternatives Konzept zur chemischen Energiespeicherung. Presentation at Dechema Kolloquium „Wind-to-Gas" Frankfurt, Evonik Industries, 7 March 2013

Markowz G (2014) Power-to-Chemistry® Strom speichern im industriellen Maßstab. Presentation at Innovationskongress Berlin, EVONIK Industries, 7 May 2014

Melaina MW, Antonia O, Penev M (2013) Blending hydrogen into natural gas pipeline networks: a review of key issues. National Renewable Energy Laboratory, Golden

Müller-Syring G, Hüttenrauch J, Zöllner S (2012) Erarbeitung von Basisinformationen zur Positionierung des Energieträgers Erdgas im zukünftigen Energiemix in Österreich: AP 2: Evaluierung der existierenden Infrastrukturen auf Grundlage der ermittelten Potentiale. Abschlussbericht, Leipzig

Müller-Syring G et al (2013a) Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz, DVGW Bericht zu Fördezeichen G 1-07-10:119

Müller-Syring G et al (2013b) Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz. Abschlussbericht, DVGW Förderkennzeichen G1-07-10, Bonn

Müller-Syring G, Henel M (2014) Auswirkungen von Wasserstoff im Erdgas in Gasverteilnetzen und bei Endverbrauchern. Gwf Gas-Erdgas:310-312

Schöß MA, Redenius A, Turek T, Güttel R (2014) Chemische Speicherung regenerativer elektrischer Energie durch Methanisierung von Prozessgasen aus der Stahlindustrie. Chem Ing Tech 86(5):734–739

Sterner M (2009) Bioenergy and renewable power methane in integrated 100 % renewable energy systems. Dissertation, Universität Kassel

Sterner M, Jentsch M, Holzhammer U (2011) Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes. Fraunhofer IWES, Kassel, p 18

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