Grid-supportive electrolysis in distribution grids: techno-economic and regulatory analysis for Austria

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Abstract

Background: Strong expansion of intermittent renewable generation puts increasing pressure on distribution grids and requires significant grid enforcement measures. Electrolysis may act as an alternative to conventional grid enforcement to overcome grid constraints in a timely and effective manner as it creates additional flexible load and thus enables renewable production peaks to be absorbed. In doing this, conventional grid enforcement measures are avoided and additional value is created through the production of hydrogen.
The focus of this work is on two aspects: First, a regulatory analysis is undertaken to develop feasible organisational models since DSOs are typically not allowed to engage in generation activities. Second, a techno-economic analysis is done for four case studies in the network area of 'Energienetze Steiermark' in Austria. Thereby, grid simulation determines the minimum grid-supportive operation and is combined afterwords with profit-maximising dispatch of the electrolysis against market prices. A technical simulation assures that non-linearities and minimum stable generation of the electrolysis are respected. In a cost-benefit analysis, the net benefit was compared against the costs of conventional grid enforcement measures.
Results: The regulatory analysis reveals that ownership of electrolysis by DSOs is almost ruled out by European and Austrian legislation. Only after an exceptional permission from the regulatory authority following a negative tender, the DSO is allowed to operate the facility in a grid-supportive way only. The results of the techno-economic analysis show that the capacity factor for the electrolysis is below 5 % when operated in grid-supportive mode only but a hydrogen price above 6 EUR/kg incentivizes market based operation and contributes to resolving the grid congestion.
Conclusions: Ownership of the electrolysis can be awarded to a market player and the flexibility service can be procured by the DSO. It is not economically viable to operate electrolysis for grid-supportive purposes only. In general, if the price of hydrogen is high enough, profit maximising behavior of the electrolysis partly resolves the grid congestion and the overall benefits outweigh the

costs. This conclusion also holds when comparing the economic results of the electrolyzer against conventional grid enforcement measures.

Keywords: Electrolysis, Distribution grid, Hydrogen, Grid-supportive operation

1 Introduction

The Austrian government has set the ambitious goal of covering 100 % of electricity demand via renewable sources by 2030 [1] and achieve climate neutrality by 2040 [2]. This massive deployment of renewable electricity generation technologies requires significant electricity grid expansion and enforcement measures to enable the system integration of these capacities. Moreover, a high share of distributed and intermittent renewable generation implies a high temporal and geographical mismatch of demand and supply, which will need to be solved through flexibility. In this respect, deployment of electrolysis could create additional value in many different aspects: It would cover the need for flexibility, avoid grid-enforcement measures and also ensure energy resilience by enabling local hydrogen production [3]. On the last point, it is undisputed that renewable hydrogen will play a significant role in a decarbonized energy system [4].

However, there are some challenges to this consideration: The first one is regulatory since grid operators are, broadly speaking, not allowed to own and operate storage or generation assets. Secondly, it is unclear whether electrolysis can act as an efficient measure to overcome congestion in the distribution grid in a techno-economic sense.

1.1 Aim and outline

This work focuses on these two aspects: First, the regulatory aspect is analysed on the basis of the new draft of the Austrian Electricity Act [5]. Electrolysis according to the law is understood as 'energy storage facility' and only few exemptions for distribution system operators (DSOs) to own and operate energy storage facilities are given. However, it is not yet clear whether these exemptions can be put into practice and how the organizational model behind this operation could look like. To solve congestion in the distribution grid, it is likely that a combination of market based and grid-supportive operation is required to find synergies between technical and economic interests, but the current regulatory setting makes it very hard to mobilize the synergies between technical and economic purposes. In this work, the feasible synergies are explored from a regulatory as well as techno-economic point of view.

Second, we investigate the techno-economic aspects of electrolysis in distribution grids. On the basis of four case studies in Styria, Austria, selected within the network area of the DSO 'Energienetze Steiermark', it is examined whether electrolysis can effectively solve grid congestion and whether it might be a more cost-efficient solution compared to conventional grid enforcement. We use detailed grid simulation in PowerFactory (described in 2.2.2) to model the actual power flows, identify overloaded network components, determine the electrolyzer nominal power and minimal grid-supportive behavior to avoid curtailment of renewable energy sources (RES). In a next step, the market based operation (described in 2.2.4) is determined through optimal behavior of the electrolysis against historical electricity price data (2023, Austria) and hypothetical prices for hydrogen. A technical simulation (described in 2.2.3) then assures a correct representation of non-linear efficiencies and minimum-stable generation of the electrolysis. Finally, the results are evaluated in a cost-benefit analysis (described in 2.2.5) and compared against the cost of conventional grid expansion.

1.2 Literature review

There are a couple of studies that investigate the operation of electrolysis in relation to the electricity grid. For example, [6] looks at the provision of primary balancing reserve in Belgium by 25 MW electrolyzer. In the work of [7], the concept of hydrogen supply chains in the context of electricity distribution grids is analyzed in the literature through a text-mining approach and finds that hydrogen production is not yet linked to solving problems arising in the electricity network. Within the H2Future project[1], a use-case for the installed demo plant (6 MW) was to test the suitability of the PEM electrolysis system to participate on the balancing markets by the provision of system services. Additionally, [8] investigated the potential of Pressurized Alkaline Electrolyzer technology for the provision of grid services based on the assessment of a 3.2 MW demo plant.

Another analysis focusing on techno-economic valuation of electrolysis with regards to balancing energy is provided by [9]. The work basically concludes that revenues from balancing services are not sufficiently attractive for an electrolyzer to be profitable. While our work focuses on electrolysis being installed to avoid overloading of grid components, one could also look at the opposite direction and check, whether electrolysis causes grid congestion on the other hand. For example, the work of [10] finds that the integration of hydrogen under the current pricing scheme may lead to higher congestion costs in Germany. Similarly, [11] use a high resolution grid optimization model and scheduling for alkaline water electrolysis to study the (high-voltage) grid impacts in Northern Germany.

Unlike the previously mentioned studies, which primarily focus on the role of electrolysis in providing balancing services or its impact on grid congestion, our work uniquely combines a regulatory analysis with a detailed techno-economic evaluation of electrolysis as a grid congestion management measure in distribution grids, based on a real-world case study. This represents a significant contribution to the current state-of-the-art.

2 Methods and data

As a first step, the regulatory analysis was undertaken to find regulatory feasible organizational models for electrolysis in distribution grids. This is done on the basis of the most recent public draft of the new electricity act in Austria 'ElWG-draft' [5].

In a second step, the techno-economic modeling was undertaken, which is in turn structured in four main steps. First, the grid is simulated with PowerFactory to determine the grid-supportive behavior and the size of the power to gas (P2G)

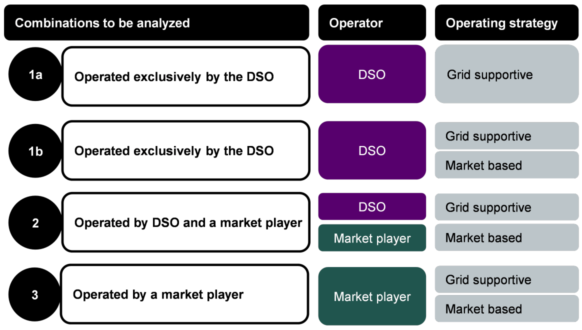

Fig. 1 Operating modes and operators/owners

system. In a second step, the market based operation maximizes profits based on market signals. This is actually done simultaneously with the third step, the technical simulation, to determine the technically correct operation considering non-linear efficiencies and the minimum stable load of the electrolyzer system. In a forth step, an economic valuation is undertaken to account for costs and revenues resulting from ownership and operation of the electrolyzer.

2.1 Regulatory analysis

The regulatory analysis is structured in three steps. The first step consists of defining potential combinations of operating strategies (grid-supportive or market based) and operators (market player or DSO). Second, options on the ownership of the electrolyzer are defined. Third, the regulatory feasibility of combinations is assessed in the results section 3.1.

2.1.1 Operating strategies and operators

Figure 1 illustrates four combinations of operating strategies and operators that are conceivable. In this case, no legal assessment is done, it is just an illustration of potential combinations of operating strategies and operators. A regulatory assessment follows in 3.1. In all variants, no assumption is made on the ownership of the plant, just the operation is considered. We consider only variants, where grid-supportive operation is included, therefore, a combination where the plant is only operated market based is not considered.

[1] https://www.h2future-project.eu/en

Combination 1a: Operated by the DSO, only grid-supportive

This variant consists of grid-supportive operation only to compensate RES-peaks. The plant is operated by the DSO.

Combination 1b: Operated by the DSO, grid-supportive and market based

This variant consists of grid-supportive operation to compensate RES-peaks as well as market based operation depending on electricity/hydrogen prices. Both is done by the DSO.

Combination 2: Operated by DSO and a market player

This variant consists of grid-supportive operation to compensate RES-peaks, operated by the DSO, while market based operation is done by a market player. In this case, the costs and revenues of the respective operating strategy need to be comprehensible and assignable to the respective operator.

