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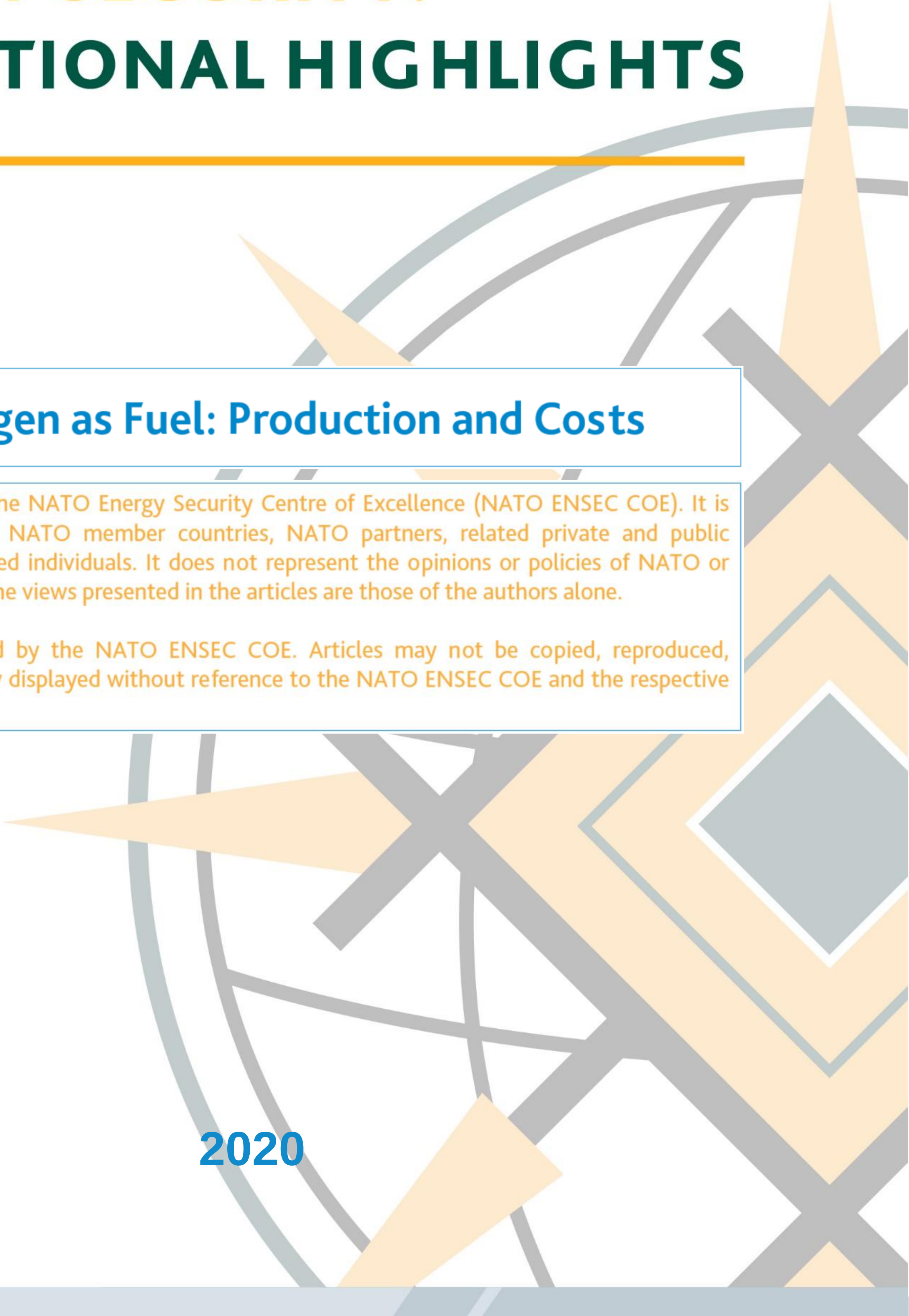

Hydrogen as Fuel: Production and Costs

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Hydrogen as Fuel: Production and Costs

with a closer look to highly regulated market situations

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1 Abstract

Hydrogen is versatile in its usage and may become an important part in efforts to reduce the burning of fossil fuels for energy. The biggest energy consuming sectors are electricity generation, transportation and heating. Transformation of the electricity generation sector seems to be the easiest goal to achieve. The replacement of fossil fuels with CO_2-neutral or CO_2-poor fuels is far more difficult. The coupling of energy consuming sectors is discussed as one of the solutions. The usage of surplus electricity to produce fuels, heat and/or chemical base materials appears to be very promising. This article provides an overview over H_2-electrolyser technologies, their input factors and costs.

The profitable operation of an electrolyser plant currently appears only possible above a threshold of 3 000 – 4 000 full-load hours (FLH) per year. The electric energy generated by wind and solar plants in Germany is not sufficient for profitable hydrogen production. Consequently, only using surplus energy from these sources is even less profitable. To reach profitability, four technical solutions are have been suggested. All aiming at the increase of FLH: 1) Usage of batteries. 2) Usage of 100 % of the electricity produced by wind/solar plants. 3) Import of power from stable renewable sources. 4) Construction of solar/wind powered electrolyser plants in regions with higher FLH and import of the produced H_2[8,11]. Financial solutions are also possible: 1) Subsidies on the investment costs until at least 5 000 FLH per year are reached. 2) Usage of non-renewable power sources for a limited amount of years without losing the status of “green” H_2.

2 Introduction

Hydrogen (H_2) is versatile in its usage and may become an important part in efforts to reduce the burning of fossil fuels for energy production and thus for mitigating global warming. Hydrogen can be used both for heating and as fuel in the transport and mobility sector. It also is an important base material in the chemical industry. Under normal conditions, hydrogen is a gas, which burns without carbon dioxide (CO_2) emissions and – depending on the technology – without producing nitrogen oxide (NO_x) emissions.

Global warming is affecting all parts of society, as the discussions about a “Green new deal” in the USA recently demonstrated[28]. NATO and the military sector are affected in at least three ways: First, causes for and regions of conflict will shift away from securing fossil carbon production sites and transport routes to e.g. water and social unrest related topics resulting in more refugee and rescue missions. Second, the costs for maintenance of military bases will increase, especially for Navy bases due to rising sea water levels[9]. Third, as an integral part of democratic societies, NATO military will become increasingly involved in efforts to reduce emission of CO_2 due to the combustion of fossil fuels.

The three biggest energy consuming sectors are electricity generation, transportation and heating. It is generally acknowledged that the transformation of the electricity generation sector to a carbon free electricity production is technologically the easiest goal to be achieved[31]. This is true due to several reasons: 1.) Produced electricity can be supplied directly to the transmission networks. 2.) Electricity production in close proximity to demand location is at least partly possible e.g. solar panels on rooftops. 3.) The existing transmission network infrastructure can be used. Only short distances have to be built anew. 4.) Efficiency losses due to the conversion into other energy forms do not occur. 5.) Both, highly fluctuating sources e.g. wind and solar as well as sources without fluctuations and a certain buffering capacity (e.g. biogas and hydroelectric dams) are available to cancel out variations in supply and delivery.

