Hydrogen Storage Technology: Application to RES

Fabian Moisl
Jiří Smetana

Co-operating Universities

Financial support by

Prague and Vienna, 2013

Abstract

This paper deals with the possibility to transform energy generated by renewable energy sources into hydrogen using electrolysis. The main research question is whether it is possible to do it efficiently under current state of technology. In the first part, the process of electrolysis is described, which can be used to perform the transformation. Consequently, the storage and uses of hydrogen are explained with a special focus on reverse engineering the transformation process to generate energy at the time of low energy supply. The process of synthesizing methane which can be buffered to public gas grid is also described. The second part shows how electrolysis can be used in reality using two case studies of hybrid power-to-gas power plants in Germany. To conclude, the paper discusses if this technology can contribute to the solution of the problems caused by replacing a high number of nuclear power plants with renewable energy sources in Germany. It finds out that the process of electrolysis has a great potential for the future but requires further research to decrease the costs which make it rather uncompetitive at the moment.

Content

1 INTRODUCTION

Over the years, humans have developed a number of devices that facilitate our everyday life: from cell phones over microwaves to washing machine. All these inventions have one common denominator: the need for energy. Energy can be stored and transmitted in many forms but the most frequent energy carrier for household appliances and devices of everyday use is electricity, as it offers the highest versatility of providing different energy forms (Grubler 2012). As the society is still evolving, the consumption of electricity is increasing and nothing seems to reverse this trend. For this reason, the electricity production must be continuously expanded and several indicators show that the importance of renewable energy sources will increase.

Since 27 member countries of the European Union have committed themselves to substitute 20% of fossil fuels by renewable energy sources (RES) by 2020, a substantial increase of their usage is expected (Krozer 2013). Another contributive factor is current negative attitude towards nuclear power, especially after the earthquake and consequent malfunctions in the power plant of Fukushima (Wittneben 2012). Moreover, the United States have decided to produce 80% of electricity from clean energy sources by 2035 and the role of renewable energy sources is expected to be crucial (Lean & Smith 2013).

Although RES are often preferred by ecologically oriented scientists, they have a number of downsides. Talking about wind and solar power plants, among these disadvantages rank for example land requirements, wildlife endangerment or hazardous materials used for their production which may have a negative impact on environment if not recycled properly.[1] However, the most important disadvantage of solar and wind power plants for this paper is their dependence on forces beyond human control. This results from their very nature: if wind does not blow, wind power plant cannot produce energy, and similarly, solar plants may not work without sufficient solar radiation. And conversely, abundant wind or solar radiation causes generation of excessive energy. Both these cases (insufficient as well as excessive energy production) may lead to grid instability and in the worst case black out if not correctly managed. Ideally, electricity generated during peak periods should be stored and used later when the electricity production declines. To achieve this, an effective way to store and later restore energy must be found.

This paper deals with one possibility of using the excessive amount of electricity generated by RES during peak periods: generation of hydrogen by electrolysis of water. Hydrogen can be stored and later used either to increase electricity supply when needed or it can find other uses in the industry. The main research question of this paper is whether excessive energy generated by renewable energy sources can be effectively transformed into hydrogen by the means of electrolysis under current state of technology. It will explain the process of hydrogen generation by the means of electrolysis and describe how hydrogen can be used to support the energy supply. The second part of this

[1] For more information see http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-of.html

work will examine the hybrid power plant Prenzlau that is already in use and the project to build the hybrid power plant RH2 WKA. The technology they use will be described and evaluated in two separate case studies.

2 CONVERSION PROCESS

Before explaining the conversion process itself, it is necessary to determine what kind of RES are suitable for hydrogen generation. As stated in the introduction, solar and wind power plants have the highest volatility of energy production, and therefore should be considered. Other RES are relatively controllable, as they are less dependent on natural forces. Their variations are less volatile or their importance in the energy mix is so low that they could not damage the grid. For this reason, out of all RES only solar and wind energy seem to be suitable as sources of energy for electrolysis. Currently, the use of wind power plants is much more wide-spread for generating hydrogen, and so this paper will concentrate on them. Nevertheless, the hydrogen production and storage process would be similar for photovoltaic plants.

2.1 Production of Hydrogen

There are many ways how hydrogen can be produced. However, as we can see in Figure 1, electrolysis is the only possibility how hydrogen can be obtained using the energy generated by wind power plants.

