POWER2GAS IN GERMANY – TECHNOLOGY AND OPPORTUNITIES

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Abstract – *For the future, Germany banks on renewable energy. That bears a challenge, because this energy generation heavily depends on climate conditions. Therefore, a proper storage technology is needed to ensure the energy supply all over the year. Furthermore, the expansion of renewable power plants and the power grid expansion advance in different pace. The power grid operators have to react with feed-in management actions to safe the grid against overloading. As a consequence, operators have to switch off some of their windmills if the wind blows to strong. Suitable storage technologies will help to avoid shutting down renewable power plants to generate the full energy potential. A promising technology is Power2Gas. These facilities transform electrical energy into gas, which could be stored in the huge German gas network.*

Keyword: *electrolysis, feed-in management, methane, power-to-gas, storage*

1. Introduction

At least since the German government determined to shut down all nuclear power plants after the nuclear catastrophe in Fukushima in 2011, the expansion of renewable energy sources speeded up. Germany wants to become a pioneer in backing out of nuclear energy generation. In 2022, the last German nuclear power plant will be shut down.

Much earlier the international community of states had realized that the global warming is the result of increasing carbon emissions. To counteract this development they created climate agreements since 1992 such as the Agenda 21, the Kyoto Protocol or the Paris Agreement. [1] Subsequently the expansion of carbon neutral energy sources is one keystone for reducing carbon emissions and to adjust the global warming.

2. Renewable energy in Germany

In order to reduce the carbon emission and to ensure the energy supply without nuclear power plants, the German government is promoting the renewable energy sources. Despite a small expansion in the 1990's, wind power, photovoltaics and biomass are covering one third of the German gross electricity consumption nowadays. [2] Nearly half of the renewable energy bases on wind energy. [3] Especially the coastal areas are qualified for this technology because of suitable wind conditions all over the year. Therefore many on- and offshore wind farms were and will be built in northern Germany. [4] Continuous increasing of electricity generation is the result (Figure 4 *landfill, sewage and mine gas).

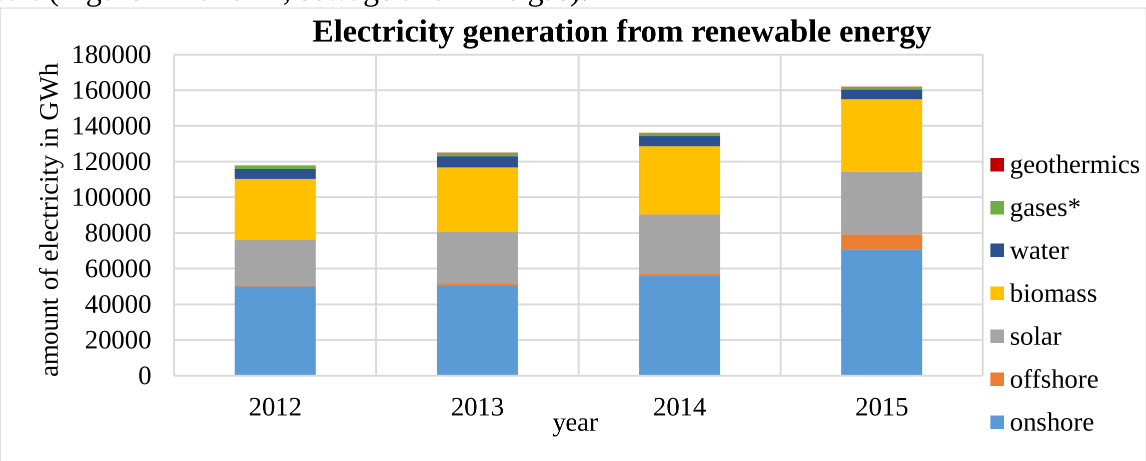

Figure 4 **Electricity generation from renewable energy from 2012 – 2015 [3, 5–7]**

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2.1. German electricity network – current problems

At first appearance the development of renewable energy generation looks good, but there is one big problem. The German electricity grid is not able to transport unlimited electrical power from the north to the south, because the grid expansion is not as fast as it should be. Therefore the grid operators have to draw on feed-in management. That means cutting down the electricity generation. [8]

Table 7

Feed-in management between 2012 and 2016 in GWh [9]

Year	1st quarter	2nd quarter	3rd quarter	4th quarter	Total
2012	-	-	-	-	385
2013	-	-	-	-	555
2014	-	-	-	-	1581
2015	1135	737	815	2036	4722
2016	1511	534	551	-*	-*

- not published, -* still not published

In the last three to four years the amount of unused renewable energy increased by shutting down the electricity generating plants (Table 7). In 2012 about 400 gigawatt hours were not fed in. Two years later this value nearly reached 1600 gigawatt hours and in the following year it was tripled. The main reasons for shutting down are to protect the power grid against overload and because affordable long-term storage technologies for excess electric energy are missing.