The replacement of fossil fuels with CO_2-neutral or CO_2-poor fuels in the transportation sector is far more difficult[31]. Most efficient is the usage of electricity without intermediates in an electric motor with an efficiency factor of 69%. (All efficiency factors in this chapter are with respect of the electricity input at the production site[10].) However, the main obstacles are low ranges in cars and trucks due to the weight of the necessary electric batteries for energy storage. Nonetheless, batteries are currently used in special applications such as military drones[17]. The transformation of electricity to H_2 and its usage in fuel cells leads to an efficiency factor of 26 % (in cars) and is e.g. used in the SilentCamp[17] and the Class 212A/Todaro-Class submarines[17]. The lowest efficiency factor of 13 % (in cars)[10] results from the synthesis of liquid carbon based fuels from electricity via H_2 and their usage in conventional internal combustion engines.

The coupling of energy consuming sectors is widely discussed as one of the solutions to reduce greenhouse gas (GHG) emissions, which CO_2 is one of the most potent ones. With respect to the reduction of CO_2-emissions, the usage of surplus electricity to produce fuels or heat seems to be very promising, as CO_2-emissions in electricity production and in fuel usage/heat production is avoided.

The present article will in the following chapters provide an overview on “electrolyser” technologies i.e. hydrogen production by electrolysis for commercial application. We will look at the costs as well as the possible sources for powering electrolyser plants with renewable electricity sources. Especially the economic potential of the usage of “surplus electricity” from renewable energy sources will be investigated. In this article we will use Germany as a case study because it already has large existing renewable energy capacities of wind and solar production and has a heavily regulated energy market.

3 Components of electrolyser systems

3.1 Electrolyser technologies

Chemical reactions during electrolysis

All chemical bonds contain energy and the more complex a chemical substance, the more energy is stored in it. The most common description of this energy content is the inferior heating value (net caloric value, H_i). It is normally expressed in watthours [kWh]. In chemistry, Joules are typically used and expressed in [kJ]. The conversion factor is 1 kWh = 3.6 x 10^3 kJ. The H_i of methane (CH_4, natural gas), depending on its origin, is ca. 10 kWh/m^3[16]. The H_i of

H_2 is 3 kWh/m^3[16]. Humans do use this energy to transform it by burning into thermal energy (heating) or mechanical energy (movement). The combustion of fuels creates chemical components, which contain less energy than the components at the beginning of the process. In the case of a complete combustion water (H_2O) and/or CO_2 is formed.

Electrolyser technologies convert H_2O and electric energy into hydrogen and oxygen gas. Chemical bonds can be broken via the input of (a) chemical energy (chemolysis) (b) electrical energy (electrolyse) or (c) thermal energy (thermolysis). The bonds between hydrogen and oxygen in water are strong. 4.5 kWh (16.2 MJ) power is needed to produce one m³ H_2 and 0,5 m³ O_2 in the classical setting[14] at standard conditions of 1 013 hPa pressure, 0% humidity and 0 ºC.

The net chemical reaction of all types of water electrolysis is as followed

$$286.02 \text{ kJ } (0.08 \text{ Wh}) + H_2O \text{ (liquid)} \longrightarrow H_2 + \tfrac{1}{2} O_2 \qquad (1)$$

Direct current is applied to a flask of water. To increase the conductibility, an acid or base may be added. The flask is separated through a barrier, the diaphragm. It is permeable for electrons, but not for H_2 and O_2. Within this setting, the formation of an explosive oxhydrogen gas is avoided, as the gases are separated effectively. The net chemical reaction (1) can be separated into a cathodic and an anodic reaction.

Cathodic reaction:
The H^+-ion, driven by the electric field, moves to the cathode, where it takes up an electron and H_2 is formed.

$$2 H^+ + 2 e^- \longrightarrow H_2 \qquad (2)$$

Anodic reaction:
The OH^--ion, driven by the electric field, moves to the anode, where it releases an electron and O_2 is formed.

$$4 OH^- \longrightarrow O_2 + 2 H_2O + 2e^- \qquad (3)$$

The complete reaction is shown in formula (1).

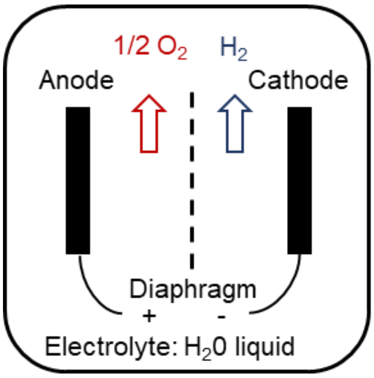

Figure 1: Setting of the original apparatus for the electrolysis of water[14]. Chemical compounds in red: oxygen related species. Compounds in blue: hydrogen related species. Liquid water is the electrolyte. Anode is the positive electric pole. Cathode is the negative electric pole. The diaphragm separates the electric poles. It is permeable for electrons. Modified after[20].

Electrolysis techniques

Several techniques in different settings have been described[14]. Three techniques are commercially in use or at the brink of usage [23] (Figure 2). In alkaline electrolysis (AEL) 20 – 40 % potassium hydroxide (KOH) is used as electrolyte at ambient air temperature. The used diaphragm is permeable for electrons and OH^--ions. In proton exchange membrane electrolyser (PEM or PEMEL) pure water is used as electrolyte at ambient air temperature. The used diaphragm is permeable for electrons and H^+-ions. High temperature electrolyser (HTEL) use water vapour as electrolyser between 100 and 900 ºC. A part of the needed energy to break the chemical bonds in water is given as heat, which leads to high efficiency factors with respect to the needed electricity. The used diaphragm is a solid oxide, which allows O^{2-}-ions to pass.

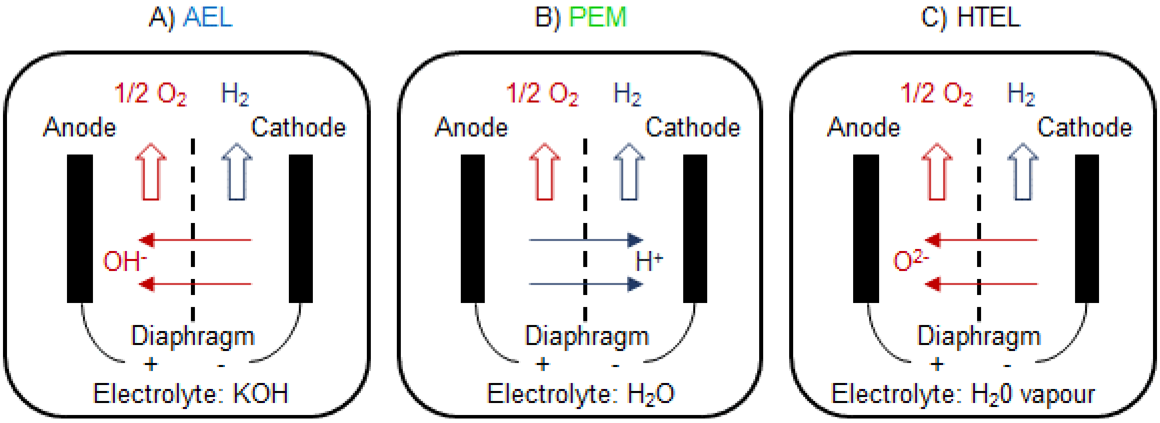

Figure 2: Settings, conditions and main chemical reactions of commercially used electrolysers. The anode is the positive electric pole, the cathode is the negative electric pole. Chemical compounds in red: oxygen related species. Compounds in blue: hydrogen related species. A) AEL: As electrolyte a 20 – 40 % potassium hydroxide solution (KOH) is used. The diaphragm is permeable for electrons and OH^--ions. B) PEM: As electrolyte pure water is used. The diaphragm is permeable for electrodes and H^+-ions. C) HTEL: Water vapour is used as electrolyte. The diaphragm is permeable for O^{2-}-ions. Modified after[20].