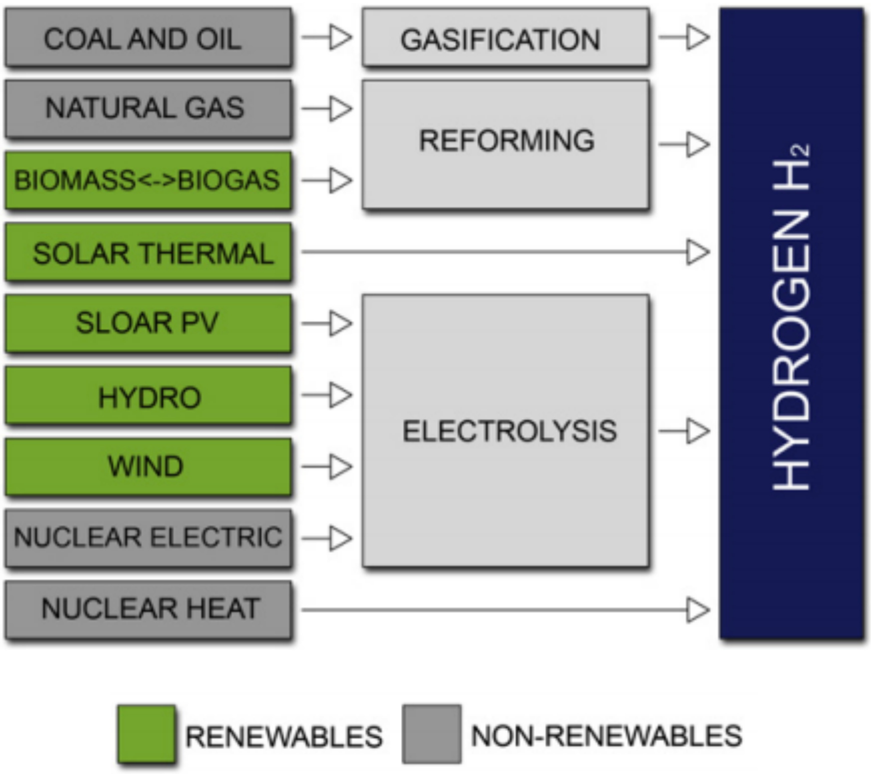

Figure 1, source: Miroslaw Stygar, Tomasz Brylewski: "Towards a hydrogen economy in Poland", in *International Journal of Hydrogen Energy 38* (2013), 7

At the moment, only about 4% of total hydrogen production is produced by the electrolysis of water. The greatest setback of this solution is that it consumes a lot of energy, which makes it less profitable than the hydrogen production from fossil fuels (Bičáková & Straka 2012). On the other hand, if excessive energy from renewable energy sources could be used, high consumption of energy would not be an insuperable problem.

Currently, the power-to-gas technology is emphasized and several pilot power plants are already in use. The scheme of a power-to-gas plant is illustrated in the following picture:

