Is Power to Hydrogen an appropriate approach to mitigate PV-induced strain on 110 kV high-voltage grids?

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Abstract

Within this work, we investigate how the PV-induced strain of rural 110 kV power-grids can be relieved through hydrogen production via electrolysis. Therefore, we simulate a PEM-electrolyzer in the vicinity of large PV-plants and vary its capacity. The produced hydrogen is subsequently transported to the high-level gas-grid. Due to gas-grid standards, a maximum H_2 concentration of 10 Vol% is allowed. However, due to its high capacity, the gas-grid can incorporate H_2 from PV-power generation, even in time frames when the 110 kV grid is not able to do so. In the work, we perform a techno-economic analysis on this H_2-based grid congestion mitigation approach. Therefore, we gathered cost information for the PEM, the balance-of-plant components of the H_2 sub-system as well as for the H_2-pipeline from scientific literature, considering future-prices for 2025. Our results show that site-dependent leveraging effects occur. This means that with the installation of an electrolyzer with a certain capacity, up to 7.5-times higher PV-capacities can be installed without grid-congestions. Smaller electrolyzer installations turned out to be more efficient. The cost perspective shows that the investment costs for the H_2-based grid congestion mitigation approach evolve to be in the same order of magnitude as for classical grid-reinforcement.

1 Introduction

2019, around three-quarters of the newly installed worldwide electricity generation capacity, was from renewables. PV-power accounted for 55 %. [1] This trend can also be seen in the Austrian electricity grids: The DSO Energienetze Steiermark GmbH, for instance, faces recent installation requests for large free-space PV-plants. Since those plants should be built mainly in a region with low population density, only a minor share of the energy from them can be consumed locally. Especially in time frames with high solar irradiation, power-flows towards the TSO (380 kV) / DSO (110 kV) interface occur, leading to significant grid-strain in the high-voltage (110 kV) grid: Since the affected 110 kV grid was originally intended only to supply a rural region, the applied line cross-sections are by far not sufficient to carry the PV-induced power-flows without overloads. To avoid grid congestions, the classical mitigation approach is grid expansion and grid reinforcement, respectively. Within this work, we introduce and investigate a novel approach to avoid power grid overloads through PEM-electrolysis-based hydrogen production in the vicinity of the large PV installations. The produced hydrogen is injected into the high-level gas grid.

1.1 State of Research

Hydrogen production via RES-powered electrolysis is one of the most cited recent research topics. It allows for the cross-sectoral use of RES-power and enables the high capacities of the gas infrastructure as seasonal power storage.

Recent literature deals often with the economics of Power to Hydrogen installation. Investigations on the economy of scale, cost-down curves, or the influence of fluctuations in electricity prices point out that Power-to-Hydrogen is already economically feasible for niche applications but not for mass-use (c.f. [4,5]). Another broadly investigated topic is the operation- and design optimization of single Power to Hydrogen facilities with and without storage-units [8]. Korpas et al [6] use generation forecasts and receding horizons to optimize the electrolyzer operation on day-ahead markets. Pan et al [7] for instance combine stochastic- and robust optimization methods to develop plant-designs to cope with the uncertain seasonal fluctuations of both demand and generation. Also, the implantation of power to hydrogen into larger energy systems is a matter of scientific discussions. Welder et al [9] for instance investigate how Power-to-hydrogen can be implemented into the German energy system. On a multi-node approach, they develop a cost-optimal design, using the produced hydrogen for industrial- and mobility purposes. However, the influence on grid congestions is not addressed. This point addresses Clegg and Mancarella [15], based on a simplified gas- and power grid of Great-Britain. Due to this simplification, the impact on real-life grids can only be estimated.

