CO-SIMULATION ANALYSIS FOR LARGE-SCALE ELECTROLYSERS INTEGRATION IN ELECTRICITY GRIDS

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KEYWORDS

Electrolysers Grid Integration, Co-Simulation, Hydrogen Production Impact, Grid Stability

ABSTRACT

The integration of large-scale electrolysers into the electricity grids presents several challenges and opportunities for the energy sector. Electricity grids' ability to accommodate very large electrolysis capacity needs to be examined in advance to guarantee the stability of the grids. Simultaneously, optimising the utilisation of electrolysers is crucial for maximising their potential contribution to the energy transition. An open-source co-simulation toolbox is presented in this work to enable studying the impacts of large-scale electrolyser deployment on the grid and the electrolysers' performance. With a scenario-based approach, the toolbox facilitates the exploration of diverse operational strategies for the electrolysers, spatial distribution variation and different grid projected conditions. This paper outlines the structure and the elements of this toolbox, which is based on the open-source co-simulation framework *mosaik*. Furthermore, two showcases are presented to demonstrate the utilisation of co-simulations, providing initial analysis and insights into the simulation results.

INTRODUCTION

The emerging focus to establish a robust hydrogen economy and infrastructure with the goal of achieving climate neutrality and to reduce dependence on energy imports highlights the significance of hydrogen as an energy carrier. For instance, the German National Hydrogen strategy (BMWK 2023) increased the target for the expansion of the electrolyser capacity in Germany from 5 GW to at least 10 GW by 2030. In this context, hydrogen is foreseen to enable long-term storage and transportation for renewable energy. Moreover, hydrogen power plants can also contribute to the short-term as well as the long-term balancing capabilities during periods of high electricity demand and limited supply from renewables. The projected increase of hydrogen demand and production in the short and medium term makes it important to ensure that the production does not cause bottlenecks or negative environmental impacts. Hence, the location and the operation of the electrolysers must be considered (BMWK 2023). Furthermore, to meet the expected demand for hydrogen, electrolysers are undergoing substantial scaling up, with production ramping up to mass quantities and individual electrolyser sizes now reaching the GW scale (Locci et al. 2024).

To ensure a seamless integration of a significant number of large electrolysers into the grid without surpassing their capacity limits or compromising their stability, comprehensive studies on various deployment scenarios are essential. Moreover, thorough investigations into the operational strategies of electrolysers for green hydrogen production are imperative to achieve competitive pricing in the hydrogen market (Bartels et al. 2022). The deployment of electrolysers is subject to the technical constraints of the power system and several issues can impact the performance of both electrolysers and the geographically distributed power system. For instance, the optimal sizing of renewable infrastructure complementary to hydrogen technology is not itself a trivial question (Longoria et al. 2021), additional to the optimisation of renewable energy-fed power systems with hydrogen production and accompanying cost estimations (Radner et al. 2023).

Studying the impact of large electrolysis integration requires on the one hand, focusing on the electrolysers themselves, building realistic models for them and investigating their performance, wear and tear as well as efficient operation strategies in line with the growing consumption of green hydrogen. On the other hand, it is necessary to investigate different deployment scenarios of electrolysers in existing power grids, taking into account the available hydrogen supply capacity and the load limit of the power grid lines, as well as to analyse and select feasible future development scenarios.

The next subsections give an overview of the related work and the use of a co-simulation approach for studying electrolysers' deployment.