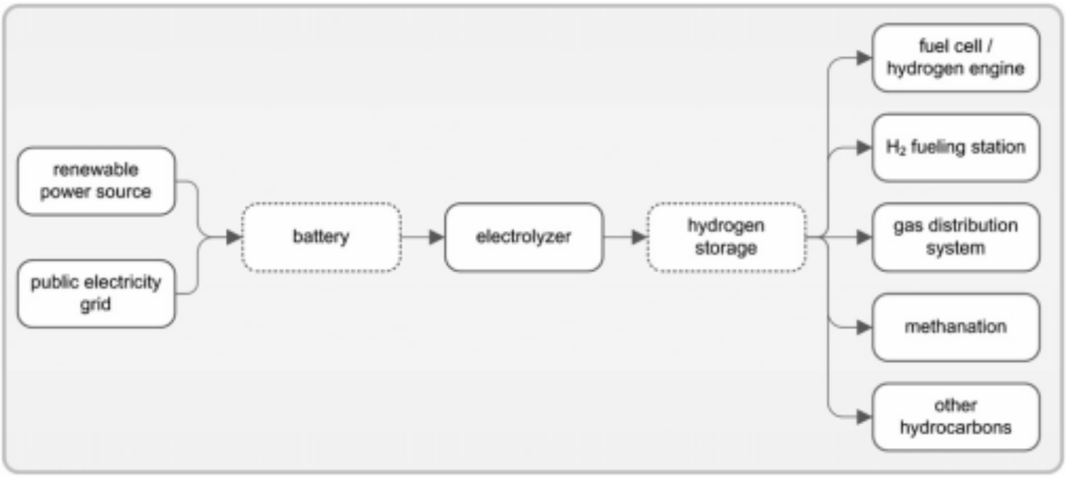

Figure 2, source: Gerda Gahleitner: "Hydrogen from renewable electricity" in *International Journal of Hydrogen Energy 38 (2013*), 2040

As shown above, this technology can be either powered directly by renewable energy sources (be a part of the solar or wind power plant) or take electricity from the grid. For the future, grid-connected and hybrid networks are preferred, since they can be used to effectively balance power fluctuation in the whole system (Gahleitner 2013).

Only about 50% of all currently running power-to-gas plants and only 2 out of 10 connected directly to the grid use a battery. It serves as a short-term energy storage and can be also used to manage power peaks. Capacity of the battery depends on the installed system size. Currently, the prevailing type is the lead-acid battery (Gahleitner 2013).

Three types of electrolyzers can be used. They are together with their specifications summarized in the following table:

	Alkaline electrolyzer	PEM electrolyzer	Solid oxide electrolyzer
Electrolyte	Potassium hydroxide 20–30%	PEM polymer (*Nafion*)	Yttria-stabilized zirconia
Operating temperature	340–420 K	320–360 K	870–1270 K
Charge carrier	OH^-	H^+	O^{2+}
Efficiency	80%	94.4%	90%
Cost	Lowest	Highest	Median

Table 1, source: Meng Ni et al.: "Potential of renewable hydrogen production for energy supply in Hong Kong" in International Journal of Hydrogen Energy 31 (2006), 1403

It is obvious that proton exchange membrane (PEM) electrolyzer is the most effective and at the same time the most costly one. As the prices are declining, the potential of this type is increasing. Alkalin electrolyzer has also a certain potential being the cheapest possibility (Ni 2006).

Most widespread hydrogen storage technology are pressure tanks and only a minority of currently running power-to-gas plants use metal hydride tanks. As for the future, pressure tanks are more likely to be preferred being a cheaper and more available technology with higher capacities (Gahleitner 2013).

2.2 Economic aspects of water electrolysis

According to the *IEA,* the commercial cost target for hydrogen production is 0.30 USD/kg H_2, corresponding to an energy price for gasoline of 2.5 USD/GJ in a competitive market. However, water electrolysis has at least 2-3 times higher production costs at the moment.

Figure 3 shows the present and future potential costs of electrolytic hydrogen. As one can easily see, the major share of total costs per kg hydrogen is the expense for electricity. If excess electrical energy with low actual values was utilized for electrolysis, the costs per kg could be decreased substantially.

Furthermore, the total energy that is needed for water electrolysis is increasing slightly with temperature, while the required electrical energy decreases. Hence a high-temperature electrolysis process might be preferable when high-temperature heat is available as waste heat from other processes (Riis & Hagen 2006).