Technical parameters and production costs of electrolysis

The technical parameters and production costs of different electrolysis procedures vary considerably and determine the applicability. The main characteristics of the three most common commercial technologies are shown in (Table 1).

Table 1: Mean technical and financial key performance indicators (KPI's) and possible future usages of the commercially available electrolyse technologies AEL, PEM and HTEL[23]. KPI's with approximate values are indicated by *.

KPI	AEL	PEM	HTEL
Technical parameters			
Efficiency factor [%]	66	63	81
Power consumption [kWh/Nm³] *	4.6	4.8	3.7
Working pressure [bar] *	18	30	4
Working temperature [ºC]	50 - 100	20 – 100	500 – 900
Offset time after 48 h of standstill [min] *	55	15	600
Offset time until 48 h of standstill [min] *	17	5	20
Aeric electric current [A/cm²] *	0.4	1.8	0.8
Durability of stack [h] *	60 000	40 000	15 000
Financial parameters			
CAPEX [€/KW] *	1 450	900	2 250
CAPEX [€/Nm³/h] * (including efficiency factor electrolyser)	4 000	7 000	8 800
OPEX fix [€/a/kW] *	13	18	32
Raw material availability	Uncritical	Partially critical	Critical
Future potentials until 2050			
Usage	ALE and PEM comparable	ALE and PEM comparable Slight advantages in decentralised plants	Industrial settings with available industrial waste heat

Key to the further development of electrolyser technologies and its related costs is the upscaling of the hydrogen demand. Germany for example is subsidising this process since 2006[3]. Assuming this scenario, a survey of leading companies producing 2/3 of the world's electrolyser production in 2017 shows the possible developments of the industry and its technologies for 2020 (Figure 3)[23].

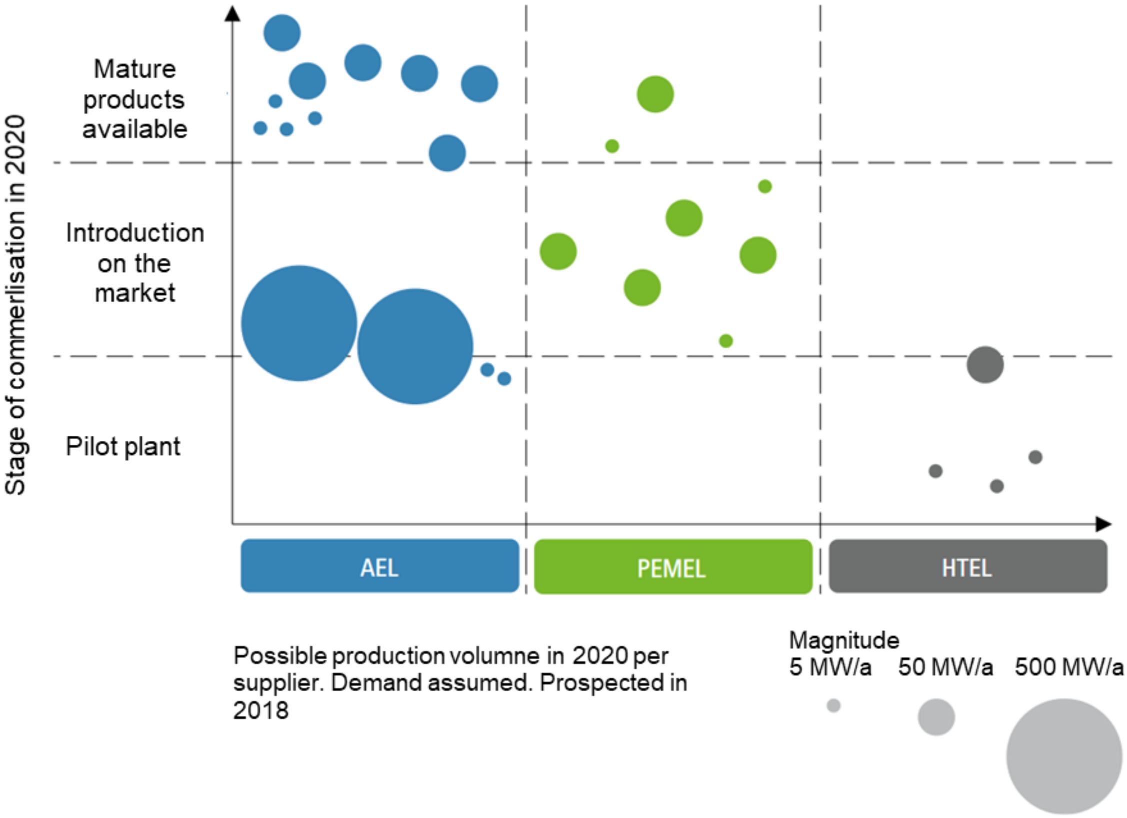

Figure 3: Stage of development for AEL (blue), PEM (PEMEL, green) and HTEL (grey) electrolyser technologies as reported in a survey which included 2/3 of the world leading electrolyser producers for 2020 on the basis of 2017. The scenarios are set in an upscaling market with rising demand of electrolysers. Size of the spheres is a measure for the peak electric power of the electrolyser. Modified after[23].

AEL is the electrolyser technology mostly used in commercial settings. It is also the most robust technology with the longest development history of several decades[15]. More than 15 suppliers worldwide are available who commercially build plant sizes from 5 – 500 MW. No critical raw materials are needed for the production of this type of electrolyser.

PEM technology has been under development for about three decades. Its efficiency rate is the lowest of the three technologies. Efficiency is predicted to rise with further technical improvements. PEM is best suited for highly fluctuating power supplies as the offset times are low.

AEL and PEM are comparable in almost all other technical KPI’s except for durability. Productions costs were also comparable.

HTEL electrolysers are on the brink of entering the market and are the most expensive of the described technologies. Pilot plants built in Germany are supported by government funding[21]. HTEL has the highest efficiency rates with respect to power input because it uses heat as additional energy source. It is best suited in industrial areas with a supply of waste heat and a demand of H_2. However, off-set times after standstill are long, therefore a constant power supply for HTEL is crucial. Only a few suppliers are currently available worldwide.

