Feasibility study on the use of electrolyzers for short term energy storage

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Abstract

Electricity grid flexibility is vital for renewable energy to be used effectively. Power-to-gas technologies are investigated to connect electricity grid to gas grid and to tackle capacity challenges. Grid management expenses consist of redispatch and feed-in management. These management procedures, next to being costly, cause a significant energy loss. Proton-exchange membrane electrolyzer installations were studied to reduce these expenses and recover energy. The change in the levelized cost of hydrogen production with varying electrolyzer capacities was presented. The sensitivity of the levelized cost and net present value with respect to installation costs, maintenance costs, and electricity prices were investigated. While the electricity prices have the most significant effect on the levelized cost of hydrogen production, the net present value was affected considerably by the hydrogen selling price. Possible energy savings were calculated between 2 – 23 GWh for 2, 5, 10, 20 MW installations. The annual grid management expense savings were in the range of 0.2 – 2.3 million Euros, increasing with the increasing electrolyzer capacity.

Keywords: electrolysis, power-to-gas, renewable energy

1 Introduction

The share of intermittent renewable sources (wind and solar) reached a significant level that causes various issues in the grid. One of these challenges is the uncontrollable amount and geographical distribution of power generation. As the storage capacity of the grid is limited, the electricity prices can be negative, or generators have to shut down to ensure grid stability. When the transmission operator changes the active generators holding the same energy production to avoid congestion, it is called redispatch. It might cause shutting off renewable power plants due to their location and maybe use fossil alternatives instead. It is called feed-in management when certain generators are shut down because the production exceeds the grid transmission capacity. In 2015, it was reported that the transmission system operators in Germany paid 412 million Euros for redispatch and 478 million Euros for feed-in management (Bundesnetzagentur, 2016). According to this report, Schleswig - Holstein is the most affected state from these measures. As a matter of fact, 65.5% of the feed-in management expenses are affiliated with this state. Its low population density (Hinz et al., 2018), high wind power (Maruf and Islam, 2021) and weakly connected grid to the demand owner states (Bencs et al., 2020) contribute significantly to the situation. Water electrolysis can utilize the redundant energy and produce hydrogen that can be sold to process industries or stored to be converted back to electricity when needed. Expenses of grid management are not the only point to consider; Schleswig - Holstein has lost over 1000 GWh of energy due to an inflexible grid in 2014 (Schermeyer et al., 2017).

Hydrogen is widely used in process industries, especially for ammonia and methanol production (Nicita et al., 2020). When it is produced from renewable resources, it has a lower carbon footprint than its fossil production route. A gray hydrogen production route, steam-methane reforming, has a global warming potential of approximately 12000 g CO_{2eq}/kg H_2, and this value is 970 g CO_{2eq}/kg H_2 for electrolysis by wind energy and 2412 g CO_{2eq}/kg H_2 for electrolysis by solar energy (Cetinkaya et al., 2012). Currently, most of the industrial hydrogen is produced via steam-methane reforming (Carapellucci and Giordano, 2020). In the last decades, hydrogen gains importance as an environmentally friendly energy carrier and as a product of power-to-gas research. It is a good candidate for decarbonizing the systems where high energy density is required. Hydrogen use in aviation (Bauen et al., 2020) and steel industry (Gielen et al., 2020) can undoubtedly contribute to achieve the lower greenhouse gas emission aims.

A variety of electrolysis methods are available for different scales with different current densities and operating conditions. Alkaline electrolysis is a mature technology. Norsk Hydro operated this type of electrolyzers for over 50 years in Norway (Posdziech et al., 2019). Although they are mature, they have low current densities and lower efficiency than the other options (Grigoriev et al., 2020). Solid-oxide electrolysis operates at a high temperature (Lei et al., 2019), and it is a very efficient system. However, the high temperature condition makes it harder to integrate into intermittent systems. The start-up time is longer to reach the 800 – 1300 K temperatures. Proton-exchange membrane (PEM) electrolysis operates

DOI: 10.3384/ecp21185234

at a lower temperature (350 K), and has a higher current density and efficiency than the alkaline method (Lümmen et al., 2019).