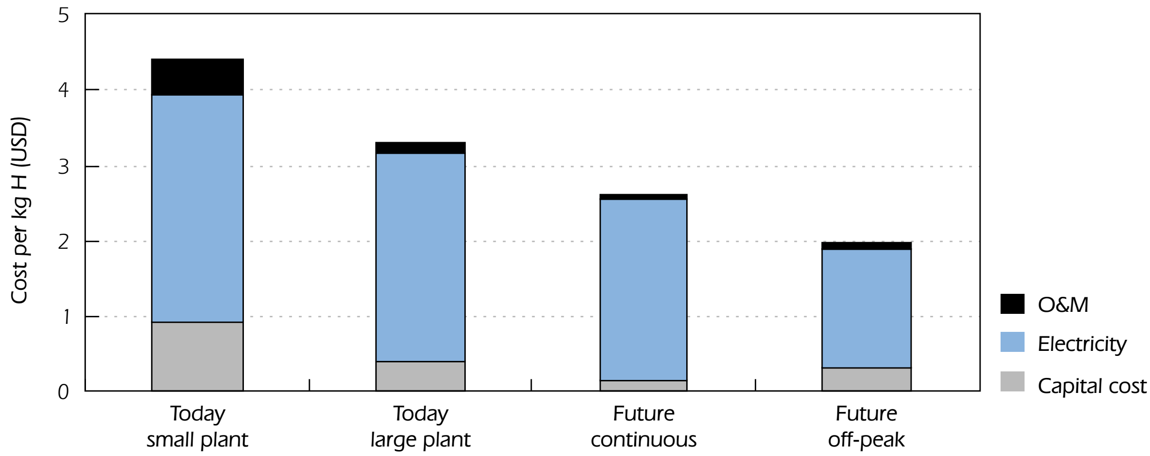

Figure 3, source: Riis T. & Hagen E. 2006, 'Hydrogen production R&D: Priorities and Gaps', Hydrogen Production and Sotrage, IEA Publications

2.3 Application of Hydrogen

Once hydrogen is produced in a power-to-gas plant, it can be utilized in the energy supply system in various ways as demonstrated in Figure 4.

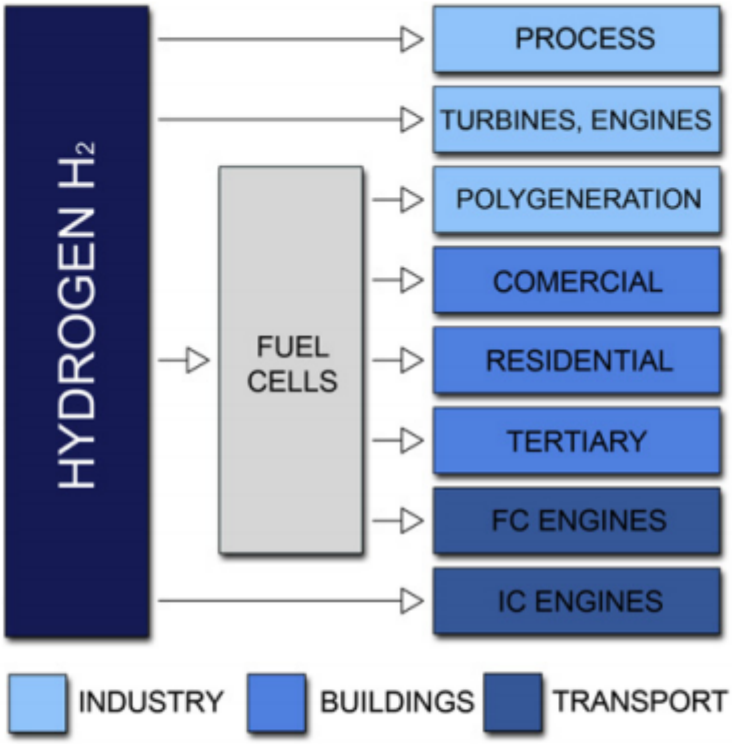

Figure 4, source: Miroslaw Stygar, Tomasz Brylewski: "Towards a hydrogen economy in Poland", in International Journal of Hydrogen Energy 38 (2013), 7

One possibility is to apply fuel cells or gas turbines in order to generate electricity. Hydrogen can also be buffered in the gas distribution system either directly or as synthesized methane. Nowadays, the use of hydrogen as a fuel for vehicles is being discussed as seen as a great potential for the future.

2.3.1 Generation of electrical energy out of hydrogen

Most of the power-to-gas plants nowadays are using fuel cells to transform hydrogen back into electricity. The most important types of fuel cells are alkaline (AFC), phosphoric acid (PAFC) and proton exchange membrane (PEMFC).

Alkaline fuel cells (AFCs) utilize an alkaline electrolyte in a water based solution, operate at temperatures between 60 and 90°C, have an electrical efficiency of 60%, and are available up to 20 kW. They have simple structures and utilize low-cost catalysts, but as they can be easily contaminated by carbon dioxide, purified air or pure oxygen has to be applied.

Phosphoric acid fuel cells (PAFCs) have a liquid phosphoric acid electrolyte, operate between 150 and 220°C, achieve electrical efficiencies ranging between 40 and 50%, and are commercially available up to 200 kW. They can be operated with air and have the advantage of long-term stability, but their initial costs are high, since a platinum (Pt) catalyst has to be used.