Combination 3: Operated by a market player

This variant consists of grid-supportive operation to compensate RES-peaks and market based operation conducted by a market player. Costs and revenues of the respective operating strategy need to be comprehensible and assignable, as the DSO will need to compensate the market player for potential losses arising from grid-supportive operation.

2.1.2 Ownership of the electrolyzer

In the regulation, electrolysis can be attributed to the category 'energy storage facility'. According to § 72 and § 73 ElWG, there are two options, in which the DSO is allowed to be the owner of an electrolyzer: Either through direct approval by the regulator (denoted as 'Deployment 1') or a negative tender result (denoted as 'Deployment 2'). In this option, the ownership of the plant should be awarded to a market player through a tender in the first place. In case this tender fails, this gives room for ownership by the DSO. In addition, there is an option for flexibility procurement ('Procurement 1') which would be achieved when the tender result is positive and the ownerhship of the plant is awarded to a market player. All options and necessary requirements are illustrated in Figure 2.

Deployment option 1: Direct approval through the regulatory authority

For this option, the electrolysis needs to qualify as a fully integrated network component (FINC). The ElWG draft introduces a definition of an FINC: It means components (including storages), "which are integrated in the transmission or distribution grid, contributing exclusively on the secure and reliable network operation, not contributing to system balancing or congestion management and typical charging/discharging intervals are significantly below the market time unit." (§ 6 (1) ElWG draft). In the annotations on the ElWG draft, it is stated that the market interval amounts to 15 minutes according to Regulation (EU) 2017/2195 [12].

Deployment option 2: Exceptional permission following a negative tender

This case requires an exceptional permission, presuming a negative tender result. A further requirement is the examination of alternatives according to § 72(3), which are available in a more cost-effective or more timely manner than the deployment of energy storages. Besides conventional grid enforcement or -extension, the market based procurement of flexibility services according to § 120 needs to be checked.

Procurement 1: Award to a market participant after positive tendering result

An open, transparent, and non-discriminatory tendering process according to §72 (2) Z2 is successful, and the ownership, construction, management, and operation of the facility are handled by a single market participant. The facility can be used by the DSO, thus enabling the 'procurement' of the flexibility service.

2.2 Techno-economic analysis

To determine whether electrolysis for grid support makes sense in an economic perspective, extensive simulation and optimisation is carried out. Therefore, four promising locations for grid supporting electrolysis in the distribution grid of 'Energienetze Steiermark' (located in Styria, Austria) are considered. Including factors for those

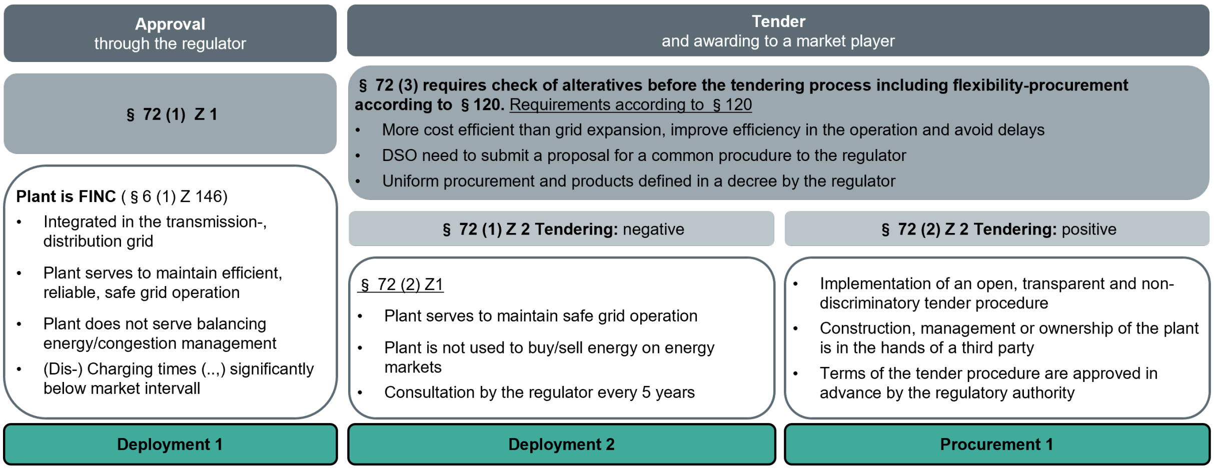

Fig. 2 Options for ownership of the electrolyzer

locations were possible limitations in the electric distribution grid by increasing electric generation over time and a nearby connection to a potential hydrogen pipeline (currently natural gas). In the following chapter, a holistic simulation approach is proposed, where a grid model, an operational optimization model and a technical simulation model are interacting.

2.2.1 Simulation approach

The idea of the holistic simulation approach is that the final operation profile of the P2G system is determined by both an optimization model and a grid model of the affected distribution grid. The optimization model IESopt is implemented to maximise profits by adjusting the production profile against the quarter-hourly electricity price and a constant hydrogen price (see 2.2.4). This operation profile is then limited both by minimum and maximum possible power restricted by the grid model (see 2.2.2) and by limitations of the technical simulation model TESCA (see 2.2.3). The technical simulation model in the end is used to model the real system more accurately, as the optimization model can be seen as a linear abstraction of the system. Figure 3 illustrates the interaction of the various tools.

Figure 4 illustrates the network area of 'Energienetze Steiermark', where four snapshot-cases were selected. The map was drawn in line with the plans of the H2 Roadmap [13] and the European Hydrogen Backbone (EHB) [14].

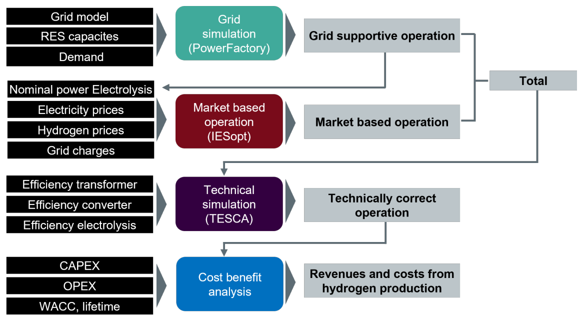

Fig. 3 Operating modes and operators/owners

In these four locations, the surrounding grid was modelled and P2G systems were positioned. The exact location of the P2G systems will not be disclosed at this point, but for electrolysis to make sense as a substitute to conventional grid-enforcement measures, potential locations need to fulfill a number of requirements. First and most obvious, grid-bottlenecks caused by future infeed and limitation of current grid capacity are expected and need to be solved. Second, and this is probably related to the first condition, these locations will be close to areas with high expected deployment of intermittent renewable generation. Third, proximity to the future hydrogen network is considered to be essential as a sink for the produced hydrogen. Put differently, electrolysis will be positioned at the intersection of i) the envisaged hydrogen network, ii) high-voltage electricity grid and iii) envisaged RES built.

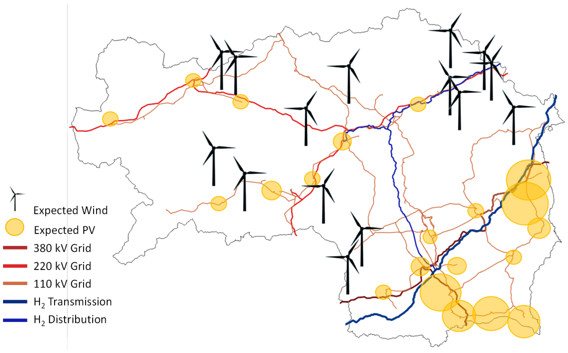

Fig. 4 Electricity-, gas and potential future hydrogen network in Styria in 2040, illustration by Energienetze Steiermark GmbH

The modelling was undertaken against historical data of 2023 with respect to RES generation and load profiles, electricity prices and grid charges. Strong expansion of RES was assumed in accordance with [1, 15], further outlined in 2.2.2. Despite some efforts to predict and estimate future prices or costs of hydrogen[2], we consider the hydrogen price as the most uncertain variable in this modelling exercise. Therefore, the hydrogen price is varied in a range between 1 and 10 EUR/kg.[3] In all locations, it is assumed that the P2G is grid-connected (front of meter) and is not working co-located being directly connected to the plant (behind the meter). This implies that grid charges are applicable to their full extent.

The overall simulation is carried out for a duration of 30 years (2025-2055) to show the increasing need of grid reinforcement due to increasing implementation of RES generation (mostly PV, but also wind), while also considering increasing electricity demand (only private EV and private heat pump rollout scenarios where considered). To represent a discretised expansion of P2G capacity to counteract grid congestion by increasing feed-in, a five-year expansion cycle was implemented.

In the beginning of each five-year simulation cycle, the maximum grid congestion was taken as reference for expansion capacity of the upcoming five years. As possible grid congestion is likely to originate from increasing RES integration, it is assumed that grid congestion has a similar fluctuation. To cope with this volatile use, the selected electrolysis technology must be appropriately flexible. Therefore, due to its higher flexibility in dealing with power ramping, proton exchange membrane (PEM) technology was chosen for the electrolyzer [19, 20]. To represent the technical lifetime of the PEM, it is assumed that after end of life, the electrolyzer must be removed or replaced. Regarding lifetime, literature diverges quite extremely by giving values of 20,000 to 90,000 hours of operation or 10 to 25 years [11, 21–23]. Therefore, a lump-sum lifetime of 15 years was assumed, even though it might seem a little overestimated for a possible full load operation (e.g. a total lifetime of 90,000 hours leads to a capacity factor of around 0.68 for a lifetime of 15 years).