There are studies in the literature, discussing electrolysis installations for Italy (Minutillo et al., 2021), Norway (Ulleberg and Hancke, 2020) and Korea (Lee et al., 2020). These studies show the location dependency of the costs, prices, and energy availability. In this work, the German state of Schleswig - Holstein is selected as the location of a PEM type electrolyzer to reduce the penalty costs and lost energy. The levelized cost of hydrogen production and the net present value of electrolyzer installation are calculated for different capacities. The sensitivities of the levelized cost and the net present value are estimated based on the expenses. The savings are calculated in terms of energy and grid management cost reduction. Finally, the internal rate of return is presented with a discussion on the feasibility of this application. New stations are planned to increase the state's existing hydrogen filling capacity; therefore, the produced hydrogen can be sold locally (Posdziech, 2019).

The next section presents the equations and parameters used to evaluate electrolyzers from an economic perspective. Additionally, case scenarios are created with varying costs and product prices, operating hours, and electricity prices to analyze the commercial possibilities. The results are presented based on these scenarios and discussed in the section that follows. Finally, in the last section, the outcomes of this work are summarized next to possible points for future investigations.

2 Methods

To assess the economic conditions of hydrogen production via electrolysis, the levelized cost of hydrogen production (LCOH) is used. LCOH is calculated by Equation 1. As can be seen in the equation, this value shows the cost per kg of hydrogen production.

$$LCOH = \frac{\sum_{y=1}^{N} \frac{CapEx_y + E_y}{(1+d)^y}}{\sum_{y=1}^{N} \frac{m_{h,y}}{(1+d)^y}} \tag{1}$$

The net present value of the installations are calculated by Equation 2.

$$NPV = \sum_{y=0}^{N} \frac{Cash_{in} - Cash_{out}}{(1+d)^y} \tag{2}$$

The internal rate of return (IRR) is also calculated to show the expected return generated by the investment. IRR is the discount rate that results in a zero NPV, which is given in Equation 3.

$$\sum_{y=0}^{N} \frac{Cash_{in} - Cash_{out}}{(1+IRR)^y} = 0 \tag{3}$$

The variables used for these equations are given in Table 1. The value of time is taken into consideration by the discount factor in all the economic assessment methods used.

Table 1. Variables used for levelized cost, net present value, and internal rate of return calculations.

Variable	*Description (Unit)*
LCOH	Levelized Cost (EUR/kg Hydrogen)
y	Year index
N	Electrolyzer lifetime (year)
$CapEx_y$	Capital expenses in year y (EUR)
$OpEx_y$	Operational expenses in year y (EUR)
E_y	Electricity cost in year y (EUR/kWh)
$m_{h,y}$	Produced hydrogen in year y (kg/year)
d	Discount factor (%)
NPV	Net present value (EUR)
$Cash_{in}$	Cash inflow (EUR)
$Cash_{out}$	Cash outflow (EUR)
IRR	Internal rate of return (%)

Capital expenses (CapEx) and maintenance expenses are calculated by using factors changing according to the capacity of the electrolyzer. These factors are given in Table 2 for PEM electrolysis.

Table 2. Variables used for levelized cost and net present value calculations.

Capacity (MW)	*CapEx*[1] (EUR/kW)	*Maintenance*[2] (EUR/kW)
2	1400	500
5	1300	455
10	1250	445
20	1200	420

The electrodes have a shorter lifetime than the system. Therefore, maintenance is considered for electrode change every five years. The electricity cost is the only operational expense that is included in this study. Instead of using a factor, this expense is calculated by using 6 ¢EUR/kWh electricity price, the capacity of the electrolyzer, and the running hours of the system. This value is the lower limit of industrial electricity price in Germany (Schmitz et al., 2020). For the base scenario, 6 EUR/kg hydrogen selling price is used. A 6000-hour operation per year is assumed for the electrolyzers considering that the high electricity prices would cause infeasible operation.

Scenarios

- *Base Scenario:* LCOH, NPV and IRR are calculated for capacities of 2, 5, 10, and 20 MW, and electrolyzer lifetime of 10, 15, and 20 years.

- *Dependency on costs and product price variation:*

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[1] (Saba et al., 2018)

[2] (Lee et al., 2020)

Each expense parameter (CapEx, OpEx, and maintenance) is reduced by 10%, and the change in LCOH is presented. In addition to the expense reduction scenarios, the change in NPV with respect to a 10% hydrogen selling price increase is calculated.