1.2 Research Questions and Structure of the work

Concerning the avoidance of grid strain through Power to Gas, to the best of our knowledge, the following research questions remain open:

1. How much additional PV-power can be installed in real-life 110 kV grids without grid-congestion in dependency of
   a. PEM power?
   b. PEM location?
   c. PEM operation strategy?
2. How is the investment cost situation in comparison to classical grid-reinforcement?
3. What Levelized-Cost-of-Hydrogen ($LCOH_2$) can be achieved in dependency of full-load hours, electricity prices, and heat sales revenues?

To answer those questions, we have structured our paper as followed: In Section 2 we firstly describe the applied methodology for modeling and assessment. Secondly, section 3 deals with the investigated case-study: After the introduction into the problem at hand, we present technical results as PEM full-load hours, PV-to-PEM-power ratios, etc. as well as economic results as investment-costs or Levelized-costs-of-hydrogen and discuss them. In section 4, finally, we conclude our work.

2. Methodology

2.1 Multi-Energy-System Modeling in HyFlow

For all simulations, we apply the in-house developed software package "HyFlow" [2,3]. "HyFlow" allows for power-flow calculations not only in the electricity- or gas-grid but cross energy-carrier power-flow calculations, respectively. For cross-energy-carrier transports, coupling elements are applied. In this work, we use therefore an element representing a PEM electrolyzer with an energetic conversion efficiency η_{PEM} of 75 % [13-14].

2.2 Economic Assessment

For economic assessment we apply classic Levelized-cost calculations according to Short et al [11], taking into account specific CAPEX and OPEX as well as costs for electricity. The latter include energy costs of 3 ct/kWh as well as grid-service charges of 1,15 ct/kWh. For the specific CAPEX and OPEX of the most relevant components, we applied the values from Table 1 [13-16], which assume the cost-situation in 2025.

Table 1: Specific CAPEX and OPEX

Component	CAPEX	OPEX
PEM	800 €/kW_{el}	3 %/a CAPEX
H_2 Pipeline	500 €/m	1 €/(m· a)
H_2 Compressor	1500 €/kW_{el}	2,5 %/a CAPEX

In the Levelized-cost of hydrogen ($LCOH_2$) calculation, the PEM and the hydrogen compressor are depreciated over 12 years, the hydrogen pipeline over 30 years. Therefore we apply a discount factor of 4 %.

3 Case-study

3.1 Description of the investigated case-study

Figure 1 depicts the grid area under investigation. It comprises a rural 110 kV grid system, with a ring-network structure. The grid is designed to transport power from a higher-level 380 kV system to customers distributed over the area, with a relatively low power demand in total. In the investigated area, PV installation requests with a total capacity of more than 600 MW exist. The substations (SS) LF (184 MW), BH (191 MW), and OG (182 MW) are the most affected.

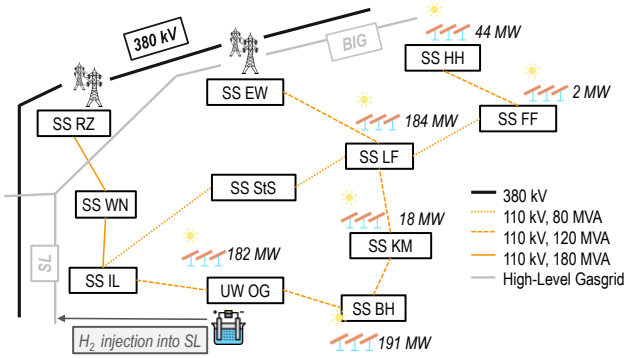

Figure: 1 grid-area under investigation

To investigate the influence of Power-to-Hydrogen on the relief of grid overloads, we simulate a PEM electrolyzer in the substation OG and vary its capacity from 17,5 MW to 227 MW. The produced hydrogen is transported from the substation OG toward the high-level natural gas pipeline SL and injected directly. In the high-level gas grid, we assume a maximum H_2-concentration of 10 Vol% [12]. Taking into consideration a minimum natural gas volume flow in the pipeline SL of around 100.000 Nm³/hr (e.g. Figure 2) leads to a maximum hydrogen injection capacity of around 40 MW. With the given efficiency (75 %) a maximum PEM capacity of 53 MW occurs. However, applying a hydrogen-storage allows for higher PEM capacities.