To represent the influence of expansion capacity of the P2G system and hydrogen price on the systems technical and economic key performance indicators (KPIs), a parameter study was carried out. Therefore, every location was simulated with a relative expansion capacity of 20 to 100 % with steps of 20 % (percentage are relative to the maximum grid congestion in the upcoming 5 years) and hydrogen prices of 1 to 10 EUR/kg in steps of 1 EUR/kg. This results in 5 variations for relative expansion capacity and 7 variations for hydrogen price resulting in a total of 35 simulation runs per location.

2.2.2 Grid simulation

As a first step, a grid simulation was undertaken to determine the grid-supportive operation. The grid-supportive operation was defined as the minimal required operation of the electrolyzer, to compensate peaks of renewables production which would have led to violation of grid constraints and as a consequence to infeed curtailment. It is a rule-based strategy and is determined on the basis of grid simulation and the respective technical limits of network components.

The grid-supportive operation is defined by a feasible production area that is constrained from two sides. On the one hand, grid-supportive operation is positive when renewables generation needs to be compensated. This is said to be the minimal required operation of the P2G to consume renewable generation and thus maintain valid operational state of the grid. Hence, the P2G is

[2] see for example [16–18]

[3] Note that this price can be interpreted 'free of charge' at the electrolyzer, i.e. no charges for transport were assumed for hydrogen

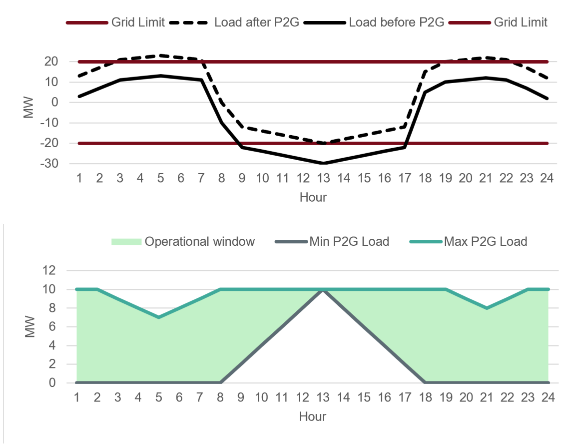

Fig. 5 Illustration of grid-supportive operation

designed in order to compensate the maximum grid-violation that can be observed within the modelled timeframe. On the other hand, the operating window is constrained from the upper side when the P2G is not allowed to operate at full capacity since the grid is overloaded from the demand side. This typically happens when renewable infeed is low or zero and consumption is high.

Figure 5 illustrates the grid-supportive operation in a simplified way by meeting primary substation capacity limit as an example of a bottleneck of a distribution grid. In this example, grid components would be overloaded from excess feed-in between 9:00 and 17:00. The maximum overload is 10 MW at 13:00. Therefore, the P2G is designed at a capacity of 10 MW. However, when running at full capacity, it would lead to a congestion between hour 2 and 7 as well as 19 and 23, hence, the operational window is reduced during these timeframes by the required amount. Typical bottlenecks of distribution grids are line loading limits (predominantly in network level 3), primary substation capacity (predominantly for network level 4 – see Figure 5), or grid voltage limits (predominantly network level 5).

The model was built in Digsilent PowerFactory[4], and the whole calculation was automatized by the PowerFactory Python interface, so future scenarios and controls where setup using Python, and PowerFactory was fully controlled via Python.

[4]https://www.digsilent.de/en/powerfactory.html

For yearly simulation, yearly consumption and generation profiles were configured in the grid, and the PowerFactory Quasi-Dynamic-Simulation function was used to calculate one year within 15 min timesteps with high performance. Yearly consumption and generation profiles were provided by the DSO, containing real measurement data from primary substation transformers and feeders in the historical timeframe from 2023-01-01 to 2023-12-31 in 15-minutes granularity.

Figure 6 shows the grid topology of all four locations. All four locations are characterized by different grid layouts and assumptions on RES expansion. Also, P2G is connected at different network levels spanning from network level 3 to network level 5. Figure 7 illustrates the assumptions on RES expansion and Figure 8 depicts the assumptions for growth of demand due to electrification of heat and mobility in all four locations. The assumptions are based on multiple sources, e.g. [24, 25] and were fine-tuned based on several discussions with the DSO, being aware of the local conditions. In all locations, significant RES expansion is expected.

Location A

The P2G is supposed to relieve the substation on network level 4. The current demand/injection (historical data 2023) spans between +9 MW (demand) and -17 MW (injection). The transformer station capacity (considering n-1 security) lies between +50 MW and -100 MW. Strong growth of solar PV is assumed.

Location B

The P2G is supposed to relieve a grid branch on 110 kV level (network level 3). The current demand/injection spans between +50 MW and -15 MW. The line capacities are between +100 MVA and -200 MVA for “lower” line and +200 and -400 MVA for “upper” line. Strong growth of wind and solar PV is anticipated.

Location C

One feeder of a 20 kV medium voltage (MV) grid is modelled that is characterized by two main branches. Current peak load in this feeder is around 2.3 MW and maximal RES generation at minimal load causes a reverse power flow -0.63 MW. To increase hosting capacity to enable

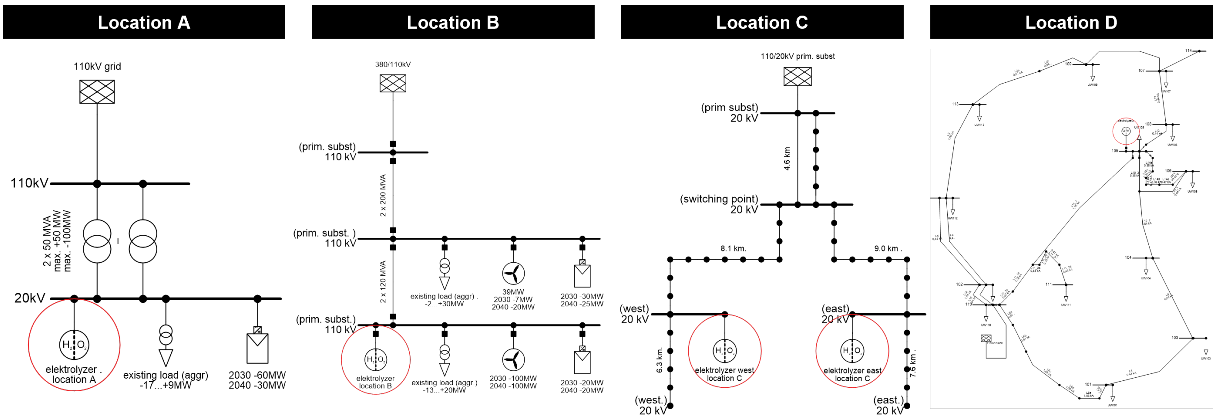

Fig. 6 Grid topologies of the four selected locations

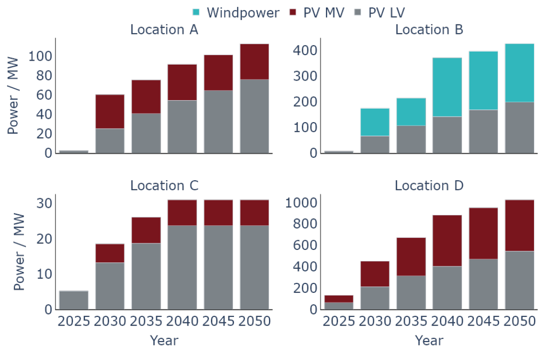

Fig. 7 Input assumptions on renewable expansion

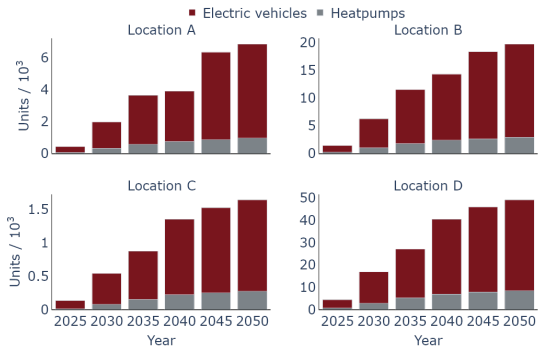

Fig. 8 Input assumptions on consumption expansion

the expected amount of PV integration, one P2G was located in each of the branches on network level 5. While one of the branches is around 19 km long and the other around 22 km, the P2G were placed on the most optimal location in the feeder to compensate future PV infeed most effectively. According to current common practice in network planning, network level 5 consumers are not allowed to consume more than 8 to max. 10 MW, which constitutes a non-technical limit for the size of the P2G.

Location D

The modelled area is a part of the 110 kV high voltage (HV) grid. Grid topology was simplified to avoid modelling the complete HV grid. Based on this simplification, maximal consumption at the 380 kV connection point is currently 230 MW, while maximal return feed is -110 MW. For this location, the best position for the electrolyzer was considered at the primary substation 105, that is around 33 km away from 380 kV connection point (as shown in the diagram). From the perspective of the electric grid, the positioning of the P2G is not ideal, since not all expected future congestions can be relieved from this position. However, it offers the best proximity to the hydrogen grid, which is highly relevant as a sink of the P2G output.