- *Runtime:* Operating hours per year is varied between 3000 – 8000 with 1000 h/y increments, and the LCOH changing trend is studied.
- *Electricity price:* A high electricity price is considered to observe the change in LCOH. Negative prices are discussed and an electricity price limit is suggested to run the systems.
- *Savings:* The annual energy savings of each electrolyzer is calculated based on the curtailment hours of the state. The payback period, when NPV reaches zero, is calculated.

The next section follows the order of these scenarios, reporting the values and discussing them against each other.

3 Results and Discussions

Base scenarios

Levelized cost, net present value and internal rate of return calculations are performed for 2, 5, 10, and 20 MW capacity, and the results are given in Figure 1, 2 and 3 for 10, 15 and 20 years lifetime. LCOH decreases with a longer lifetime of the installation, but this decrease is not linear. The installation of 2 MW has an LCOH of below 5.5 EUR/kg, which is below the selling price of hydrogen even with the shortest lifetime.

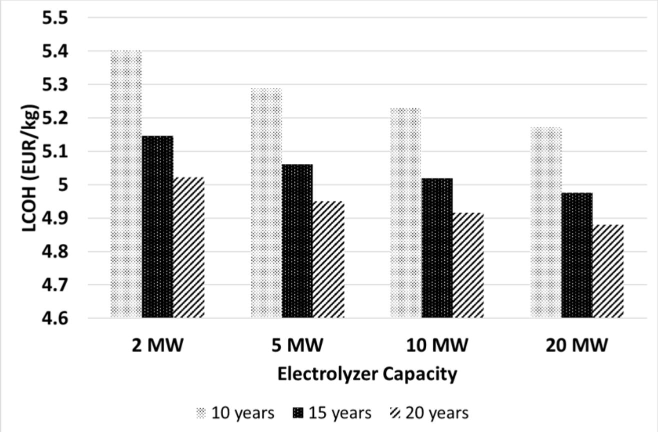

Figure 1. Levelized cost of the electrolyzers with respect to capacity and lifetime.

NPV increases with the electrolyzer lifetime, and similar to the LCOH decrease, this increasing trend is not linear.

IRR and NPV show the same trend as expected. The increasing capacity lowers the effect of a longer lifetime on the generated value. These values of LCOH, NPV, and IRR, calculated for 6000 h/y operating period and 6 ¢EUR/kWh electricity price, are taken as the base cases, and all the percentage calculations use these values.

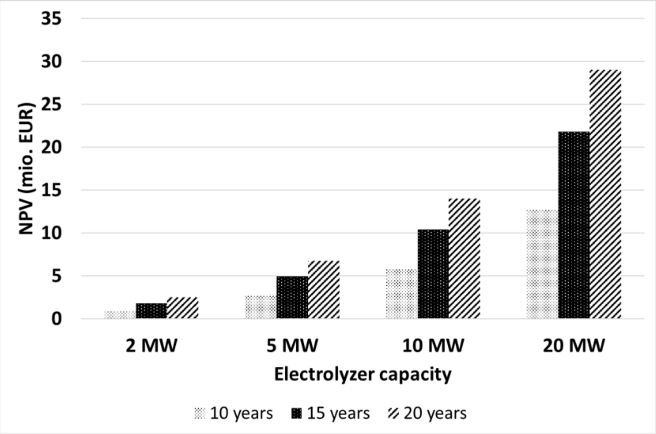

Figure 2. Net present value of the electrolyzers with respect to capacity and lifetime.

Additionally, these results show the low effect of the capacity on LCOH and IRR. The electrolyzer stacks can be installed as needed, as a bigger capacity brings only a slight LCOH improvement.

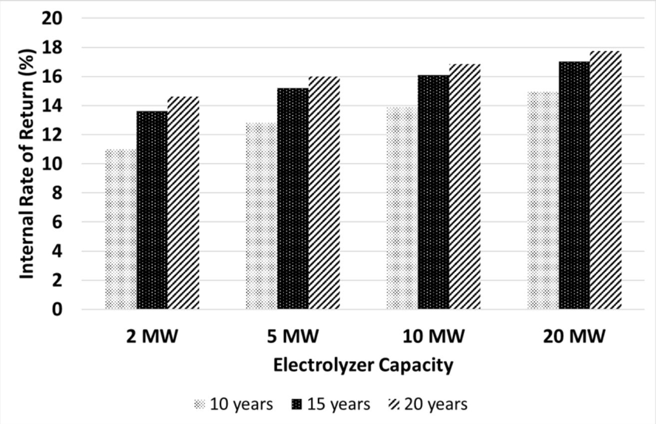

Figure 3. Internal rate of return of the electrolyzers with respect to capacity and lifetime.