The „Hydrogen Strategy“ of the German Government „Wasserstoffstrategie“:

Germany created a long term “Program for Innovation for Hydrogen- and Fuel Cell Technologies 2006 – 2016 (NIP)” at the beginning of this century[3]. The follow up “Government Program Hydrogen- and Fuel Cell Technology 2016 – 2026 - from Introduction on the Market to Competitive Products” aims at the upscaling of markets for hydrogen related technologies with the aim of becoming a spearhead in this sector, creating jobs and reducing the costs for these technologies. These aims are means to reach the CO_2-reduction targets for Germany[3]. On 10th of June 2020 the government announced subsidies of 310 x 10^6 € from 2020 – 2023 for research and development projects for the production, storage, transport and distribution of hydrogen[2]. On an international basis, Australia, China, Japan and South Korea are also working intensely on hydrogen related topics[12].

3.2 Power provision/supply using the example of Germany

In this section, the conditions of the electricity supply from renewable sources for running electrolysers are discussed using the example of Germany. With its government energy transition plan (German: Energiewende) Germany attempts a true energy revolution. The country is boosting the market share of renewable sources such as wind, solar and water plants for the production of electric power. Simultaneously it attempts to phase out fossil and nuclear energy. However, wind and solar electricity production is highly volatile i.e. variable during the day and it shows a pronounced seasonality. Mean wind electricity production is peaks in spring while mean solar electricity production peaks in autumn. In December, the dark doldrums with almost no wind and no sunshine typically result in the lowest electricity production seasonally during the year (Figure 4). This situation may occur for up to two weeks with a probability of one in every 2-3 years[11,24]. Consequently, such volatile electricity production requires intermediate storage capacity as a buffer for providing a stable and predictable electricity supply to the consumer. The geological and topographic options for affordable temporal energy storage by building new pumped storage hydro power stations in Germany are almost exhausted[11]. Other forms of temporal electric energy storage are still very expensive.

Energy transition (Energiewende), Renewable Energy Law (Erneuerbare-Energien-Gesetz 2017, EEG), Federal Network Agency (Bundesnetzagentur, BNetzA):

The energy transition in Germany was initiated in 1998 by the former Red-Green coalition under Chancellor Gerhard Schröder. The aim was the increase in electricity production from renewable sources, e.g. solar, wind, water, biomass and biogas etc.[18]. This could only become a reality, when the former quasi regional electricity providing monopolists were split up. They regularly unite the business unites of electricity production, transmission network, distribution network, distribution and consumption measuring. The Renewable Energy Law[4] (EEG in its actual version from 2017) was created in 2000 with the aim to enable all producers of electricity (big e.g. commercial offshore wind farms and small e.g. private rooftop solar plants) to feed electricity into the network and all customers to select a national electricity provider, other than the former regional monopolist. To ensure the right to use the electricity network for all electricity producers, among other duties, the regulation authority Federal Network Agency (BNetzA) was created. Nowadays the EEG is mostly known for its regulations regarding the privileges of electricity produced from renewable over fossil sources.

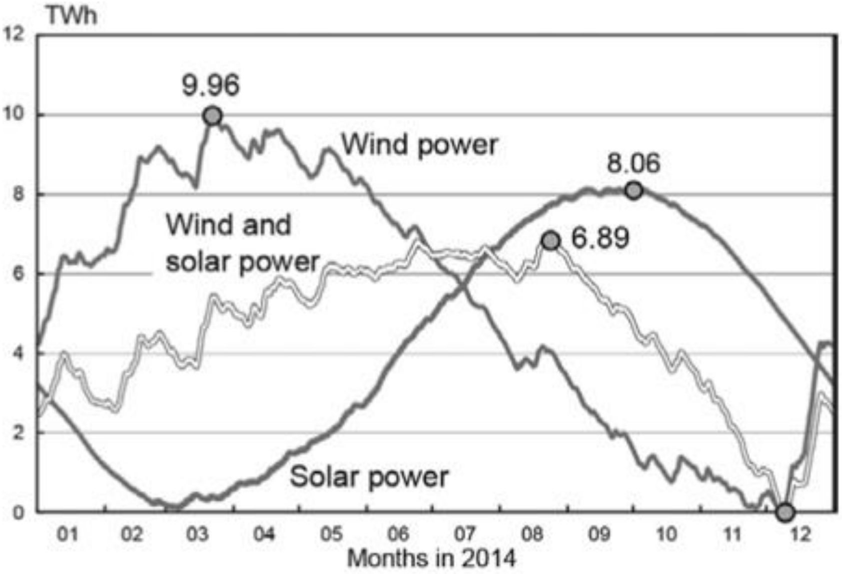

Figure 4: Seasonal electricity production in 2014. A) Solid grey line: electricity production by wind plants. B) Solid grey line: electricity production by solar plants. C) Solid with line: electricity production by wind and solar plants subtracted by a virtual consumption of the average daily German consumption as stored in a pumped storage hydro power station[11]. The dark doldrums effect in December can clearly be seen.

While 100 % of the German electricity demand could be met in theory by the capacity of all renewable production sources, buffering strategies are needed because of temporal mismatches in electricity supply and demand. At night the demand exceeds what wind and hydroelectric plants are able to supply while the supply from solar and wind plants on bright windy winter weekends may be higher than the demand. In this carbon dioxide reduced electricity production scenario 60 - 70 GW of power in highly flexible gas powered electrical plants (using methane or H_2) are needed to stabilise the system[24]. At the moment, buffering is also achieved by maintaining a back-up set of conventional power plants which is very expensive as it involves double fixed costs (see below). As Germany is phasing out nuclear and coal powered plants in the coming years, back-up plants usually use natural gas, which is a more expensive but a cleaner fuel than coal and oil. In the first half of 2016 one kWh cost 29.69 €-ct for German end customers, while a French end customer had to only pay 16.85 €-ct per kWh[11].

Solutions for the storage of excess electricity (when supply is higher than demand) are needed. Electric energy can be e.g. stored in batteries, but the capacity needed to buffer the power demand of an entire country is not realistically achievable at the moment. Electricity can be used instantly for heating purposes in district heating grids (power-to-heat) bridging the gap between energy consuming sectors (sector coupling). This storage method is widely used in Denmark[19] where in 2014 about 45 % of its needed electricity was produced by wind-solar sources [11]. Electric energy can also be stored as H_2 using electrolysers. As early as 1960 several electrolysers were installed at the Aswan dam in Egypt with a capacity to produce 40 000 m^3 of H_2 per hour under standard conditions (Figure 5)[15]. H_2 is needed in large quantities for industrial processes e.g. in the production of fertilisers using the Haber-Bosch-process[13].