The approach on location D also differs strongly from the other locations since parallel grid enforcement needs to be assumed. Taking this approach of parallel grid reinforcement was necessary since the grid-supportive operation of the P2G at the given position in the grid is not sufficient to allow for all expected future PV integration. Additional demand from the P2G relieves problems in one branch of the grid but creates problems in another branch of the grid.

To solve this contradiction, a simple grid reinforcement algorithm was developed that reinforces overloaded lines that cannot be relieved by P2G operation.

2.2.3 Technical Simulation

The system simulated in this study is designed to provide a realistic representation of a P2G system. Starting at the coupling point to the electrical distribution grid, alternating current is converted into direct current using an ACDC converter. For location B, an additional transformer is needed at the substation due to technical specifications.[5] Direct current is fed into the electrolyzer, which is assumed to be of PEM technology. The output of the electrolyzer would normally be buffered in a small-scale hydrogen storage tank (with a storage time of about two hours based on the electrolyzer output) to ensure a constant or quasi-constant back pressure to the hydrogen output stream of the electrolyzer. Due to the limited losses of the storage tank and its small size, which makes it only usable for technical purposes, it is neglected in the simulated system. The compressor required to increase the pressure of the hydrogen gas before feeding it into the pipeline is assigned to the gas grid. The compressor therefore has no influence on the P2G in technical or economic terms and is also neglected.

The technical modelling is carried out using TESCA, an internal AIT framework for deterministic time series simulations [26]. The simulation framework provides models for various components of energy systems in the electricity, hydrogen and heat sectors. For this study, the electricity and hydrogen grids were implemented as unlimited source and unlimited sink, respectively. Therefore, the P2G system was only restricted by its own technical boundaries, like nominal power of the components. The transformer and the ACDC converter were implemented with load-dependent efficiency curves.

In contrast to the models of transformer and ACDC converter, integration of the core component of the P2G, the PEM electrolyzer, into the entire system is based on in-depth modeling of the electrochemical process. The efficiency of electrolysis η_{el} is calculated as a combination of voltage efficiency η_V and faraday efficiency η_F. Voltage efficiency on the one hand accounts for electric losses in the PEM cell. It is calculated as

$$\eta_V = \frac{V_{tn}}{V_{cell}} \tag{1}$$

with thermoneutral voltage $V_{tn} = 1.482\ V$ and total cell voltage V_{cell} as

$$V_{cell} = V_{rev} + V_{act,an} + V_{act,cat} + V_{ohm} \tag{2}$$

with the reversible voltage V_{rev} depending on both operational temperature and pressure, activation overpotentials of anode $V_{act,an}$ and cathode $V_{act,cat}$ accounting for kinetics at the electrodes, and ohmic overvoltage V_{ohm} accounting for ohmic losses in the membrane. As activation overpotentials increase with the natural logarithm of the applied current and ohmic losses linearly to the applied current, voltage losses are increasing for increasing applied electrical power. Faraday efficiency on the other hand accounts for back diffusion of hydrogen through the membrane by the pressure difference, reducing the actual hydrogen throughput of the electrolyzer. As hydrogen back diffusion is not depending on the theoretical throughput, and therefore the applied electrical current, but rather by the pressure difference between cathode and anode side (which are assumed constant as 30 bar at the cathode and 1 bar at the anode side in this study), the faraday efficiency increases to 100 % asymptotically. For auxiliary technology such as water pumps, water treatment and cooling system, a constant auxiliary power of 5 % of the electrolysis nominal power is assumed, reducing the stack efficiency η_{el} even further to an overall system efficiency of the electrolysis system η_{system}. Due to the constant nature ot the balance of plant (BoP) power the influence on the overall system efficiency is decreasing with increasing load of the electrolyzer. The influence of the described loss components on the total efficiency are depicted in Figure 9 for a PEM electrolyzer operating at a temperature of 80°C. [27]

[5] Additional losses for further transformation of the voltage level from the substation to the converter were neglected.

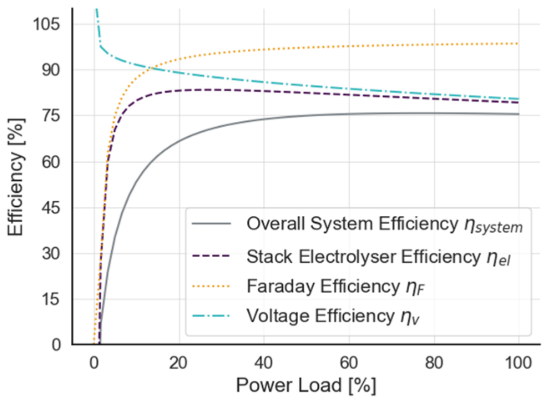

Fig. 9 Efficiency components of the system efficiency of a PEM electrolyser from [27]

2.2.4 Market based operation

The optimal operation based on market signals is determined by solving an optimization problem, implemented in the IESopt framework [28]. IESopt is an open-source optimization framework built on top of the JuMP modeling language [29] written in Julia [30]. The Julia core source code of IESopt [31] and a Python interface [32] are available on GitHub.

The optimal market-based operation is a result of the marginal costs of hydrogen production and the hydrogen price. The former is determined by the electricity price, the grid charges and the conversion ratio of the P2G. For the electricity price, quarter-hourly historical spot market prices for Austria in the year 2023 are considered. The grid charges are taken from historical data for the network area of Styria and consist of an energy component in EUR/MWh and a peak-load component in EUR/MW for the monthly quarter-hourly consumption peak. The optimization maximizes yearly profits by choosing electricity consumption of the P2G, being constrained by the size of the P2G and facing electricity prices and grid charges as costs. The output value of the P2G is determined by the exogenously assumed hydrogen price. Historical input data like electricity prices and grid charges are described in Figure 12 and Table 2.

The modeling assumes perfect foresight on the electricity prices over one entire month, because peak-load grid charges are settled monthly in Austria. Hence, market based operation is determined month-ahead on a quarter-hourly resolution. Since the market-based operation is implemented as linear program (LP), the conversion ratio of the P2G as output mass flow in kg/h per input energy of the electric grid in kWh is assumed at a constant value. As the optimization model is implemented as a linearized abstraction of the entire P2G, this conversion ratio is determined by the non-linear technical model (see 2.2.3) at nominal input power of the system. The optimization always chooses full load as long as the marginal costs of production fall below the hydrogen price, considering fixed costs arising from peak load grid charges. Therefore, no minimum load arising from the technical specifications of PEM electrolysis is considered in the optimization model.

The monthly operation schedules determined by the optimization model are then used as operation strategy by the technical simulation model. Due to the non-linearity of the technical simulation model, the exact values of conversion can vary to the ones determined by the optimization model. Therefore, slight differences in output of hydrogen between both models can occur even though the same input is applied. However, as use of the P2G system is triggered by the optimization model either at full load or not at all, there is no difference in the conversion factor. Hence, one might argue that there is no need for such a deep technical simulation. It is still of significant value, because the final operational strategy is also affected by results from the grid model for congestion management. Therefore, not only full load operation is simulated but also partial load by the grid model.

It is common practice in the electricity market that grid operators undertake market intervention after the market has settled. Therefore, in our analysis, we assume that the market-based operation is settled before the grid-supportive requirement is determined on the part of the DSO. Hence, it modifies the profit-maximizing operation from market-based operation and reduces the profits.

2.2.5 Cost benefit analysis

A cost benefit analysis (CBA) is done for the time frame between 2025 and 2055, i.e. 30 years. In

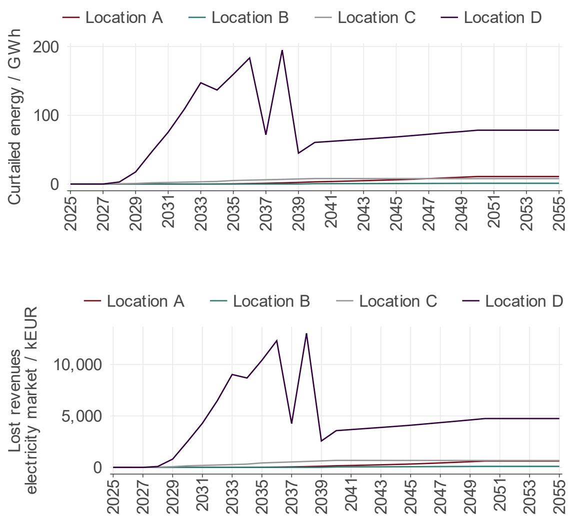

Fig. 10 Basic indicators of the baseline scenario

a first step, the baseline scenario for the entire time frame is defined. In the baseline scenario, the surplus renewables generation is curtailed so that the network can still be operated in its technical boundaries. Then, both scenarios (classic grid enforcement-scenario and electrolyzer-scenario) can be compared to the baseline scenario. Figure 10 shows the main characteristics of the baseline scenario: curtailed energy in GWh and lost revenues from sales on the electricity market in thousand euros. The curtailed generation mainly follows the renewables expansion path in combination with congested grid components.