The effect of expenses and product price on LCOH and NPV

PEM electrolysis is a hot research topic, and the ongoing scientific work increases the expectations of cost reduction. The sensitivity of LCOH is investigated based on expected technological improvements to decrease the CapEx, OpEx, maintenance cost, and electricity price. The decrease in the LCOH with a 10% decrease in each of these expenses is given in Figure 4 for all evaluated electrolyzer capacities. Electricity price change has the most significant effect on LCOH, followed by CapEx and maintenance, respectively. Therefore, it can be said that it is more critical to reach cheaper electricity compared to technological advances. The sensitivity of LCOH with respect to CapEx and maintenance slightly decreases with the increasing capacity. However, since the electricity consumption increases with the increased capacity, the higher capacity electrolyzer has a more sensitive LCOH to the electricity price.

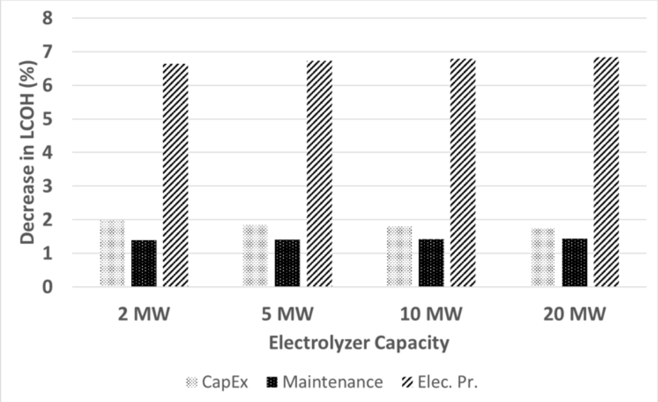

Figure 4. Decrease in LCOH with respect to 10% decrease in each expense type.

The sensitivity of NPV is also investigated concerning the same expenses. Additionally, NPV depends on the hydrogen selling price. Therefore, the effect of a 10% increase in the hydrogen selling price is also investigated. The results are given in Figure 5. For the 2 MW capacity, almost 65% increase is observed with a 10% increase in the hydrogen selling price. As all the expenses are lower for the small scale, the product creates more value. NPV becomes less sensitive to the product price with the increasing capacity, although this value is still the most important parameter. The expenses affect the NPV in the same order as they affect LCOH. However, the sensitivity decreases with the increasing capacity. Both LCOH and NPV used for the sensitivity analysis are for 20 years electrolyzer lifetime. Of course, a 10-year lifetime causes a higher dependency on the expenses.

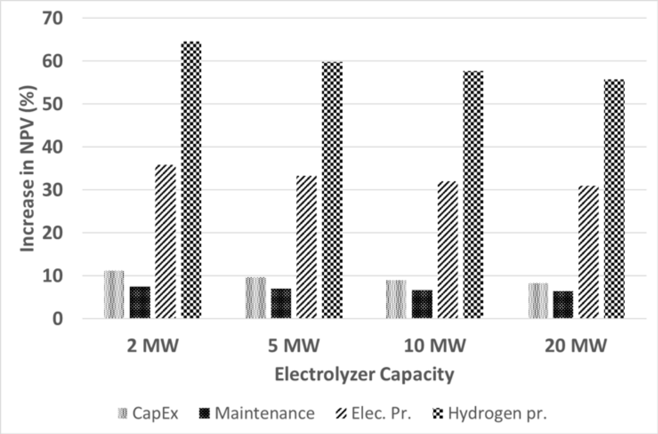

Figure 5. Increase in NPV with respect to 10% increase in hydrogen selling price and 10% decrease in each expense type.

The effect of runtime on LCOH

If the 2 MW electrolyzer runs less than 5000 hours a year, the production costs exceed the selling price of 6 EUR/kg, and the net present value after 20 years becomes negative. Of course, a higher-capacity electrolyzer can tolerate more extended downtime due to higher production. The change in the LCOH with respect to the runtime of the electrolyzer is given in Figure 6 for different capacities for 10, 15, and 20 years lifetime. The LCOH values are quite high for the low operating hours. However, in an average node in Schleswig - Holstein, 1443 hours of curtailment occurred in 2015 (Schermeyer et al., 2017). Considering that the electricity price will be zero (or lower) for these hours, LCOH will be affected by the annual curtailment events significantly.