For all these feed-in management actions the grid operators have to pay monetary compensations to the owners of the affected power plants. In 2012 the grid operators payed 33.10 million euros. For the following twelve months 43.74 million euros have been incurred and one year later the compensations increased to 82.69 million euros. For the year 2015 there was a strong increase up to 314.84 million euros. [3]

Table 8

Distribution of lost renewable energy generation according to energy sources between 2012 and 2015 in GWh [3, 5–7]

Year Energy source	2012	2013	2014	2015
Wind energy	358.5	480.3	1221.5	4124.9
Solar energy	16.0	65.5	245.2	227.6
Biomass	9.4	8.8	112.1	364.4
Others*	1.1	0.4	2.2	5.1
Total	385.0	555.0	1581.0	4722.0

*gases, water, geothermics and cogeneration

The values for the year 2016 will be published at the end of the year 2017.

Table 8 shows the distribution of lost renewable energy generation according to energy sources. Worst affected from shutting down is the wind energy. Especially the electrical power generated by wind turbines in Schleswig-Holstein exceeds the capacity of the German power grid. In this state alone, about 3079 gigawatt hours were not generated in 2015, which represented 65% of the total value. By far, Brandenburg, Lower Saxony and Mecklenburg-Western Pomerania are following with 689 gigawatt hours, 429 gigawatt hours and 265 gigawatt hours. [3] The power loss from solar energy and biomass is much lower, because these power plants are distributed evenly all over Germany. Therefore the power grid load caused by them is not as focused as it is by wind energy.

Altogether the development of proper storages for renewable energy is a critical factor to promote the energy revolution successfully. In different projects around the world electric power devices are tested in pilot experiments. Currently, they are often used for short term storage. Excess electrical power that is generated by day can be stored for the night. Tesla, around its founder Elon Musk, installed a solar park with 272 Tesla-Powerpacks on the Hawaiian island Kauai. Thereby the inhabitants do not use diesel generators anymore. [10]

Another pilot project is planned in Varel, Germany, in close vicinity to the Jade Hochschule of Wilhelmshaven by the Japanese consortium Nedo. The battery storage device will need the area of a football pitch and should store plus distribute the renewable energy that is generated in this region. [11]

3. Alternative storage opportunity– gas network in Germany

One promising alternative to electrical power devices is a technology, which converts electrical power into gas. This technology is known as power-to-gas and allows the use of the gas network and gas stores for long-term energy storage. After a look on the German gas grid, the technical and chemical explanation of power-to-gas plants follows in chapter 4.

The volume of work of the German gas grid is about 27.6 million standard cubic metres, which corresponds around one quarter of the European capacity. [3, 12] This quantity represents 30% of the annual German gas consumption. [3, 13] Behind USA, Russia and Ukraine, Germany is the worldwide number 4 in terms of gas storage capacity. [14] This fact shows, how big the German potential is, to store renewable energy in form of gas. 51 underground gas stores allow this high number of storage capacity. In Germany almost exclusively pore and cavern storages are used. [15] With the conversation of electrical power into gas, Germany has the possibility to use renewable energy also for non-electrical processes.

In the last year, German companies and research institutes built power-to-gas plants for testing purposes all over the country. One pilot project is the Audi e-gas project in Werlte, Lower Saxony, about 120 km south west of Wilhelmshaven, which is operated by the automobile manufacturer Audi AG. This plant serves to generate hydrogen for further testing and supply of vehicles with fuel cell drive. In another step it is also possible to convert the hydrogen into methane. This gas can be fed into the normal gas grid and makes the long term storage of renewable energy possible. After some months of research the plant is integrated in the German gas network, since autumn 2013. [16]

In the year 2015, the electrical supplier RWE Deutschland AG activated another demonstration plant in Ibbenbüren, North Rhine-Westphalia. The main research objectives are investigations about the operation flexibility and analysis of the storage process. This plant generates hydrogen, which is fed into the RWE-gas network. [17]

4. Power2Gas – Technological fundamentals

In general, Power2Gas uses electric energy, primarily the excess of renewable energy sources arising because of fluctuation, to generate hydrogen or synthetic methane. Even if the gravimetric energy density of pure hydrogen is the highest, the focus of this paper is the production of methane. The reasons are the higher volumetric energy density of methane and many aspects regarding the easier handling in comparison to pure hydrogen. [18]

4.1. Chemical action principle

Electrolysis, the decomposition of an ion conductor with the help of electricity, forms the technological basis of Power2Gas. Thereby, water is separated into its components oxygen and hydrogen. Figure 5 shows the general principle of water electrolysis. [19]