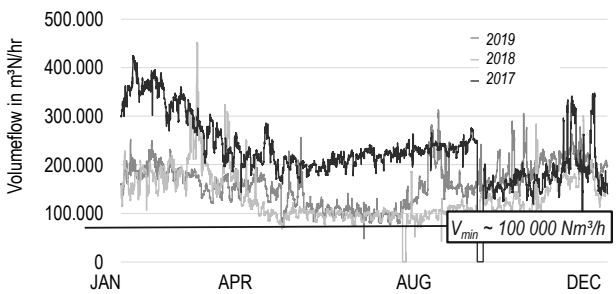

Figure 2: time-resolved natural-gas volume flow in the high-level gas pipeline SL

In our study, we control the PEM electrolyzer in substation OG based on the residual-load P_{res} (e.g. Equation 1).

$$P_{res}(t) = P_{Load}(t) - P_{PV}(t) \quad (1)$$

Two operation strategies are applied: In operation strategy 1 we consider the residual-load of the overall area under investigation. If the residual-load P_{res} turns negative, meaning that the PV-production exceeds the electricity demand in the area under investigation, the electrolyzer turns on. Otherwise, the electrolyzer remains off. Operation strategy 2 is similar but considers for turning the PEM on- and off, only the residual-load of the sub-stations OG and BH.

3.2 Results and discussion

Figure 3 shows the maximum deployable PV capacity per substation. Without any measures to reduce strain, the existing grid bears around 200 MW of PV installations. With a 17,5 MW PEM installed in the substation OG, the maximum PV installations increase up to around 320 MW, mainly due to additional PV plants feeding power into the substations in close vicinity of the PEM-site (Substation OG and BH). Higher PEM capacities continue this trend till a PEM with a capacity of 52,5 MW produces as much hydrogen to reach the 10 Vol% H_2-limit of the pipeline SL. Compared to the 17,5 MW PEM only sightly higher PV power can be integrated. With a PEM power of 227 MW, the maximum electrolyzer-induced grid-relieve is reached, allowing for around 500 MW of PV. Any further PEM- or PV capacity increase leads to congestions somewhere in the power-grid. Even in that case, the remote substations LF and HH, which face also huge PV requests, are only rarely relieved.

The reason for this effect is that the grid capacity is not sufficient to cover the additional load-flow to transport energy from those substations to the substation OG. It also needs to be mentioned, that this case makes huge hydrogen storage capacities necessary.

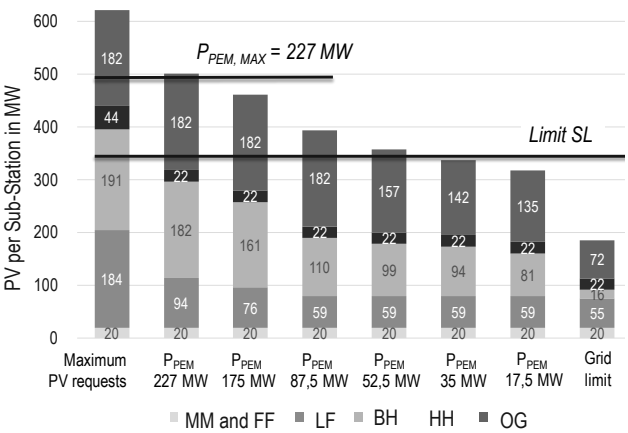

Figure 3: Maximum PV-installations per substation (SS) in dependency of the PEM capacity in substation OG

However, the operation-strategy influences the maximum deployable PV capacity only minor. The main influence of the operation strategy is on the PEM electrolyzer's full-load hours of operation (e.g. Eq.2). Figure 4 discusses this for the investigated PEM capacities is substation OG:

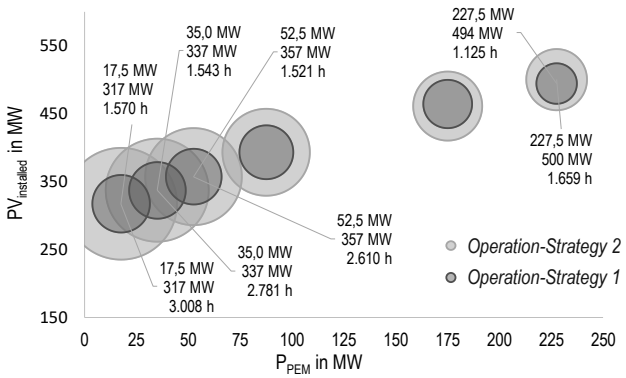

Figure 4: Influence of the operational strategy on the PEM's full-load hours.

Operation strategy 2 that takes into account only the residual-load of the substations OG and BH, leads to significantly higher full-load hours. The effect increases for smaller PEM capacities: With a 17,5 MW PEM, operation strategy 1 leads only to half of the full-load hours of operation strategy 2. With a 227 MW PEM, the difference between the operation strategies is only around 30 %.

The reason for this behavior is that with the consideration of a smaller spatial area in operation strategy 2, negative residual-loads occur more often. Consequently, the electrolyzer turns on more frequently.

$$full\ load\ hours, PEM = \frac{W_{res,neg.}}{P_{PEM}} \quad (2)$$

The PEM full-load hours follow Equation 2. If we compare the influence of the operating strategy as a function of the PEM power, we see that at higher PEM capacities P_{PEM} in operating mode 2, the increase in PV-induced negative residual energy $W_{res,\ neg}$ no longer occurs to the same extent as at lower PEM powers. This explains the above-mentioned large influence of the operating strategy, especially at low PEM capacities.

Table 2 compares results for 17,5 MW and 52,5 MW PEM installations. Detailed data on additional PV-Power, which means the difference between the existing grid-limit and the maximum possible PV-power with PEM grid-relief, is given. Also, full-load hours of the PEM, PEM electricity demand, amounts of hydrogen production, and maximum amount of heat recovery are shown. The ratio between PEM capacity and additional PV Power turns out to be especially interesting: The ratio is around 3,3 for a

52,5 MW PEM. With a small PEM installation of 17,5 MW, the factor rises to around 7,5 whereas a PEM with 227 MW only allows for 1,4 times more additional PV power. These results, together with the rising full-load hours facilitate the message, that smaller PEM capacities turn out to be more beneficial.

Table 2: detailed operational data for 17,5 MW and 52,5 MW PEM installations

P_{PEM}	17,5 MW	52,5 MW
Add. PV-Power	132 MW	172 MW
Full-Load hours PEM Operation Strategy 2	3.008 h	2.598 h
Electr. Demand PEM Operation Strategy 2	52,7 GWh	136,4 GWh
Produced H_2 $\eta_{PEM} = 0,75$	1002 t/a ≙ 39,5 GWh	2608 t/a ≙ 102,3 GWh
Max. heat recovery Low-temp. Heat, 65°C $\eta_{PEM,Heat} = 0,2$	Up to 10,5 GWh	Up to 27,3 GWh

The 52,5 MW PEM allows for up to 27,3 GWh, the 17,5 MW PEM for up to 10,5 GWh of possible heat-use. Since the PEM operates at low temperatures, appropriate heat-consumer must be taken into account. Due to the temperature level of 65 °C, modern low-temperature district heating systems may be suitable. Taking into account an average heat-demand of 10 MWh/a for a single-family household, the 52,5 MW plant can supply around 2730 units, the 17,5 MW plant around 1050 units respectively. Especially the latter seems to be possible, concerning the settlement structure in the vicinity of the PEM-site. However, the presented numbers take only into account energetic heat potentials and –demands. The time- and power-difference between them make further investigations necessary.