Electricity price

The electricity price and lifetime – runtime analyses show the importance of when to run the electrolyzer decision. The electricity price has the highest effect on LCOH. Germany has relatively higher prices for small-scale industrial electricity; the highest value for the large-scale industry is around 14 ¢EUR/kWh (Schmitz et al., 2020). If the highest electricity price is considered, LCOH increases significantly. The LCOH values for the expensive electricity scenario are given next to the percent increase compared to the base case scenario in Table 3.

Table 3. LCOH for the high electricity price and percent increase from the base scenario.

10 years	*LCOH (EUR/kg)*	*% increase*
2 MW	9.8	82.28
5 MW	9.7	84.05
10 MW	9.6	84.97
20 MW	9.6	85.91
15 years	*LCOH (EUR/kg)*	*% increase*
2 MW	9.5	86.37
5 MW	9.5	87.82
10 MW	9.4	88.56
20 MW	9.4	89.32
20 years	*LCOH (EUR/kg)*	*% increase*
2 MW	9.4	88.5
5 MW	9.3	89.77
10 MW	9.3	90.41
20 MW	9.3	91.07

On the other hand, average electricity prices can be misleading. In 2020, electricity price was below zero for 298 hours, and from February to May, the price range was generally 0 – 3 ¢EUR/kWh (Kern, 2021). If the selling price is kept constant, up to 8 ¢EUR/kWh, a feasible operation is possible. As the selected PEM electrolyzer has a fast startup, 15-minute prices of the power market can be used for

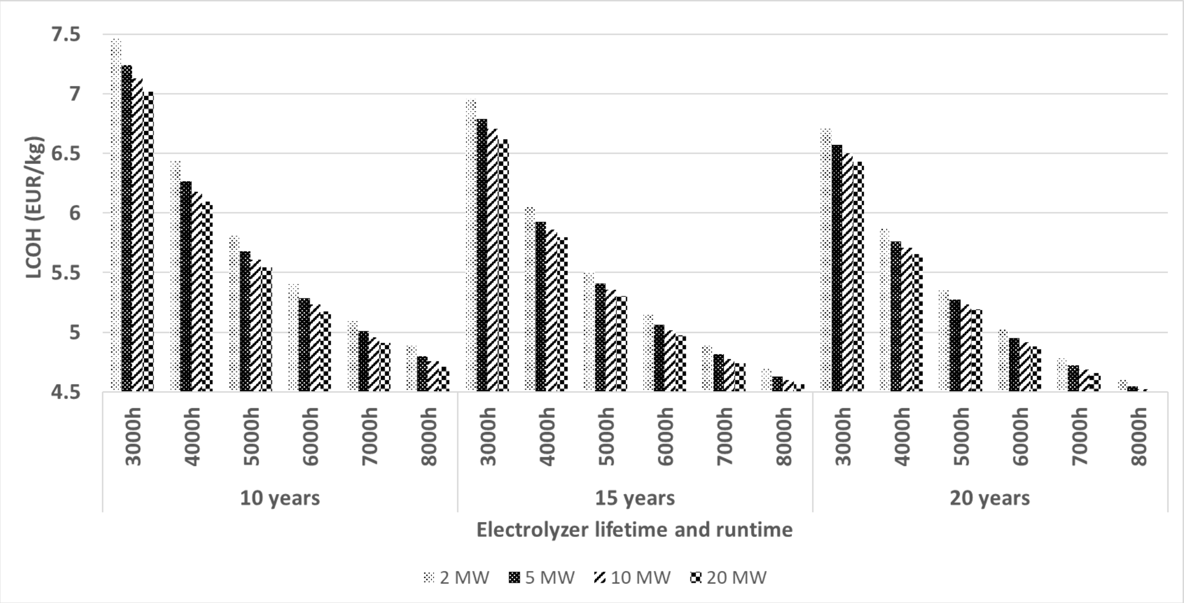

Figure 6. Change of LCOH for changing running hours of electrolyzers.

this decision, rather than a fixed average price.