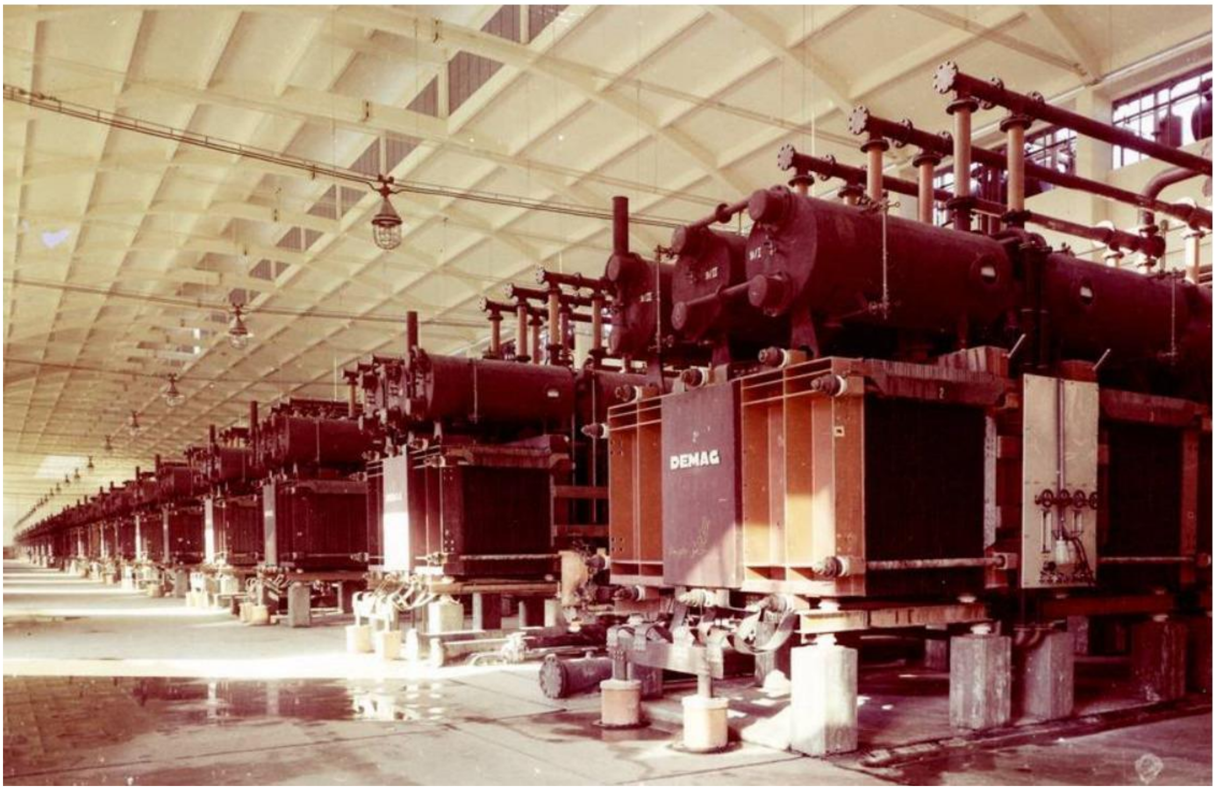

Figure 5: Array of electrolysers in the Aswan hydroelectric dam, Egyt[15]. These electrolysers were installed in 1960 and were mainly used for providing hydrogen for nitrogen based fertilizer production.

H_2 and carbon can be further synthesized to methane or liquid fuels, such as synthetic diesel[10]. However, these storage compounds are not able to re-convert the stored energy into electric power at acceptable costs. Electricity storage using pumped hydro power plants is only possible for a small amount of the needed electricity in the European Union, as the topographic and geologic preconditions are not present[11]. The production of H_2 with surplus power is often suggested as an option for regions outside the global Sun Belt. Areas within the Sun Belt may use other storage technologies. The Andasol solar thermal power plant in southern Spain is able to bridge a gap of ca. 7.5 hours of darkness under full-load operation. Surplus solar energy is accumulated as heat in a liquefied sodium nitrate/potassium nitrate salt mixture at a minimum temperature of 240 ºC. The energy can be recovered in a heat exchanger to produce water vapour to run a turbine.[29]

In accordance with the EEG[4], renewable electricity production plants are entitled to several privileges within the first 20 years of production. One is financial compensation for electricity which cannot be supplied to the transmission network due to low or non-existing distribution capacities. Similar issues exist within the United Kingdom, where wind turbines in Scotland have to be temporarily shut down and owners compensated during surplus power production[5]. Due to obligatory compensation payment, the amount of surplus power from renewable sources is well documented by the Grid Agency BNetzA. The amount of surplus power from 2009 to 2019 is shown in Figure 6 [6]. Ca. 95 % of these 5.4 GWh are produced in the northern part of Germany (Schleswig-Holstein, Mecklenburg Western Pomerania, Lower Saxony and Brandenburg[1]). The amount of surplus power is expected to rise constantly, as Germany aims to further increase power production from renewable energies[11].

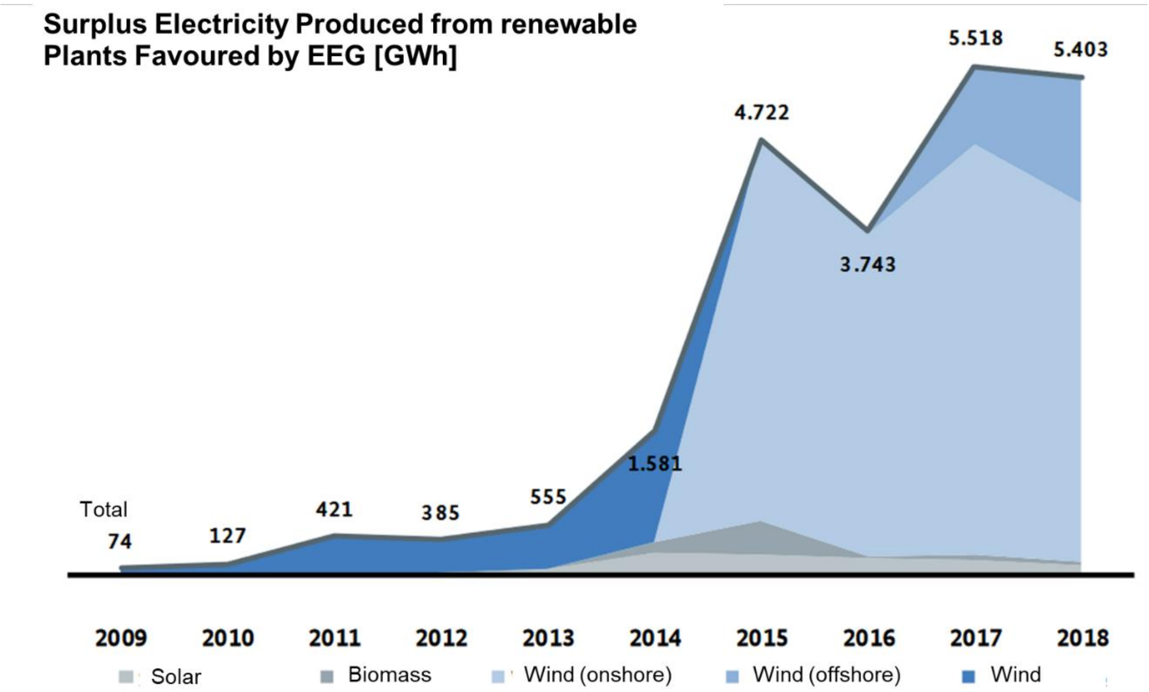

Figure 6: Surplus electricity production from renewable sources from 2009 to 2019 in Germany differentiated according to source of production[6]. Data source: Governmental office of BNetzA. Light grey: solar plants. Middle grey: biomass plants. Light blue: onshore wind plants (since 2015). Middle blue: offshore wind plants (since 2015). Dark blue: total of onshore and offshore wind plants (2009 to 2014).