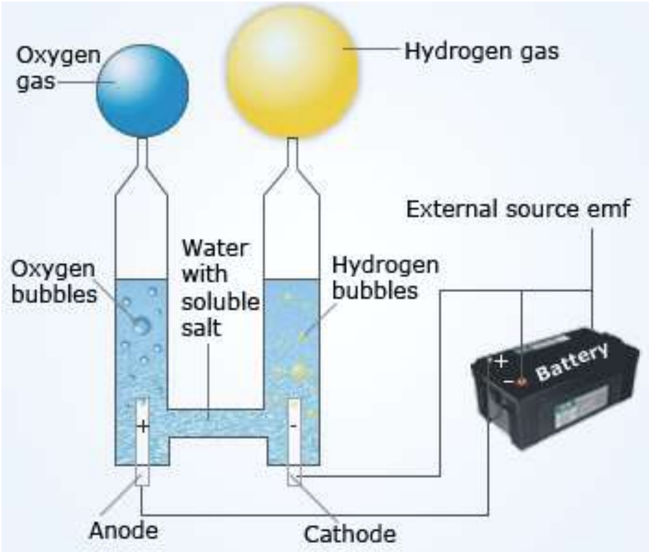

Figure 5 **Schematic of electrolysis principle [20]**

Two electrodes bathed in an ion conductor are connected to an external power supply. Since pure water is an isolator, acids, alkali or soluble salts are often used to raise the electrical conductivity. The voltage at the electrodes leads to a lack of electrons at the anode and a spillover of electrons at the cathode. OH^--anions (in alkaline aqueous solutions) or H_2O-molecules (in acid aqueous solutions) move to the anode where they release an electron, meaning they are oxidated. As a result, oxygen rises in its gaseous state. In contrast, positive hydrogen-ions (in acid solution) and H_2O-molecules (in alkaline solutions) wander to the cathode. Hence, each of those cations absorbs an electron, is reduced to hydrogen. Finally, hydrogen gas rises at the cathode and can be absorbed. [19]

The following redox reactions express these processes:

Table 9

Terms of redox reactions for water electrolysis [19]

type of aqueous solution	reduction at cathode	oxidation at anode
acid	$4\,H^+ + 4\,e^- \Leftrightarrow 2\,H_2$	$2\,H_2O \Leftrightarrow O_2 + 4\,H^+ + 4\,e^-$
alkaline	$4\,H_2O + 4\,e^- \Leftrightarrow 2\,H_2 + 4\,OH^-$	$4\,OH^- \Leftrightarrow O_2 + 4\,e^- + 2\,H_2O$

In sum, hydrogen gas occurs at the cathode and oxygen gas at the anode, independent of the type of solution. The reaction can be summarized to:

$$2\,H_2O \xrightarrow{el.energy} 2\,H_2 + O_2 \text{ [18]}$$

Subsequently, the generated hydrogen can either be stored, transported or used directly for example as fuel in vehicles. But in Germany the preferred way is the subsequent methanation. In this case, a chemical synthesis transforms hydrogen and added carbon dioxide into methane (CH_4). [21]

The the redox reaction of the methanation process shows, that there are no other byproducts despite water, what is an advantage relating to environmental aspects:

$$4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O \text{ [19]}$$

This synthetic methane can then be led into the existing infrastructure for natural gas without any limits. [19] If the system uses already existing carbon dioxide and does not release it from fossil sources only for this purpose, the generated methane is CO_2-neutral. Examplary sources are biogas, waste products from sewage or composting plants as well as the carbon dioxide existing in the atmosphere. Stripping CO_2 from the air is relatively expensive compared to other methods but would reduce its concentration in the atmosphere. [18]

4.2. Implementation

The implementation of complete systems for power-to-gas plants requires the combination of various components. These are:

- power supply
  - best case: near renewable energy sources
- transformers and rectifiers
  - because electrolysis presumes a d.c. supply at low voltage levels
- **electrolyzer** including electrolyte supply
- supporting components
  - e. g. cooling systems, electrolyte reconditioning, inert gas supplies
- downstream components
  - e.g. compressors, gas cleaners, a **methanation** complex, storages

Sometimes also reconversion attachments are added to generate electrical power from the gas again. But such constructions lower the degree of efficiency distinctly and do not redound to a long-term storage of energy for which reason this paper neglects those. [18, 22]

Two of those components are most important: electrolyzer and methanation complex. For realizing electrolysis in big scales there are three main methods available. These are alkaline electrolysis (AEL), membrane electrolysis (proton exchange membrane, PEMEL) and high temperature electrolysis of steam (HTES, also called solid oxide electrolysis SOEL). They differ in the way of construction, operating behavior under pressure and under dynamic conditions based on fluctuating power supply, temperature and used electrolyte. They have in common that one electrolyzer consists of many electrolytic cells built up in stacks to generate appropriate amounts of gas. [18]