Proton exchange membrane fuel cells (PEMFCs) operate at low temperatures between 60 and 100°C, achieve electrical efficiencies of between 40 and 50% and are available up to

250 kW. The systems are compact, their start-up process is rapid and the sealing is easier due to the solid electrolyte. PEMFC have a longer lifetime and are cheaper to manufacture than other technologies.[11]

Figure 5 gives a survey about the number and capacity of fuel cells used in various power-to-gas plants and the year of commissioning. Almost all pilot plants use PEMFCs. It is fair to say that his technology is the only one relevant at the moment.

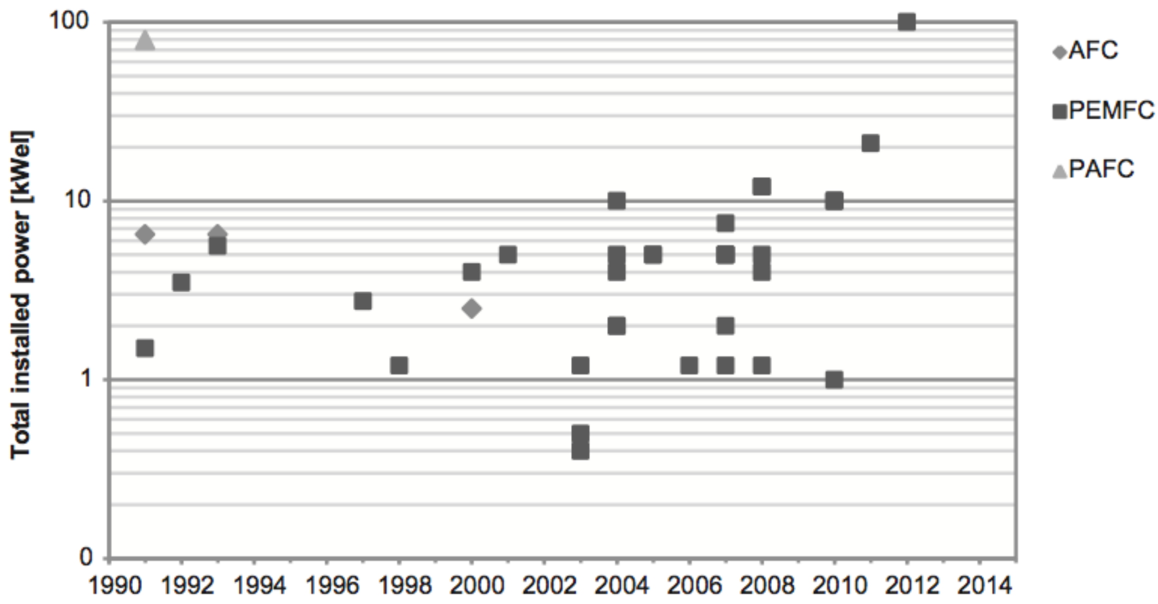

Figure 5, source: Gerda Gahleitner: "Hydrogen from renewable electricity" in International Journal of Hydrogen Energy 38 (2013), page 2053

2.3.2 Buffering hydrogen in the public gas distribution system

Great expectations are put on the possibility to store hydrogen in the natural gas grid. An already existing infrastructure and large capacities are the obvious advantages of this idea. The key question is how high the amount of hydrogen can be without causing damage or other problems in the pipelines and other distribution facilities. While some pilot plants are dealing with pure hydrogen others apply further treatment to convert hydrogen into methane, which can be fed into the gas grid without any problems.

To synthesize methane out of hydrogen the so-called Sabatier-process with the chemical equation as follows, is used.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Figure 6 shows a possible Sabatier-process. „The flue gas (coming from the combustion of methane in a gas turbine) will have to be cooled by a heat exchanger to reach the optimum reaction temperature. The water formed during the combustion of methane and the Sabatier reaction will be removed from the stream coming from the methanation reactor.