4 Financial Cost aspects of H_2 generated from renewable power

In the following chapter, the cost aspects of using electrolyser technology are discussed in the context of using surplus power production from renewable sources.

Economic law of mass production

Costs for H_2 production from renewable power sources follow the general economic laws of production: Costs in companies are typically split into capital (capex) and operative (opex) expenses. Typical capex's are the funds needed for acquiring assets e.g. electrolysers. Opex's are further divided either in terms of dependency of the output into fixed plus proportional expenditures, or in terms of the duration of the contracts into fixed plus variable expenditures (see Table 2). In the literature, it is often not clear which definition of costs is used.

In this article the respective definition is always stated explicitly. Payroll costs in production units are most critical in terms of dependency of the output (fixed/proportional) or the duration of the contract (fixed/variable). In economies with mandatory employment protection (like Germany) they are proportional in terms of the output, but fixed in terms of the duration of the employment contract. In economies without employment protection (like in the US), they are proportional in terms of output and variable in terms of duration of the contracts. Overhead payroll costs are always fixed costs.

Table 2: Examples of capex, opex and their assignment to fixed, proportional or variable costs with respect to operating an electrolyser plant in an economy with employment protection.

Costs	**Example**	**Dependency on output**		**Duration of contract**	
		Dependant	**Name**	**Timeframe**	**Name**
Capex	Acquiring of an electrolyser	No	Fixed costs	Long term	Fixed costs
	Housing of the plant	No		Long term	
Opex	Rent for a building	No		Long term	
	Employees overhead units	No		Long Term	
	Employees production units	Yes	Proportional costs	Long term	
	Electricity	Yes		Short term	Variable costs
	Network usage fee	Yes		Short term	

Cost curves relate the expenses to the output. Depending on the economy in which the plant is operating, payroll costs from employees in production units are fixed or proportional. They are useful tools in economics as they highlight the general relationships between costs and output[30]. Figure *7* shows the relation of average fixed costs (AFC), average proportional costs (APC) and the average total costs (AC) in relation to the total output. As a general rule AFC are reduced with every additional unit produced[30]. This phenomenon is called "economy of scale" and is the underlying principle of cost reduction in mass production. APC do rise from a certain output onwards, as for example, labour cost are rising for additional work shifts at night and on weekends. The minimum costs of production occur are at the minimum of the Average Cost curve.

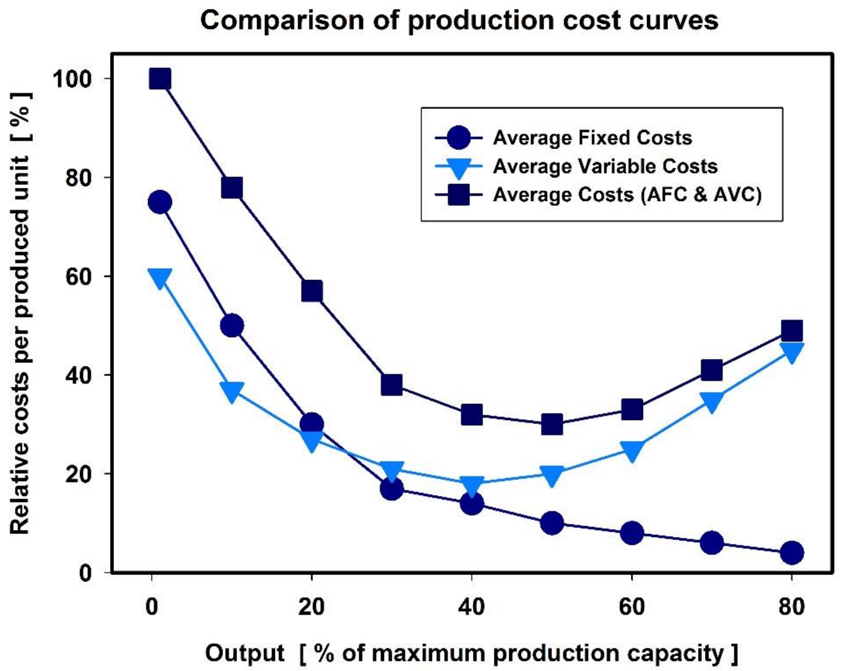

Figure 7: Dependency of costs per unit on total output. APC is the Average Proportional Cost and AFC the Average Fixed Cost. AC is the Average Cost, which is the total of APC and AFC. Payroll costs in production units are defined as proportional costs[30]. All values in the graph are normalized to % based on the highest value of AC at zero output.

Current costs of Hydrogen production using Germany as a reference:

A calculation of the H_2 cost curve using renewable power sources in Germany is shown in Figure 8. The FLH are a measure for the output. In the case of hydrogen production via electrolyses they are directly proportional to the output. The costs of the three commercially available technologies in 2017 are used and weighted according to the market share using data from 2017[23]. In the specific situation of H_2 production by electrolysis from electricity produced by renewable plants according to German EEG[4], three main cost drivers have to be accounted for (Figure 8):

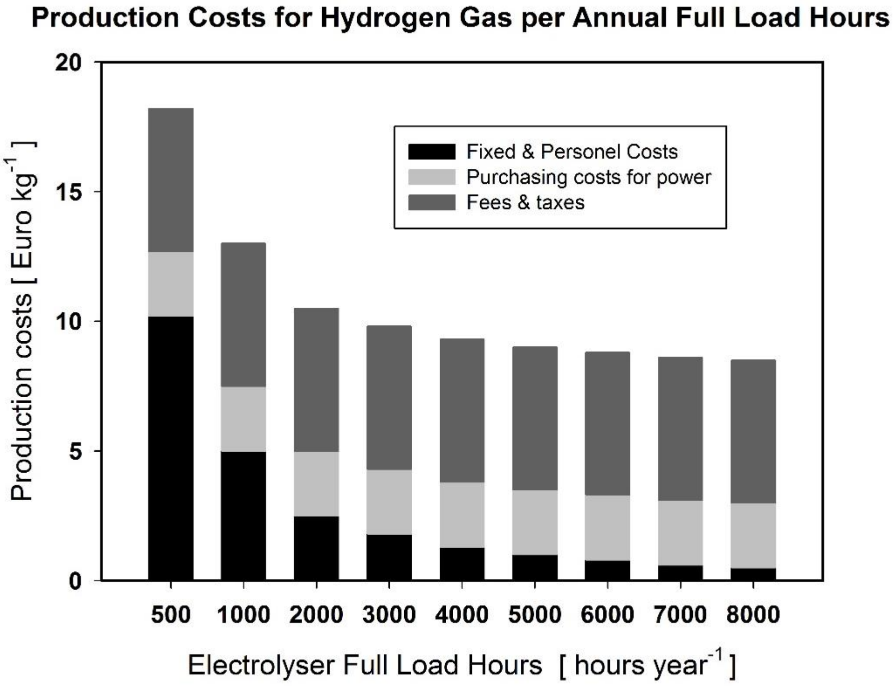

Figure 8: Calculated cost curve of operating electrolysers for the three commercial available technologies of energy production in Germany (based on the market shares in 2017) in dependence of the FLH [23]. Dark grey: Fees and taxes according to German laws. Light grey: Electricity purchasing costs. Black: Fixed and personnel costs.