The lost revenues on the electricity market consist of the product of the curtailed generation and the historical electricity prices 2023. The computation of the lost revenues is shown in Equation 3, where $q_{y,t}$ represents the curtailed electricity in year y at time t and p_t the corresponding electricity price in the respective time interval t. This calculation is repeated and then summed up for each year y between 2025 and 2055, whereby a discount factor r is applied.

$$R^{Lost} = \sum_{y=1}^{30} \frac{\sum_{t=1}^{N} q_{y,t} \cdot p_t}{(1+r)^y} \tag{3}$$

At this point, it is worth mentioning that the economic evaluation takes a global perspective, without a specific view on the ownership structure

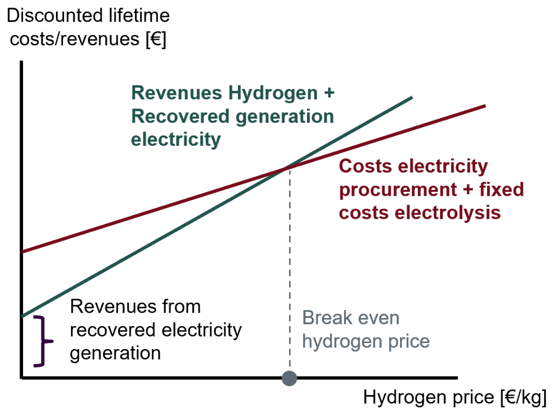

Fig. 11 Exemplary illustration of cost-benefit analysis for electrolysis in distribution grids

of the components. For example, lost revenues on the electricity market concern the owner of the renewable plants, not the DSO or the owner of the electrolyzer. However, in a global cost-benefit analysis, revenues and expenses can be added without specific attribution to actors. The composition of costs and benefits in a global perspective are illustrated in Figure 11. First, it can be concluded that, independently of the hydrogen price, the recovered revenues from renewables generation (that would be curtailed in the baseline scenario) contribute to the overall benefits. Assuming a hydrogen price of zero, no market based operation could be observed, but an (unprofitable) grid-supportive operation would maintain network operation within its limits and ensure that all renewables production could be injected into the grid.

However, it is obvious that global costs and benefits depend on the assumed hydrogen price. With an increasing hydrogen price (equivalent to willingness to pay for the output of the electrolyzer), revenues from hydrogen sales increase. This is a result of two sources: first, hydrogen output is evaluated at a higher price and, second, the output of the electrolyzer increases since market based operation finds more profitable hours. At some point, we can observe a 'break-even hydrogen price' where benefits start to outweigh the costs. Please note that the curves depicted in Figure 11 are drawn for illustrative purposes only. In fact, both curves are highly non-linear and proportions are very different.

Furthermore, it is worth nothing that lifetime-results are considered for the cost benefit analysis. For each location, costs and revenues are accumulated and discounted over the entire time horizon from 2025 to 2050. Equation 4 represents revenues, where $x_{y,t}$ denotes the hydrogen output, h the hydrogen price. Index t represents all quarterly hours of the year and therefore runs from 1 to 35,040. Equation 5 in combination with annual costs C_y^{H2} in Equation 6 illustrates the costs arising from hydrogen production, where $w_{y,t}$ denotes the electrical input energy and p_t the electricity price. Of course, there are some inter dependencies in these equations. Electrical input $w_{y,t}$ depends on the hydrogen price h and is determined by optimization (based on a linear relationship between $x_{y,t}$ and $w_{y,t}$) to maximize profits from operation of the electrolyzer. In the technical simulation, $x_{y,t}$ is then determined as a (non linear) function of $w_{y,t}$, considering a number of efficiency-curves. The investment costs in the respective future year y ($CAPEX_y$) are determined by the electrolyzer capacity (illustrated in Figure 14) multiplied by the specific CAPEX value expressed in EUR/kW illustrated in Table 1. The costs for maintenance in the respective year ($OPEX_y$) are compound by the CAPEX value and the value of 2 % of CAPEX per year.

$$R^{H2} = \sum_{y=1}^{30} \frac{\sum_{t=1}^{N} x_{y,t} \cdot h}{(1+r)^y} \tag{4}$$

$$C^{H2} = \sum_{y=1}^{30} \frac{C_y^{H2}}{(1+r)^y} \tag{5}$$

$$\begin{aligned} C_y^{H2} = & \sum_{t=1}^{N} w_{y,t} \cdot p_t \\ & + GC_y^{Peak} + GC_y^{Energy} \\ & + CAPEX_y + OPEX_y \end{aligned} \tag{6}$$

Grid costs (GC) for peak load consumption are illustrated in Equation 7, where $\overline{w}_{y,m}$ denotes the peak consumption (maximum load value) within month m and g_p denotes the peak-load grid tariff. In Austria, they are formed by the average across all monthly peak consumption values. Grid costs for energy consumption are illustrated in Equation 8 which are composed of the total energy consumption multiplied by the variable grid tariff g_v.

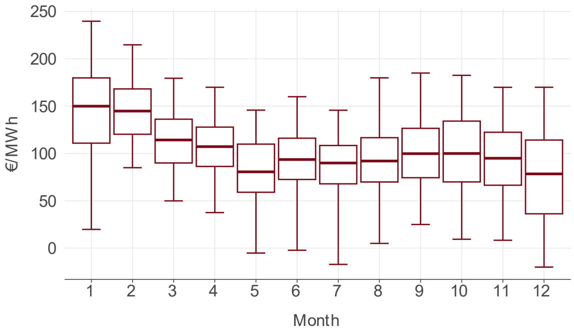

Fig. 12 Boxplot of electricity prices for Austria, 2023, Day-ahead, EXAA 15M

$$GC^{Peak} = \frac{\sum_{m=1}^{12} \overline{w}_{y,m}}{12} \cdot g_p \tag{7}$$

$$GC^{Energy} = \sum_{t=1}^{N} w_{y,t} \cdot g_v \tag{8}$$

Electricity prices consist of historical data for the Day-ahead (15M) EXAA Spot auction from the year 2023 [33] and were kept constant over the entire lifetime. It is clear that this is a strong assumption, however, electricity prices, in particular the upper and the lower end of the price range is notoriously hard to project with long term fundamental models. Figure 12 shows a boxplot of the corresponding prices. It can be observed that prices are rather volatile and were facing a downward trend since prices were rather high in times of the energy crises during 2022. The average price is around 100 EUR/MWh with prices ranging between 75 EUR/MWh and 130 EUR/MWh in around 50 % of time.

Table 1 illustrates the cost for investment and operation of the PEM electrolyzer. Assumptions were taken from the 'Technology Catalogue for Renewable Fuels' from the Danish Energy Agency [22]. CAPEX and OPEX assumptions are chosen for a system size around 10 MW. Actual values for investment in any future year are interpolated from the anchor year values in 2025, 2030 and 2040.

In the case modeled here, it is assumed that the P2G is connected to the electricity grid (front of meter), feeds into the hydrogen network and does therefore *not* consume exclusively renewable

Table 1 Investment cost assumptions for electrolysis

	2025	2030	2040
CAPEX [EUR/kW]	1,425	950	725
OPEX [%/CAPEX/a]	2	2	2

electricity. Thus, it is assumed that grid costs and taxes are fully applicable for the electrolyzer, even if it is contributing to congestion management. Only FINC are exempted from grid tariffs and this is, as outlined in the regulatory analysis in 2.1, rather unlikely. At the moment, there are relieves for electrolysis in Austria regarding the 'Netzbereitstellungsentgelt' and the 'Netzzutrittsentgelt' for electrolysis above 1 MW which exclusively consume renewable electricity and do not feed into the gas grid.

Both cases, the qualification as FINC as well as the relieves, do not apply to our case here, therefore we consider grid costs as illustrated in Table 2. The data is based on grid costs for Styria [34] and refers to the second amendment in 2023 of the original 'Systemnutzungsentgelte-Verordnung' [35]. In this version, reductions were granted from the state to the consumer in light of the energy crises in the sharply rising costs for electricity during 2022. For simplification, we have not assumed grid tariffs for injection.[6]

Table 2 Grid charges for 2023 in the network area of Styria

Grid level	Peak load	Energy
3	29,880 EUR/MW/a	13.1 EUR/MWh
4	35,520 EUR/MW/a	18.4 EUR/MWh
5	47,520 EUR/MW/a	24.26 EUR/MWh

All historical economic data (electricity grid enforcement, electricity prices, and grid charges) refer to the year 2023. Therefore, the economic valuation is defined in real money terms for the year 2023. The weighted average cost of capital (WACC) is assumed at 4 % in real terms. The hydrogen price is considered the most uncertain variable in this modeling exercise. Therefore, the hydrogen price is varied in a range between 1 and 10 EUR/kg and all results are illustrated (where relevant) in relation to the hydrogen price.