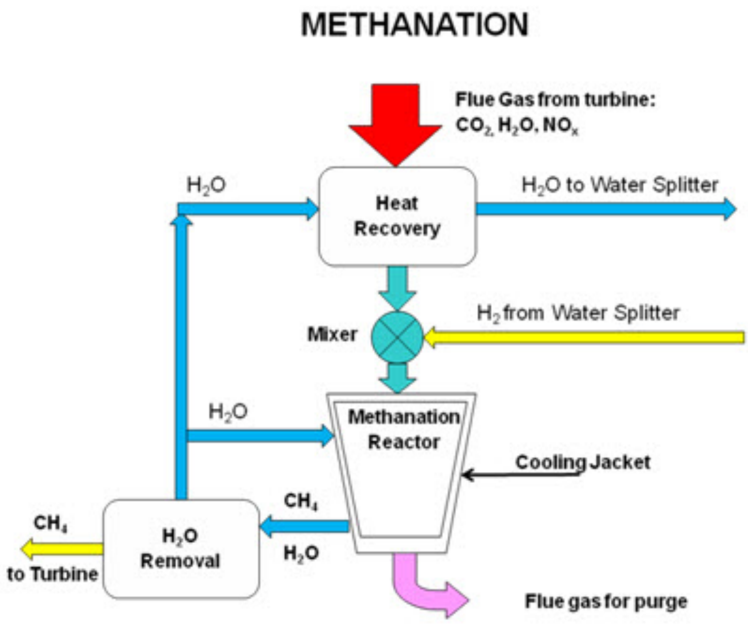

Figure 6, source: Ralston, John 2010, 'The Sabatier Reaction, Possible Solution to CO2 Emissions', pennenergy.com

This water will be used to cool the flue gas and the methanation reactor. After recovering this heat the water will be sent to the water splitter. Hydrogen generated in the water splitting reaction will be mixed with the flue gas from the turbine before it enters the methanation reactor. The methane generated will be mixed with the make-up natural gas needed to operate the gas turbine at the desired capacity. It will not be necessary to isolate and compress the CO_2. The reaction between the CO_2 and hydrogen will take place in the gaseous phase. The amount of methane produced will depend on the amount of hydrogen produced by the splitting of water. The most efficient catalyst for this reaction and the optimum temperature range for this reaction have already been determined. A 98% conversion of CO_2 to methane has been achieved at a Space Velocity of more than 15,000h^{-1} and at a temperature of around 350ºC." (Müller-Syring 2011)

While CO methanation is being applied in with an efficiency between 75% and 85% at operating temperatures between 250°C and 500°C. The efficiencies of a CO2 methanation process is similar to those with CO, but only tested on a laboratory scale.

3 CASE STUDIES

In this chapter, two power hybrid power-to-gas power plants situated in Mecklenburg-Vorpommern are described. Firstly, the power plant in Prenzlau is described that combines the hydrogen generation using wind energy with electricity generation from biogas. The second project under study is the RH2 WKA which is planned to be one of the biggest onshore wind farms in Germany. We can see the location of both plants in Figure 7.

Figure 7, source:maps.google.com

3.1 Hybrid power plant Prenzlau

This chapter discusses the hybrid power plant built in a German city called Prenzlau, located about 100 km north of Berlin. The project aimed at building a hybrid power plant in this location started already in 2005, however, it took three more years to begin with the construction (Enertrag.com 2013). The principal idea was to build a wind power plant that would use electrolysis to create hydrogen using water and excessive energy generated at peak periods. Secondly, the plant was planned to use the stored hydrogen and biogas to generate power and heat (Patel 2012).

The plant was put into operation in late 2011 after a ceremonial opening by the Prime Minister of the State of Brandenburg, Matthias Platzeck. The power plant was financed by both public and private investors. Public sponsors, the State of Brandenburg and the Federal ministry of Transport, participated because the project was understood as a milestone in energy and hydrogen production. Private sponsors include current operator ENERTRAG, oil and gas company TOTAL, electricity supplier Vattenfall and DB Energie. All of these companies are currently interested in developing new technologies to either produce hydrogen or reduce the CO2 emissions (Fuelcellsworks.com 2011).

The plans described in the first paragraph of this chapter were met. At peak periods, an electrolyzer can transform the excessive energy into hydrogen, while in low periods the output of the power plant can be supported by the power plant produced biogas. Thus, the fluctuations of wind is not likely to endanger the stability of the energy output (Greennewdeal.eu 2011). The output of the power plant is six Megawatt.