1) Fees and Taxes: According to the EEG[4], fees and taxes for the usage of the transmission networks, the EEG-compensation (a fee for financing of the energy transition in Germany), electricity tax and other fees must be paid. These costs are proportional to the amount of electricity procured and do not vary on the basis of the total amount of H_2 produced.

2) Procurement costs: They are given as 15.40 € ct/kWh. These are the conditions for industrial contracts within the range of $16 * 10^4$ and $60 * 10^6$ kWh per year. Globally the total costs from wind/solar plants are decreasing constantly and are even now lower than the total productions costs from nuclear or fossil power plants[22,24]. In Germany they are less than 6 €-ct/kWh and still falling due to the regulations of the §§ 22 ff. of the EEG[4]. Procurement costs are proportional to the output with no depreciation with rising output/FLH.

For 1) and 2) the total of fees, taxes and electricity procurement cost are constant across the entire range of the output/FLH (ca. 8.00 €/kg H_2).

3) Other costs: All costs which are not fees, taxes or electricity procurement costs are fixed costs in this context. They contain for example the capital costs for acquisition and housing of the electrolysers. Maintenance costs are calculated as a fixed percentage of the installed capacity of the electrolyser. Employee costs are fixed, because labour contracts are long term and electrolysers do work fully automated. The fixed costs do vary from ca. 10.20 €/kg H_2 at 500 FLH to ca. 0.50 €/kg H_2. This means that, depending on the FLH, the percentage of the fixed cost related to the variable costs do vary from 6% (8 000 h) to 128% (500 h). Therefore 3 000 to 4 000 FLH a year are needed to benefit from the economies of scale. With each added unit of output the cost effects are getting smaller. FLH of > 8 000 are considered a continuous operation (hours per year = 8 760). The remaining time span is normally required for plant maintenance.

The determining cost factors show that the total production costs are mostly driven by the fixed costs of the plant and therefore directly depend on the amount of the FLH of the plant: The more FLH the electrolysers are running, the better the cost/benefit ratio.

5 Supply and demand of electricity from renewable sources

Approximately 5.4 GWh of surplus electricity were theoretically available in Germany in 2018. The main sources were wind and solar plants[6] (Figure 6). The peak power supplied from solar plants was 29 GW and remained relatively constant between 2012 and 2018. The term “power” in this article always means “performance” in watt [W]. The peak power supplied from wind plants has doubled from 2012 (24 GW) until 2018 (50 GW). The increase of the combined peak power supplied has followed the increase in the wind power plants and is highly influenced by it (see Figure 9)[6]. The core area for wind power plants is Northern Germany while solar power plants are mainly located in Southern Germany. At the moment, the usage of electricity from both types of plants in the same H_2-production site is not possible due to the technical capacity limitations of the transmission networks[6].

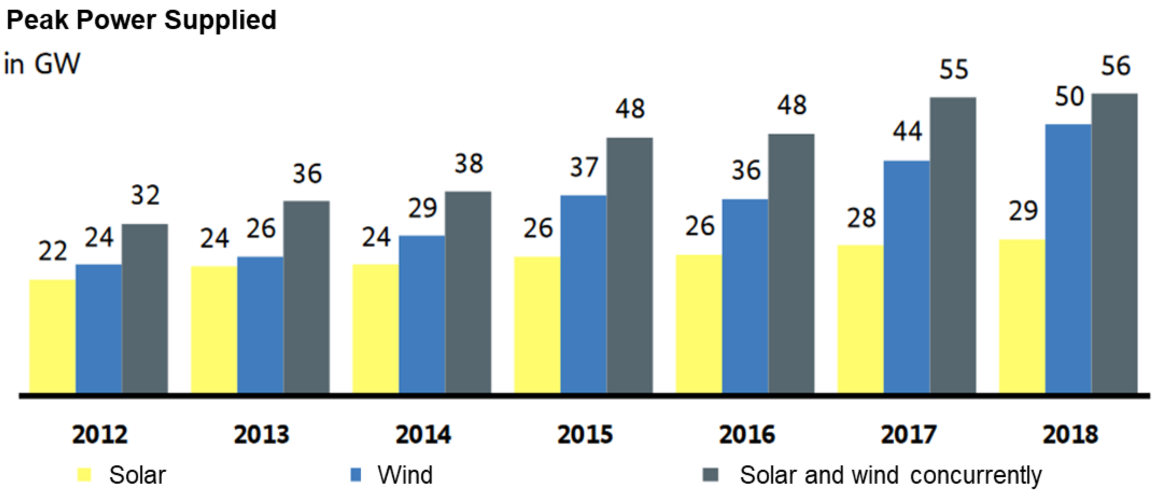

Figure 9: Peak power in GW supplied by solar and wind plants in Germany between 2012 and 2018. Yellow: solar plants. Blue: wind plants. Grey: Total of solar and wind plants. Modified after[6].

Production by solar powered electrolyser plants is limited to a maximum of 12 hours a day during summer and about 8 hours a day during winter. Cloud coverage and fog further reduce the possible operating time. Wind power is even more volatile as shown in Figure 11[6]. Power peaks resulting from storms normally do not last more than 2-3 days. Estimates of the combined wind & solar FLH in Germany vary between 2 750 and 4 400 h per year (Table 3). The volatility of the power supply increases dramatically when solely “surplus power” is used for H_2 production. Although about 5.4 GWh of surplus energy is available, the usage for H_2 generation is difficult due to the start-up times of the electrolysers (Table 1) and the peak power of the plants.

Thus, the concept of using surplus energy for H_2 production with electrolysers from wind turbines and solar plants is economically not profitable. Both, scientists and operators of pilot electrolyser plants do agree, that electrolysers should be operated with a maximum of 8 000 FLH per year [10,11] or at least with 3 000 – 4 000 h per year[8] to reduce costs to the lowest possible level. Only a few companies do work on the basis of surplus electricity supply only, e.g. since 2012 the test plants of uniper in Falkenhagen, Northern Germany (Figure 10)[19,25]. The usage of surplus power seems to be a promising path in terms of CO_2 reduction but not in terms of cost reduction.

Figure 10: The Power-to-Gas Plant Falkenhagen in Brandenburg, Germany is operated by Uniper SE since 2012. Uniper was outsourced in 2015/2016 from e.on AG, one of the former regional monopolists for electric power generation in Germany. The two containers on the right hand side of the picture hold the electrolysers. The left hand side shows the methanation unit for conversion of carbon dioxide (CO_2) into methane (CH_4)[24].