Besides the technical analysis shown, our work presents results from economic investigations on the task at hand. Firstly, table 3 shows the investment costs for PEM-electrolyzer sites from 17,5- to 52,5 MW. Whereas the PEM investment scales linearly with the plant capacity, the compressor- and the hydrogen pipeline cost are independent of power and stay constant. The total investment costs range from 21,7- to 55,1 Mio. €. With rising PEM-capacity, the investment-share for the PEM increases relative to the shares of compressor and pipeline. If one compares the determined total costs with the costs for conventional grid expansion to integrate the respective PV power (Table 2: from 132- to 172 MW), one can conclude that they are in a similar range.

Table 3 shows, secondly, the Levelized-costs of Hydrogen ($LOCH_2$). Thereby the specific-electricity-costs (3 ct/kWh) lead to specific-energy-costs for hydrogen production of around 5,5 c/kWh_{H2}. These costs are independent of the PEM capacity. They dominate the full-load-hours independent costs (spec.-OPEX + spec.-energy-costs), since the specific-OPEX are low.
The specific-CAPEX ranges from 5,1- to 5,32 ct/kWh_{H2}. As explained previously, for smaller PEM-capacities, the full-load-hours increase. Generally, this leads to declining specific-CAPEX. Here the constant absolute-costs for compressor and pipeline overlay this effect, that only minor CAPEX differences in the investigated PEM-power range occur.

Table 3: Investment-costs and $LCOH_2$

	17,5 MW	35 MW	52,5 MW
PEM in M€	14	28	42
H_2-pipeline in M€	5,5	5,5	5,5
H_2-compressor in M€	0,645	0,645	0,645
Total Invest in M€	21,7	37,1	55,1
spec. CAPEX in ct/kWh_{H2}	5,1	5,03	5,32
spec. OPEX in ct/kWh_{H2}	1,16	1,20	1,32
spec. Energy-costs in ct/kWh_{H2}	5,53	5,53	5,53
$LCOH_2$ in ct/kWh_{H2}	11,79	11,76	12,17

One can conclude that for the investigated PEM-capacity classes, the $LOCH_2$ varies only in a small range. The statement from the technical analysis that smaller PEM sizes are preferable is no longer valid without further ado. However, PEM-capacities higher than 52 MW are economically not preferential either since they require cost-intensive hydrogen storage due to gas grid limits.

4 Conclusion and Outlook

To mitigate PV-induced strain on 110 kV power-grids, PEM-based Power-to-Hydrogen seems to be an appropriate future option. In our work, we show that PEM installations with low capacity allow for the grid-integration of huge PV-plants. Such PEM installations reduce strain in power-grid lines in the vicinity of the site. Remote substations and lines are hardly affected. The

effect does not change substantially, even integrating large PEM units. That leads to the conclusion that the site of the PEM electrolyzer is crucial. Maximum grid relief may be achieved with more than one smaller-scale PEM installation in dedicated substations near the natural-gas grid. However, in this study, we have not investigated multi-PEM installations. That should be the subject of future works.

We show that the investment-costs for PEM installations of appropriate size are in a similar range compared to costs for conventional grid re-enforcement. Combined with the operational-costs and the costs for electricity, we could demonstrate Levelized-costs-of-hydrogen between 11-and 12 ct/kWh. This corresponds to current literature values. The operation strategy influences the full-load hours of the PEM electrolyzer at its most. Rising full-load hours lead to reduced specific-capital-cost. We show that grid-serving operation-strategies which involve the residual-load of a larger area lead to good results. However, upcoming works should investigate operation-strategies that combine grid-serving operation with approaches taking into account current exchange prices. This offers the potential to reduce both specific-capital-costs and specific-energy-costs and thus contributes to future hydrogen integration

5 Acknowledgements

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