The whole process how this hybrid power plant operates can be best described using the following illustration:

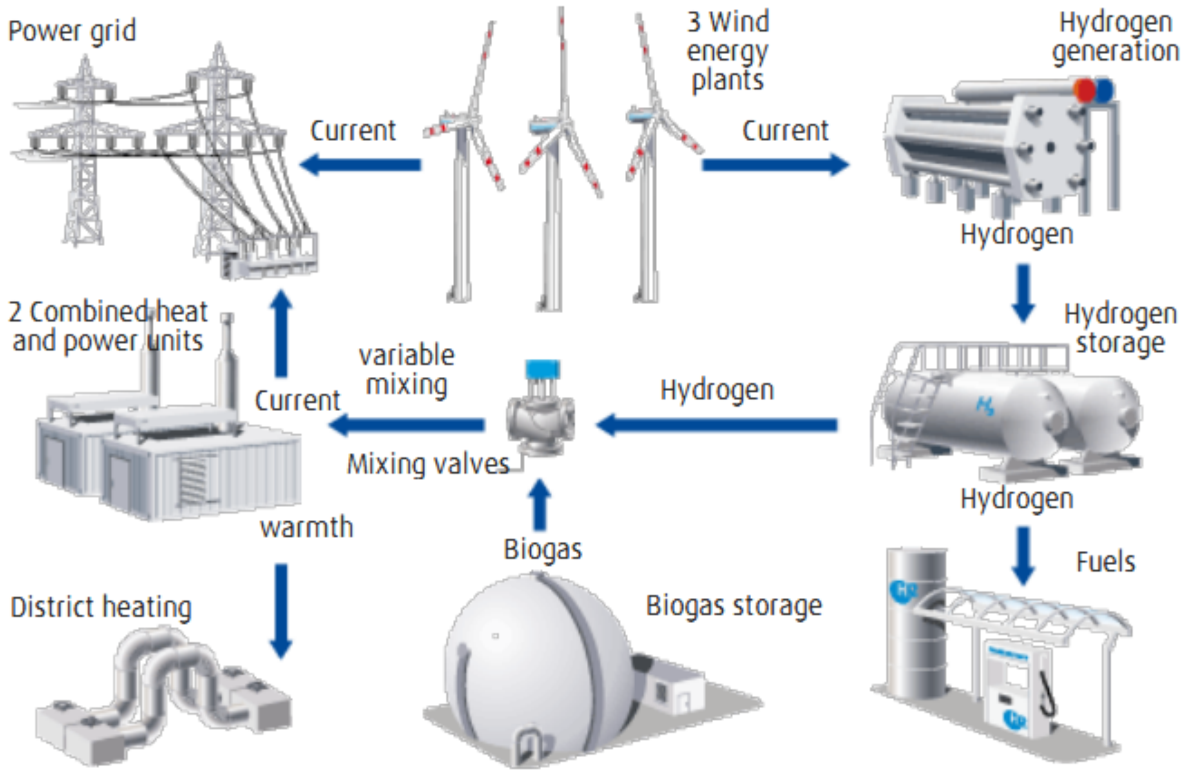

Figure 8, Source: https://www.enertrag.com/en/project-development/hybrid-power-plant.html

As apparent from the illustration, the power plant has three inputs, wind, biogas and hydrogen. The description of the whole process follows.

The power plant is equipped with three windmills that can be used to generate electricity. The whole output of electricity or its part is then transferred to the power grid. The remaining part is used to split the molecules of water creating oxygen and hydrogen. The latter is subsequently stored in hydrogen storage tanks.

The hydrogen stored in tanks can be then used either as another input for the power plant or as fuel. For example, 50 fuel cell electric vehicles are currently in operation across Berlin using hydrogen from Prenzlau (Fuel Cells Bulletin 2012). Having hydrogen as fuel means zero CO2 emissions because the waste product is only water. In comparison with significantly more spread electric cars, hydrogen cars can be refueled within a few minutes. The second possibility how stored hydrogen can be used, is to mix it with biogas and pump it into combined heat and power units where it gets burnt, which generates energy. This energy is then used to produce electric current and warmth. Afterwards, electricity enters the power grid and can be transported to all sorts of users. The second product, warmth, is distributed to district heating, and consequently to consumers.