Table 3 Estimated cost for conventional grid enforcement

P2G Location	Costs [MEUR]
Location A	1.5
Location B	8
Location C	9.5
Location D	116

In a last step, the results of the CBA are compared to the cost of conventional grid enforcement measures. For this purpose, the DSO 'Energienetze Steiermark' has estimated the cost of undertaking conventional measures, the values are illustrated in Table 3. These numbers represent the cost of grid enforcement to ensure that all anticipated renewable generation can be absorbed by the grid. The numbers can be understood as net present values in real 2023 money terms and can be compared to the lost revenues computed by Equation 3 and illustrated in Figure 11. However, due to the different structure of the grid of Location D also congestion management by electrolysis must be accompanied by grid enforcement with a total cost of 83 MEUR. Note that a comparison of grid enforcement costs and the economic value of the additional feed-in is not necessarily in favor of grid enforcement.

3 Results and discussion

First, results of the regulatory analysis are presented by combining operating strategies and ownership options. It will be concluded that ownership by the DSO is limited to very few cases, but the option where the plant is owned by a market player and procurement of flexibility services is done by the DSO remains feasible. Second, the results of the techno-ecnomic analysis are presented over a set of relative nominal P2G power and hydrogen prices.

[6] In Austria, generators >5 MW are required to pay variable grid fees for injection. Since i) we do not make specific assumptions on the composition of the renewable generation fleet (all generators could theoretically be below 5 MW per connection point) and ii) these grid fees are rather small, this was not considered further.

3.1 Regulatory Analysis

A valuation of combinations of operation and deployment options regarding their regulatory feasibility is illustrated in Figure 13. Under deployment option 1, it is not possible to operate the facility grid-supportive, since (dis-)charging intervals will typically lie above 15 minutes for the purpose of smoothing wind power and photovoltaic peaks. This also holds for the case in which a third-party acts as the operator since the *facility* is not allowed to charge and discharge more than 15 minutes on a regular basis. In addition, market based operation under deployment option 1 is definitely excluded, as the unit may be used *exclusively* for secure network operation.

Under deployment option 2, the facility is not allowed to buy and sell electricity on markets, which rules out all market based operation strategies. In fact, there is only one feasible option for DSOs to own and operate electrolysis: Presuming a negative tender result, DSOs are allowed to operate the unit for grid-supportive purposes only (operating Strategy 1a).

However, there are significant limitations to this option as well. As outlined in Figure 2, DSOs need to check for potential alternatives (§72 (3)) which are available in a more cost effective or more timely manner including the market based procurement of flexibility services according to § 120 ElWG or conventional grid extension- and enforcement measures before issuing a tender. The results in 3.4 do not always support the case of electrolysis to be more cost effective than conventional grid extension.

So, considering this finding, we can conclude there is not much room for DSOs to own and operate electrolysis. However, this does not necessarily rule out electrolysis as alternative to conventional grid enforcement completely. An organizational way to implement it, is to outsource the ownership of the electrolysis to a market participant. A regulatory feasible organizational model consists in ownership and operation of the electrolysis by a market player, while the DSO procures flexibility services for a certain price.

In a tendering process, the DSO defines the technical requirements and the required operating times, as for example illustrated in the lower part of Figure 5, for the grid-supporting electrolyzer. The requirement for a positive award is that the grid service is more cost-effective than traditional grid expansion and that the contractor (operator and/or owner) is able to provide the necessary grid service. If the contract is awarded, monetary compensation for the service could, for example, take the form of regular payments. The regular payment could be a fixed amount or dependent on the operating times. In addition to run the electrolysis grid-supportive, the operator will participate in the regular energy market and operate the plant market based. This dual use enables the operator to offer grid-supportive operation at lower costs since synergies arise from sharing of fixed costs and higher capacity utilization than in purely market based operation result in a positive effect for both parties.

The corner stones of such a tendering process are not yet defined, however the following points (no full exhaustive list) would need to be considered:

- Exact location and grid level
- Timeframe of operation (e.g. 5, 10 or 15 years)
- Required operational window, as illustrated in the lower part of Figure 5
- Lead time for announcement and potential change of the operating strategy

It is worth noting that the hydrogen produced by the electrolysis does not fulfill the definition of ‘renewable’ hydrogen, i.e. is not defined as ‘Renewable Fuel of Non-Biological Origin’ (RFNBO) in accordance with the renewable energy directive (RED II) Delegated Acts [36, 37], which provide a profound definition of RFNBOs. The electrolysis modelled here is consuming electricity from the grid and therefore, the produced hydrogen does not classify as renewable since share of renewables in the electricity generation mix is below 90%. An article that discusses the legal framework for hydrogen production in Austria under the context of European regulation is for example [38].

3.2 Grid-supportive operation only

It was discussed in 2.2.5 that the baseline scenario consists of curtailment of renewable generation over the considered timeframe. The operation of the electrolyzer allows to avoid the curtailment and enables the renewable generators to inject 100 % of their production into the grid. Figure 14 depicts the main results of this scenario. It can

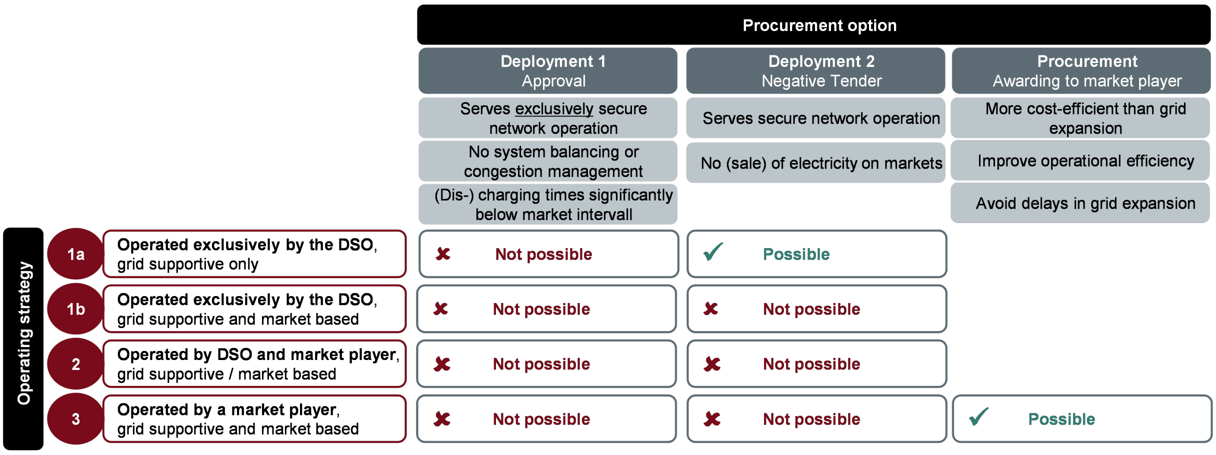

Fig. 13 Regulatory assessment of operating variants and operators according to the ElWG draft

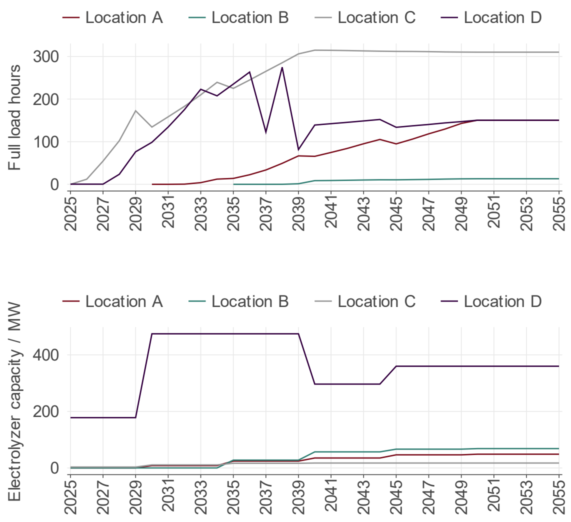

Fig. 14 Nominal power of the electrolyzer and corresponding full load hours

be seen that a certain electrolyzer capacity is required to allow 100% of renewable generation to be injected to the grid, ranging between 10-40MW for location A, 0-60MW for location B, etc. The corresponding full load hours for the electrolyzer-generation-fleet are depicted in the lower part of Figure 14. It can be seen that full load hours (FLH) are rather low, ranging between 20 hours for location B to 500 hours for location C.

From these figures, we can conclude that the operation in 'grid-supportive mode only' is far from economic viability and it is evident that additional utilization is required through market based operation 'on top' of the grid-supportive behaviour.

3.3 Grid-supportive and market based operation

We have seen that economic viability for the electrolyzer can not be built on grid-supportive operation only but needs additional load from market based operation. Market based operation does in turn depend on the price relation between hydrogen and electricity. In this modelling exercise, the prices for electricity were kept constant while prices for hydrogen were varied between 1 and 10 EUR/kg, reflecting the willingness to pay.

Figure 15 illustrates the resulting full-load-hours for the electrolyzer under different hydrogen prices. We can see that full-load-hours start to increase continuously with hydrogen prices from 4 EUR/kg upwards. To the left of this point, the electrolyzer mostly operates in grid-supportive mode and the relation between the hydrogen price (e.g. 4 EUR/kg) and the hourly structure of electricity prices does not justify profit maximizing operation. The load factor of the electrolyzer increases rapidly between 4 to 8 EUR/kg. Thereafter, the curve flattens again since the load of the electrolyzer already reaches time periods with higher electricity prices.