Savings

If the electrolyzer of 2 MW capacity ran on the curtailment hours (1443 h/y), 2.31 GWh energy would have been saved if the conversion efficiency is 80 %. For the 5, 10, and 20 MW electrolyzers, energy savings would be 5.77, 11.5, and 23.1 GWh, respectively. Additionally, the transmission system operators could reduce the feed-in management costs by a rate of 101 EUR/MWh (Bundesnetzagentur, 2016). The cost reduction for each electrolyzer capacity is given in Table 4.

Table 4. Feed-in management cost reduction by the electrolyzer capacity.

Capacity (MW)	2	5	10	20
Cost reduction (Mio. EUR)	0.23	0.58	1.16	2.34
% of CapEx	8.21	8.92	9.28	9.75

Thanks to the German Renewable Energy Sources Act (EEG), many renewable energy producers have a guaranteed selling price (BGBI. I S. 1066, 2014). It should be noted that part of the grid management savings might be shifted to the EEG surcharge (EEG-Umlage) due to the difference between the guaranteed price and the market price. This difference might be high, considered that the curtailment events mainly occur when there is a high renewable share in the grid.

For this study, an average value of 6 EUR/kg is taken as the selling price of hydrogen. There are studies taking higher and lower values (Song and Ozkan, 2010; Dufo-López et al., 2009). The price range of gray hydrogen is much lower, around 1.8 EUR/kg (Salkuyeh et al., 2018). An effort from governments to use a mixed hydrogen stream can make the high price range justifiable. Thanks to a similar effort, market diesel is a mix of petro-diesel and bio-diesel in Germany as in many other countries (BGBI. I S. 590, 1318, 2016). The investment might be feasible when the savings' rate to CapEx and feed-in management costs, given in Table 4, are also considered. These values show the economic potential of the electrolyzer from different perspectives. If the transmission system operators can cut grid management costs, the business case will be less dependent on the hydrogen selling price.

Water electrolysis produces high purity oxygen gas next to hydrogen. As it is not relevant to the energy calculations, the monetary value of this side product is not considered for this work. However, selling high purity oxygen can bring additional value.

4 Conclusions

The state of Schleswig – Holstein has high grid management expenses due to the high share of wind power generation. Four different capacities for PEM electrolysis are investigated for this state to save energy and cut expenses. LCOH and NPV are calculated for economic assessment, and how these values change according to CapEx, maintenance, and electricity expenses are shown. Their trend shows the importance of cheap electricity. CapEx and maintenance costs affect the LCOH much less than the electricity price. The feasibility is found highly dependent also on the hydrogen selling price. However, the possible grid management cost reduction of up to 9% of the CapEx can lower its effect. Internal rate of return values are found satisfactory, ranging between 14 - 17 % for the 20-year lifetime electrolyzers. With its possible product utilization alternatives of electricity generation, heat generation, and chemical feedstock, electrolysis is a substantial investment candidate to gain grid flexibility. Future work can focus on the comparison of different alternatives to cut grid management costs of this state. Additionally, instead of selling the produced hydrogen to process industries, different scenarios for converting it back to electricity can be considered.

References

Ausilio Bauen, Niccolò Bitossi, Lizzie German, Anisha Harris, and Khangzhen Leow. Sustainable aviation fuels: Status, challenges and prospects of drop-in liquid fuels, hydrogen and electrification in aviation. *Johnson Matthey Technology Review*, 64(3):263–278, 2020.

Peter Bencs, Mohammed Al-Ktranee, and Károly Marcell Mészáros. Effects of solar panels on electrical networks. *Analecta Technica Szegedinensia*, 14(1):50–60, 2020.

BGBI. I S. 1066. Gesetz für den ausbau erneuerbarer energien, 2014. `http://www.gesetze-im-internet.de/eeg_2014/EEG_2021.pdf` Accessed on 15.06.2021.

BGBI. I S. 590, 1318. Verordnung zur durchführung der regelungen der biokraftstoffquote, 2016. `http://www.gesetze-im-internet.de/bimschv_36/36._BImSchV.pdf` Accessed on 15.06.2021.

Bundesnetzagentur. Quartalsbericht zu Netz- und Systemsicherheitsmassnahmen. Technical report, Arbeitsgruppe Energie-Monitoring, 2016.

Roberto Carapellucci and Lorena Giordano. Steam, dry and autothermal methane reforming for hydrogen production: A thermodynamic equilibrium analysis. *Journal of Power Sources*, 469:228391, 2020.

E Cetinkaya, I Dincer, and GF Naterer. Life cycle assessment of various hydrogen production methods. *International journal of hydrogen energy*, 37(3):2071–2080, 2012.