Although the technology itself works and seems to have great potential for the future, the total investment of 21 million euro makes the hybrid power plant in Prenzlau rather uncompetitive in comparison with conventional gas or coal power plants. It is estimated that the hybrid power plant can generate 1 MW for 3,5 million euro, while a gas power plant or a coal power plant generates the same amount of electricity for only 1 – 1,5 million euro. This means that further technological development would be needed to reduce the costs and to make the technology more competitive (Patel 2012). On the other hand, considering almost zero impacts on the environment and the possibility to create hydrogen and energy without plundering the environment, further investments are more than justified.

3.2 Hybrid power plant RH2 WKA

The „RH_2 WKA" or "WIND-project" is one of the biggest onshore wind farms in process of construction in Germany. It is located northward to Neubrandenburg in Mecklenburg-Vorpommern. RH_2 means regenerative hydrogen and "WKA" are the initials of the surrounding communities Werder, Kessin and Altentreptow.

On the site 28wind energy plants are being built, half of them are of the type Enercon E-126 / NH135 7,5 MW, the most powerful wind energy plants in the world. The finished wind farm will have a total performance of about 140 MW with two connections to the 110 kV al well as the 380 kW electricity grid. Under normal conditions the "WIND-project" is going to provide energy for 125.000 households. This equals 15% of all demand of Mecklenburg-Vorpommern private household. Most of the energy produced in the wind farm will be fed in the electrical grid directly, while excess wind energy will be transferred into hydrogen by use of the pressurized alkaline electrolizer HySTAT® made byCanadian company *Hydrogenics Corporation*. Its power input amounts to 1 MW (Rh2-wka.de 2013). In combination with a hydrogen compressor 210 Nm^3/h hydrogen at a storage pressure of 310 bar can be provided. For retransformation of hydrogen into electricity two cogeneration units by the South German firm Senergie GmbH are applied with an overall performance of 600 kW. In contrast to many other hybrid power plants, pure hydrogen without any addition of hydrocarbons is fired. This implies that the power plant emits only steam and no CO_2.

Operating numbers	
Connected load	ca. 140 MW
Wind energy plants	15 x E-126, 13 x E-82 (Enercon)
Hydrogen system	Electrolyzer 1MW Cogeneration unit 250 kW (el), 400 kW (th)
Power connection	110 kV / 380 kV
Power production	for ca. 125.000 households
CO2 savings	ca. 250.000 tons per year

Table 2, source: http://www.ostsee-zeitung.de/nachrichten/mv/index_artikel_komplett.phtml?SID=340648bdbab27dad0318916a38dc464c&param=news&id=3346892

The overall costs of this giant wind farm are estimated of about 220 million Euros, which equals 1,58 million Euros per MW installed. As investments for conventional power plants are between 1 and 1,5 million Euros per MW the costs for this wind farm are competitive to other ways of energy production. The storage project is government-sponsored by the national innovation program for hydrogen and fuel cell technology with 4,5 million Euros (Ostsee-Zeitung 2013).

4 CONCLUSION

In this paper, we first showed why it is crucial to explore ways of storing energy generated by renewable sources, more specifically by wind and solar power plants. We mentioned that one of the solution is to generate hydrogen using electricity created at peak periods which can be used in the industry or transformed back into electricity. Then, we discussed the hydrogen generation process, storage and possible uses of hydrogen. We concentrated on reverse-engineering the process of hydrogen generation and on the possible use of hydrogen in the public gas distribution system. Then, we examined two power plants that use the technology.

Two case-studies showed that it is possible to generate hydrogen by wind power plants, and by doing so, solve the problem of varying electricity output. It is safe to say that analogous process could be used for solar power plants as well. It is clear that the technology has a great potential and could contribute to the solution of problems caused by replacing nuclear power plants with renewable energy sources. However, this technology, as showed in previous chapters, suffers from the typical problem of each new technology – high costs. Its profitability is much lower that of conventional power plants due to extremely high initial costs. On the other hand, we can expect that the costs will with further research decrease, and thus, make the profitability of this technology comparable with conventional power plants. Given low to zero CO_2 emissions, no dangerous waste products, practically no operating costs and no need to devastate the planet to get raw materials, further research of this technology is more than desirable.

To conclude, we can say that efficient hydrogen generation process is possible in power-to-gas power plants under current state of technology. However, it is not as profitable as using conventional energy sources at the moment, and so further research is of utmost importance.

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