In addition, we can observe a strong synergy effect with the grid-supportive operation:

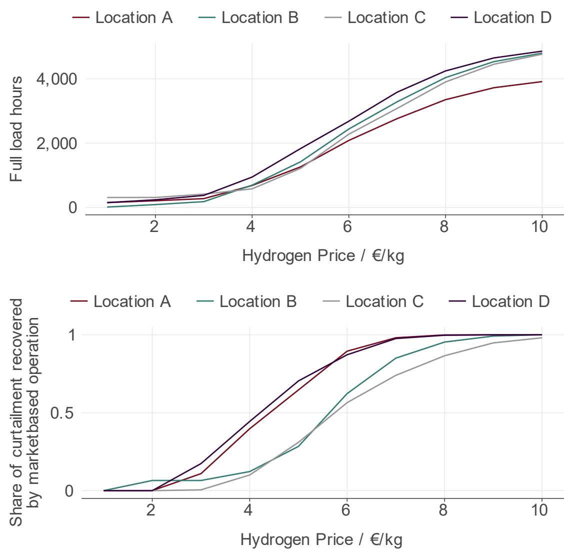

Fig. 15 Electrolyzer full load hours in 2050 as a function of hydrogen prices (upper) and share of curtailment recovered through market based operation (lower)

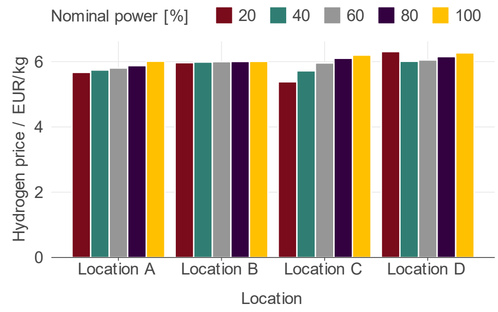

Fig. 16 Break even hydrogen prices

with increasing full-load-hours, the required grid-supportive operation is already resolved through the market based operation. At a hydrogen price of 8 EUR/kg, already more than 85% of the grid-supportive load is already resolved through the market based operation. At 10 EUR/kg, virtually 100% of the generation, that would need to be curtailed in the baseline scenario, can be recovered through market based operation only and no further grid-supportive operation is required. This is a remarkable result in light of 4000-5000 full-load-hours at 10 EUR/kg.

At this level of full-load-hours, the entire renewables surplus is absorbed since peaks of renewables production and price-valleys on the electricity market are correlated. Market based operation of the electrolyzer creates additional demand in hours where it is actually needed, incentivized by the electricity price only. At hydrogen prices beyond 10 EUR/kg, no further intervention from the DSO is required to resolve the total congestion.

Following the illustration of the cost-benefit analysis outlined around Figure 11, Figure 16 now depicts the values of the break even prices for hydrogen required to make the installation of electrolysis beneficial compared to the baseline scenario across different electrolyzer capacities. It can be seen that this price lies around 6 EUR/kg and is rather robust for all locations. For comparison: hydrogen produced from conventional fossil sources ranges between 1 and 3 EUR/kg [39]. The break even values rise with increasing capacities, which implies that a smaller electrolysis might be somehow beneficial in economic terms. This will be analysed further in the following section 3.4.

Location C is somewhat different and exhibits the lowest break even price. This results from the fact that in this location, the grid-supportive mode leads to a high number of FLH compared to the other locations, which is helpful in economic terms. In location D, the result is also different compared to the other locations since the highest break even price occurs at 20% capacity. This is a direct consequence of the approach taken for location D: conventional grid enforcement measures need to be undertaken *in parallel* to the electrolyzer capacity for reasons outlined in section 2.2.2. For the parallel grid enforcement measures, costs of 83 MEUR were assumed, independent of the electrolyzer capacity, which affects the lowest capacity of 20 % the most.[7]

3.4 Sensitivity on the electrolyzer capacity and comparison to conventional grid enforcement

The results shown so far rely on the assumption that the electrolyzer is designed to compensate the maximum grid-violation that can be observed

[7] At this point, it needs to be noted that the 83 MEUR are assumed to be independent of the electrolyzer capacity. In this respect, the modelling approach could be further refined since the parallel grid enforcement measures would obviously depend on the nominal power of the electrolyzer.

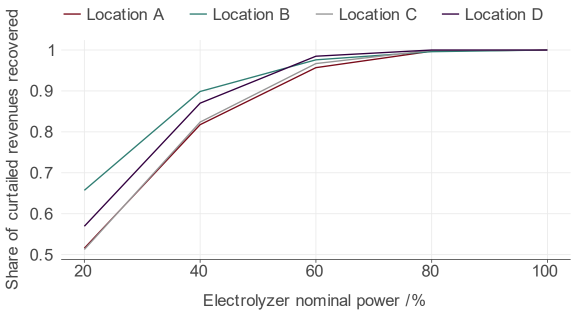

Fig. 17 Share of recovered electricity market revenues as a function of electrolyzer nominal power

within the modelled time frame, as discussed around Figure 5. In this section, we will weaken this assumption and investigate whether an economic optimum of the electrolyzer capacity can be found. For this purpose, the electrolyzer capacity is varied between 20-100% of the design capacity.

Figure 17 supports the assumption that designing the electrolyzer at full capacity might not be very useful in economic terms. When the capacity is reduced to 50%, around 90% of revenues (that would be lost in the baseline scenario through curtailment) can be recovered.

Again, this result is based on historical electricity prices and needs to be seen in light of further renewables expansion in many countries. In recent years, the number of hours with negative prices in the electricity market has experienced an exponential increase (as also indicated by the ACER Market Monitoring Report [40]). This is a direct consequence of market cannibalization from wind and PV production and it is reasonable to assume that this tendency will continue in the future. Therefore, the economic value of wind and solar peaks is questionable and the costs to have them integrated into the grid increase exponentially.

When looking at the results of market based operation, it became evident that a large share of the curtailed energy could be recovered through the market based operation. Figure 18 illustrates the share of (in the baseline scenario curtailed) energy that can be recovered through market based operation in form of heat maps. The results confirm the conclusion from above that an electrolyzer capacity of 60 % is able to recover around 95 % of the energy that would be curtailed otherwise. When the hydrogen price is high enough (10 EUR/kg), this is entirely resolved through the market and means that no intervention on behalf of the DSO is required.

Looking for an economic optimum, the net-present value of the cost benefit analysis over the entire lifetime across different hydrogen prices and electrolyzer capacities is investigated. Which electrolyzer capacity is optimal given a certain hydrogen price and how does this compare to cost of conventional grid enforcement? Figure 19 gives insights on this question. For clarity, only electrolyzer capacity of 20, 60 and 100 % are illustrated.

First of all, it is evident that the net present value of the grid enforcement measures can be negative in some locations. This means that the costs of conventional grid enforcement is actually not justified by the (discounted) expected revenues of renewable generators. This might be a little bit surprising, but might well be the case since not every action on behalf of the DSO is subject to a cost benefit analysis and our present cost benefit analysis does not include all indicators (benefits from a higher renewable quota in the grid, for example).

If the willingness to pay for hydrogen is low (2-4 EUR/kg), then the best option is to implement conventional grid enforcement measures. Above 4 EUR/kg, the deployment of a rather small electrolyzer (20 %) is the best option in Location B and C. This implies that it is efficient in economic terms to accept a certain amount of renewable energy to be curtailed. For location B, the reason for this result can be attributed to rather high costs of conventional grid enforcement. For location C, the electrolysis exhibits the highest capacity factor based on grid-supportive mode only. Therefore, electrolysis in this location helps to recover a high share of curtailed revenues even with a small capacity.

At higher hydrogen prices, above the break even price of hydrogen, e.g. beyond 6 EUR/kg, the benefits outweigh the costs and the recommendation is to build the electrolyzer as large as possible, since market based operation is profitable. This is perfectly in line with the observation that the market based operation kicks in at prices above 6 EUR/kg where resolving the grid congestion is incentivized by market forces and the