Theoretically methanation can be implemented in two basic manners, catalytic and biological, though biological procedures are only used in laboratories yet. Catalytic procedures need to be developed, too, especially in relation to their flexibility. At the moment it is difficult to work with unsteady gas streams (H_2). But particularly this characteristic is important if the power-to-gas technology shall be used to compensate fluctuating electricity generation. That is why buffer storages for hydrogen are needed at the moment. Anyway, they can be used in sufficient dimensions to make methanation possible. [22]

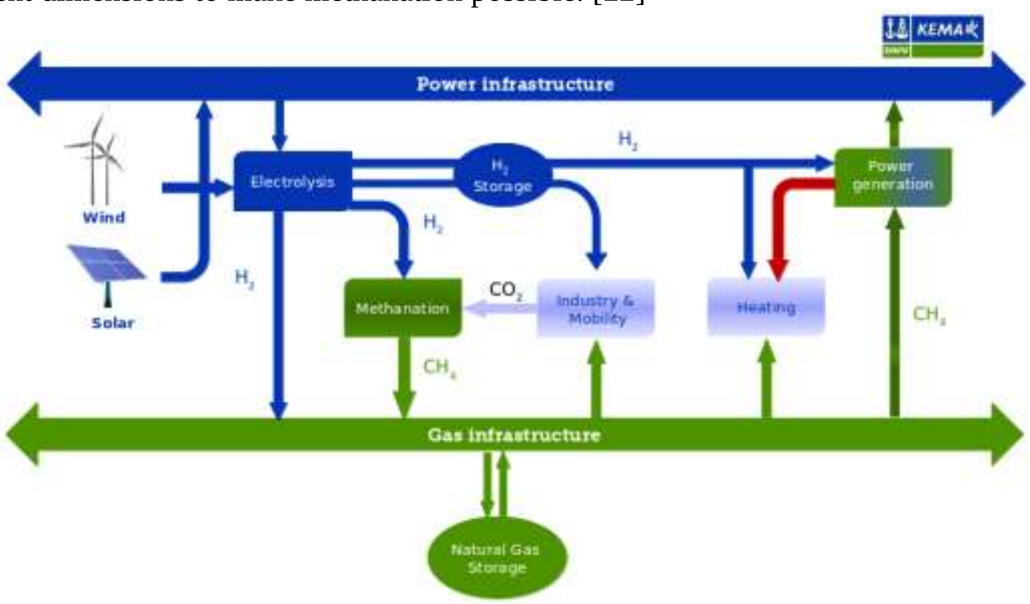

Figure 6 **Integration of P2G into power and gas infrastructure [23]**

Figure 6 shows a possible integration of complete systems into the existing infrastructure. Produced hydrogen can either be stored, used directly for heating, power generation, in industry and mobility or it can be transformed to methane and then be led into the natural gas infrastructure.

4.3. Technical and economic efficiency

The technical efficiency of the power-to-gas technology depends on many different aspects. Important are for example the sort of electrolyzer, used carbon dioxide sources for methanation, the methanation process itself and whether process heat is used or wasted. [22]

Table 10

Degrees of efficiency

system	degree of efficiency
Power-to-Gas without use of process heat	46 - 53 % [22]
Power-to-Gas with further use of process heat	49 - 79 % [18]

Table 10 assume full use to capacity. So, under realistic conditions efficiency would be a bit smaller. But it still makes clear that a reasonable use of process heat should be considered while planning power-to-gas plants, for example creating a block-type thermal power station or to use the heat for generating steam if HTES electrolyzers are used. [18]

At the moment, a profitable operation is not possible because specific investment costs vary between 2500 and 5000 €/kW and production costs strongly depend on the electricity rate. Compared to prices for natural gas from conventional sources or biogas plants, synthetic methane from power-to-gas plants is too expensive. [18]

But prospectively, power-to-gas can portray an interesting economic opportunity considering German laws and targets regarding a full energy supply through renewables. Especially if the technology can be developed in a way that major plants with higher outcomes can be built and excessive energy from renewables can be used, economic operation is more likely to occur. [18]

5. Conclusion

Summing up, power-to-gas may not be a profitable technology from the economic or financial point of view right now. For a competitive usage degrees of efficiency are too low, investment and operating costs are too high and the systems are not flexible enough to adopt to fluctuating energy supply.

But considering objectives of the German government, for instance to achieve an energy supply that is completely based on renewables, power-to-gas offers opportunities to reach these goals by using the existing gas infrastructure and make long-term energy storages possible. Moreover, further development will lead to a decrease of costs on the one hand and to an increase of efficiency on the other hand. So, economic solutions can probably be realized in the future.

Concluding these aspects, the idea of power-to-gas is a good approach, especially if current problems can be reduced to a minimum, which should be pursued.

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