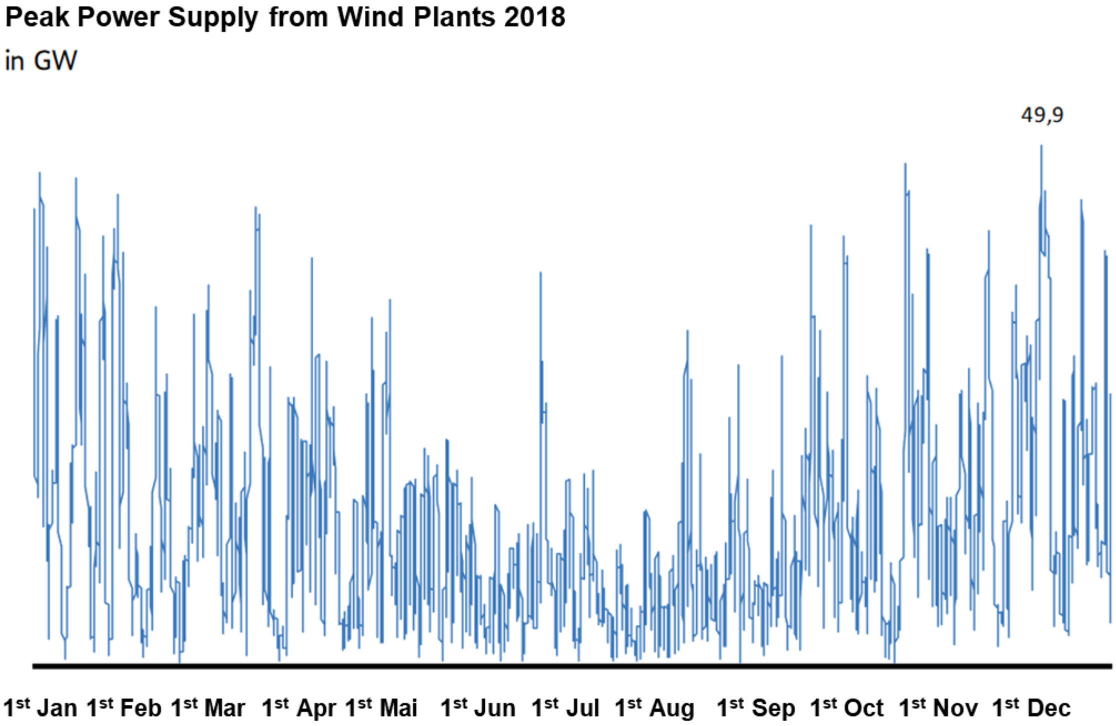

Figure 11: Peak electric power [GW] supplied by wind plants in Germany in 2018. Modified after[6].

6 Conclusions

Current profitability

The profitable operation of an electrolyser plant appears currently only possible above a threshold of 3 000 – 4 000 FLH per year. Using the example of Germany, even offshore wind parks located along the North Sea and Baltic Sea and land based wind parks in Northern Germany are unable to deliver enough surplus energy to allow this amount of FLH operation. The same applies to solar power plants, which are mostly located in the southern part of Germany. At the moment, the electric energy generated by wind and solar plants in Germany is not sufficient for a profitable hydrogen production. Consequently, using only the surplus energy from renewable sources is even less profitable.

Future options

To reach technological implementation or even profitability for electrolyser plants, four technical solutions are suggested:

1) Usage of batteries for buffering the supply volatility and for increasing FLH. This method is expensive and will only cover time scales of hours, rather than days. It is a small scale solution. In 2017 Australia built a wind powered battery buffer of 120 MWh capacity with the aim to stabilise the electric power supply of 30 000 household during the summer months[7].

2) Usage of 100 % of the electricity produced by wind/solar plants which no longer benefit from the privileges of the German EEG[11]. These plants are more than 20 years old and sometimes difficult to re-power. Therefore the owners run the old turbines mostly looking for new business models. Re-powering means the usage of the same place for a new, bigger and

more effective wind turbine which will benefit again for 20 years from EEG[4] privileges. This measure will reduce the volatility of the supply, but it will not erase it.

3) Import of power from more stable renewable sources (e.g. hydroelectric, geothermal), at least during times without domestic supply. For example, cooperation with Norway's hydroelectric power dam operators is already practised and could be enlarged. In this scenario Norway would supply electricity from dams during low wind/solar power generation to Germany[11]. In the beginning of the upscaling of the H_2 production, this scenario is possible, as only a small amount of the surplus electricity is needed for the electrolysers. Iceland has huge potentials for geothermal electricity production, which is currently unused, because the domestic demand is saturated. The technology itself is proven and runs in nearly permanent operation (> 8 000 FLH). The construction of an electric power transmission sea cable from Iceland to Scotland (1,100 km) was discussed several times in the past. This project has never been realised due to low global energy prices[5].

4) Construction of solar/wind powered electrolyser plants in regions with higher FLH of the plants and import of the produced H_2[8,11]. In Table 3 the calculated possible FLH of renewable electricity plants in different regions of the northern hemisphere are listed. Even in regions which are located in the global sun belt, such as North Africa and the Middle East, FLH of >4 000 are not guaranteed and can only be achieved by a combination of wind and solar plants. Due to the double investment for both technologies, fixed costs will rise significantly. Both regions are also politically unstable raising the respective risks for the supply chain. Means for transportation of huge amounts of H_2 are not yet established. This option would not address the problem of the available surplus power in Germany and has a low potential for realisation.

Table 3: Estimated Full Load Hours (FLH) in different regions of the earth for different power production technologies.

Region	Technology	FLH [h] Scenarios
North Africa[8]	Photovoltaic (single axis tracking)	2 100 – 2 500
	Wind onshore	2 000 – 3 400
	Photovoltaic (single axis tracking) + wind onshore	3 485 – 5 015
Middle East[8]	Photovoltaic (single axis tracking)	2 200 – 2 600
	Wind onshore	2 400 – 2 500
	Photovoltaic (single axis tracking) + wind onshore	3 910 – 4 335
Iceland[8]	Geothermal energy + big hydroelectric power dam	8 000
Norway[11]	Big hydroelectric power dam	8 000
North/Baltic sea Germany[8]	Wind offshore	3 500 – 4 400
North/Baltic sea Germany[23]	Wind offshore	< 3 000
Germany[27]	Wind on-/offshore	2 750

(5) Besides technical solutions for reducing the production costs, financial solutions are also possible: (a) Governments could provide subsidies on the investment costs as long as it isn't possible to procure power from renewable sources for at least 5 000 FLH per year[26]. (b) Governments provide temporary incentives to electrolyser plant operators by allowing the usage of fossil or nuclear power sources without denying the privileged tax status of producing "green" H_2[26].

In conclusion, hydrogen generated from renewable electricity certainly is an environmentally clean option which will help to reduce the use of fossil fuels and mitigate the negative effects of global climate change. Hydrogen should be an important part of a future energy mix and is also a chemical base material for further chemical syntheses. This paper has reviewed both the current processes and technologies available for using electrolysers in the production of hydrogen and the costs for installation and operation of electrolyser plants. While several proven electrolyser technologies exist, the main obstacle is the availability of constant power sources to run electrolyser plants on a large scale and under full load for a sufficient time yearly to be profitable. Neither surplus electric power generated by solar nor by wind parks provides sufficient and stable energy needed at a large enough scale to be economically feasible.

While several short and long term technological and fiscal solutions for reducing the costs of H_2 production from renewable power sources are available, the realisation of hydrogen production for fuel on a large scale appears not to be imminent due to significant, mainly financial, obstacles. A conversion from a fossil, carbon based energy system to a hydrogen based system requires both a very large H_2 production capacity and a stable power supply. Establishing such a capacity will continue to be a challenge for the coming years.

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