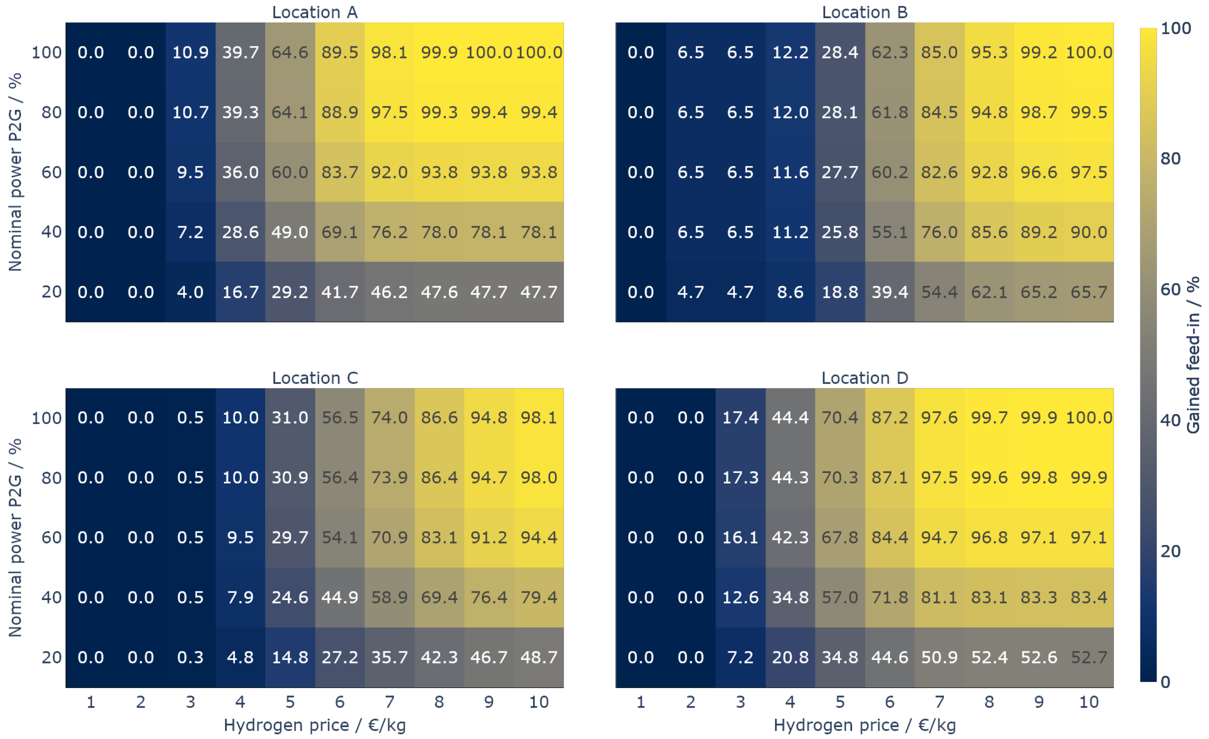

Fig. 18 Share of recovered electricity through market based operation under different electrolyzer nominal power

most profitable production schedule creates additional demand so that additional feed-in by RES becomes possible.

4 Conclusion

The objective of the present work was to assess the deployment of electrolysis as an alternative to conventional grid extension in a regulatory and techno-economic perspective. It has been found that ownership and operation of electrolysis by DSO is only possible in one scenario: before issuing a tender (and awarding the ownership of the electrolysis to a market participant), the DSO is required to check for alternatives. Only if e.g. flexibility procurement according to § 120 ElWG or conventional grid extension is not preferable to the deployment of an electrolysis in economic terms or faster to implement, the DSO is allowed to issue a tender. Only if this tender fails, the ownership is granted to the DSO. This right to own and operate the facility is limited to a certain time horizon and enables grid-supportive operation only.

Techno-economic modeling showed that a combination of multiple revenue streams is required to make the electrolysis economically viable. If the electrolyzer is operated for grid-supportive purposes only, the resulting capacity factor is very low, e.g. below 5%. If the plant pursues also market based operation, the level of hydrogen price determines the economic viability. In general, if the willingness to pay for the output of the electrolyzer is above 6 EUR/kg, the overall benefits outweigh the costs, the grid congestion gets resolved through profit maximizing behavior of the plant and no remedial action on behalf of the DSO is required. At hydrogen prices above 6-7 EUR/kg, the cost benefit analysis also favors electrolysis over conventional grid enforcement measures.

For two out of four locations, a smaller electrolyzer capacity of 20% turns out to be the best option at hydrogen prices between 4-6 EUR/kg and is more cost efficient compared to conventional grid enforcement. It can also be concluded that the electrolysis does not necessarily need

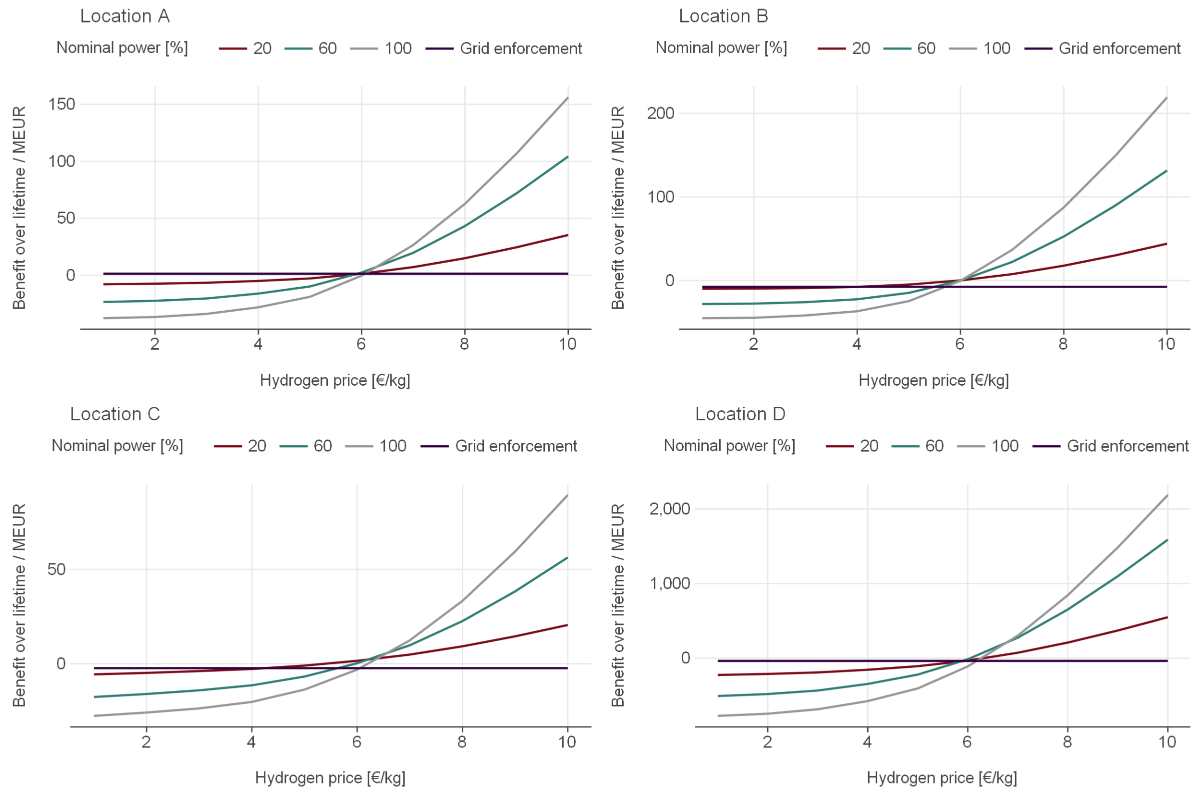

Fig. 19 CBA across different hydrogen price levels and electrolyzer capacities compared to conventional grid enforcement measures

to be designed to absorb the renewable generation peaks as the economic value of those peaks decreases continuously.

Prices below 4 EUR/kg do not justify consumption of electricity from the grid to produce hydrogen. In addition, it needs to be emphasized that the hydrogen produced by the electrolysis is not 'renewable' in a sense of an RFNBO defined by European regulation. This might also lower the willingness to pay from industrial or consumer side.

The results of the study need to be seen along some limitations. For example, the comparison to the baseline scenario is not perfect, since demand for hydrogen is not considered in the baseline scenario. To be entirely correct, we would need to take assumptions on the demand for hydrogen in the baseline scenario and assume, that corresponding amounts of hydrogen come from other sources, e.g. imports at different prices. In addition, it is obvious that the cost benefit analysis did not consider other factors such as 'security of supply' for hydrogen in the future and the build-up of an energy system that is resilient to supply-side shocks from outside.

Further limitations in this analysis are given by the number of case studies considered: four locations where considered, therefore, the conclusions are not universal. However, these four locations correspond to the most promising ones in the network area of 'Energienetze Steiermark' and were selected in light of expectation of high renewables curtailment and proximity to the hydrogen network and expected grid congestions. Additional added value (which was not considered in this study) is a potential grid-supportive operation on the transmission level. Electrolysis in the distribution grid could also relieve some grid components in higher grid levels, which would further contribute to the cost benefit analysis.

It is also clear that the present study is built on the basis of historical day-ahead prices which do not reflect increasing price volatility caused by the further expansion of intermittent renewable generation.

The above mentioned limitations support the conclusion that the study underestimated the positive effects of the electrolysis in distribution grids. Hence, focus of future research could be on resolving those limitations by refining the assumptions.

5 Declarations

5.1 Ethics approval and consent to participate

Not applicable.

5.2 Consent for publication

Not applicable.

5.3 Availability of data and materials

Not applicable.

5.4 Competing interests

The authors declare that they have no competing interests.

5.5 Funding

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5.6 Authors' contributions

P.O. supervised the project from side of the Austrian Institute of Technology and drafted the manuscript, R.S conceived the grid simulation with PowerFactory, A.P. carried out the technical simulation with TESCA and edited the manuscript, K.M. performed the cost benefit analysis, D.S. developed the optimisation framework IESopt, C.M. contributed to the regulatory analysis, S.F. supervised the project from side of the 'Energienetze Steiermark', B.S. contributed to the regulatory analysis, M.P. was responsible for data provision, B.K. contributed to the regulatory analysis and all authors discussed the results and approved the final version of the manuscript.

5.7 Acknowledgements

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