Rodolfo Dufo-López, José L Bernal-Agustín, and Franklin Mendoza. Design and economical analysis of hybrid pv–wind systems connected to the grid for the intermittent production of hydrogen. *Energy Policy*, 37(8):3082–3095, 2009.

Dolf Gielen, Deger Saygin, Emanuele Taibi, and Jean-Pierre Birat. Renewables-based decarbonization and relocation of iron and steel making: A case study. *Journal of Industrial Ecology*, 24(5):1113–1125, 2020.

SA Grigoriev, VN Fateev, DG Bessarabov, and P Millet. Current status, research trends, and challenges in water electrolysis science and technology. *International Journal of Hydrogen Energy*, 45(49):26036–26058, 2020.

Fabian Hinz, Matthew Schmidt, and Dominik Möst. Regional distribution effects of different electricity network tariff designs with a distributed generation structure: The case of germany. *Energy Policy*, 113:97–111, 2018.

Timo Kern. Deutsche strompreise an der börse epex spot in 2020. Technical report, Forschungsgesellschaft fuer Energiewirtschaft mBH, 2021.

Hyunjun Lee, Boreum Lee, Manhee Byun, and Hankwon Lim. Economic and environmental analysis for pem water electrolysis based on replacement moment and renewable electricity resources. *Energy Conversion and Management*, 224:113477, 2020.

Libin Lei, Jihao Zhang, Zhihao Yuan, Jianping Liu, Meng Ni, and Fanglin Chen. Progress report on proton conducting solid oxide electrolysis cells. *Advanced Functional Materials*, 29 (37):1903805, 2019.

Norbert Lümmen, Assma Karouach, and Stine Tveitan. Thermo-economic study of waste heat recovery from condensing steam for hydrogen production by pem electrolysis. *Energy Conversion and Management*, 185:21–34, 2019.

Md Maruf and Nasimul Islam. A novel method for analyzing highly renewable and sector-coupled subnational energy systems—case study of schleswig-holstein. *Sustainability*, 13 (7):3852, 2021.

M Minutillo, A Perna, A Forcina, S Di Micco, and E Jannelli. Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the italian scenario. *International Journal of Hydrogen Energy*, 46(26):13667–13677, 2021.

A Nicita, G Maggio, APF Andaloro, and G Squadrito. Green hydrogen as feedstock: Financial analysis of a photovoltaic-powered electrolysis plant. *International Journal of Hydrogen Energy*, 45(20):11395–11408, 2020.

Nina Posdziech. Schleswig-holstein's first hydrogen filling station opens in handewitt, 2019. Retrieved 09.09.2021 from `https://www.now-gmbh.de/en/news/pressreleases/schleswig-holsteins-first-hydrogen-filling-station-opens-in-handewitt/`.

Oliver Posdziech, Konstantin Schwarze, and Jörg Brabandt. Efficient hydrogen production for industry and electricity storage via high-temperature electrolysis. *International Journal of Hydrogen Energy*, 44(35):19089–19101, 2019.

Sayed M Saba, Martin Müller, Martin Robinius, and Detlef Stolten. The investment costs of electrolysis–a comparison of cost studies from the past 30 years. *International journal of hydrogen energy*, 43(3):1209–1223, 2018.

Yaser Khojasteh Salkuyeh, Bradley A Saville, and Heather L MacLean. Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. *International Journal of Hydrogen Energy*, 43(20):9514–9528, 2018.

Hans Schermeyer, Michael Studer, Manuel Ruppert, and Wolf Fichtner. Understanding distribution grid congestion caused by electricity generation from renewables. In *Smart Energy Research. At the Crossroads of Engineering, Economics, and Computer Science*, pages 78–89. Springer, 2017.

Joachim Schmitz, Sonja Rinne, and Sebastian Pieper. Strompreise: Neue wege bei der finanzierung. Technical report, Bundesministerium fur Wirtschaft un Energie, 2020.

Hua Song and Umit S Ozkan. Economic analysis of hydrogen production through a bio-ethanol steam reforming process: Sensitivity analyses and cost estimations. *International journal of hydrogen energy*, 35(1):127–134, 2010.

Øystein Ulleberg and Ragnhild Hancke. Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in norway. *international journal of hydrogen energy*, 45(2):1201–1211, 2020.

DOI: 10.3384/ecp21185234