Electrolyser Deployment and Modelling

Several studies have focused on specific cases and local conditions to examine the role of hydrogen production and consumption from an economic and environmental perspective, see e.g. Sorgulu and Dincer (2018), de Santoli et al. (2014), Khouya (2020), El-Taweel et al. (2019). However, there are few recent studies about the effects of the integration of electrolysis facilities on power grids. For instance, Bodal and Korpas (2017) investigated the capacity sizing of the electrolyser and H_2 storage in Northern Norway, considering the impacts of electrolysis in a simplified power grid of ten buses. They represented a transmission grid by DC power flow equations and show that a high utilisation rate of H_2 storage reduces grid congestion, but the regional expansion of the grid itself has a negative effect as it increases the congestion level.
Vom Scheidt et al. combined the electricity system model and hydrogen supply chain model to estimate the effects of regulation on grid congestion due to electrolysis integration in Germany. They calculated electricity prices and congestion management costs and show that, for instance, given current uniform single prices in Germany, hydrogen production increases congestion costs in the electricity grid by 17%.
Schlund and Theile presented a model framework including mixed-integer linear equations and a Markov chain Monte Carlo simulation for stochastic electricity prices to assess a grid-connected electrolyser's dispatch. Within a case study of the German electricity market, the effect of simultaneity on the dispatch was assessed. They state that the simultaneity regulations at the interface between hydrogen and electricity must consider the trade-off between economic viability, full load hours and associated emissions of electricity-based hydrogen.
Whereas the reviewed works mostly adopt an optimisation approach, this paper presents an open co-simulation approach to address the challenge of studying the impact of electrolysis on the grid. By utilising a scenario-based methodology, various combinations of operational strategies and electrolysers' placement are used to formulate scenarios which are simulated to unfold the impact on the grid, the electrolysers and the environment.

Co-Simulation Approach for Power Grid Evaluation

Due to the increasing complexity of heterogeneous energy systems, evaluating their behaviour at every stage of their development is becoming steadily more difficult, ranging from early what-if architectural analyses to real-time simulations of the extension of existing energy systems. There are two ways to to keep benefiting from the results of simulation-based analyses: the entire system can be modelled and simulated with a single tool which is referred to as monolithic simulation, or established tools for the respective subsystems can be coupled in a so-called co-simulation (Schweiger et al. 2019). When the analysis requires the inclusion of models of existing energy systems in the simulation, their integration into monolithic tools is difficult or even impossible without developing them from scratch. Co-simulation allows integrating heterogeneous domain-specific simulators creating a shared simulation environment, which is the case of modelling of electrolysers and different power grid components. The co-simulation approach is also effective when dealing with multi-domain complex systems in which analytical assessment is no longer feasible considering their complexity and large scale (Schweiger et al. 2019).
mosaik is a Python co-simulation framework designed to combine existing models and simulations within a single data and time flow. It is language agnostic and provides an API and components for either different programming languages (i.e. Python, C++, and Java) or simulator software (e.g. MATLAB). This framework offers easy implementation of a co-simulation scenario and is well-documented (Barbierato et al. 2022). In this work, *mosaik* is employed and integrated an electrolyser model as well as power grid models so that they can be used as an open software solution to investigate different deployment scenarios.
The rest of this paper is structured as follows: the *Co-simulation design* section provides a description of the co-simulation setup, components and the used electrolyser model in particular, as well as the developed control algorithm. *Showcase I* & *Showcase II* sections describe use cases with the analysis of the impact of deploying large electrolysis capacity into German the extra high voltage level (EHV) and the Medium voltage level (MV) grids respectively, with related grid congestion and electrolyzer degradation analyses. Finally, the conclusion and the future work are presented.

CO-SIMULATION DESIGN, COMPONENTS AND THE SCENARIO SETUP

The co-simulation scenarios using *mosaik* are designed with the goal of analysing the impact of connecting a large number of electrolysers to the electricity grid. The co-simulation's main components are shown in Fig. 1 and explained in detail in the following subsections. A generic scenario in this work comprises a number of electrolyser models, electrolyser controllers, a grid model and a market model. The connection of the electrolysers (as loads) to the respective buses in the electric grid, the orchestration, and the data flow between the components of the simulation are handled by *mosaik* (Ofenloch et al. 2022). In a *mosaik* scenario, each model type is managed by a simulator (for details, see https://mosaik.readthedocs.io) which handles multiple entities of the same model, for example, one electrolyser simulator creates, initialises and manages stepping a number of electrolyser models as shown in Fig. 1. Further simulators are used: the fleet controller to host the electrolysers' operation strategies, and the data storage adaptor to save the results to a database.

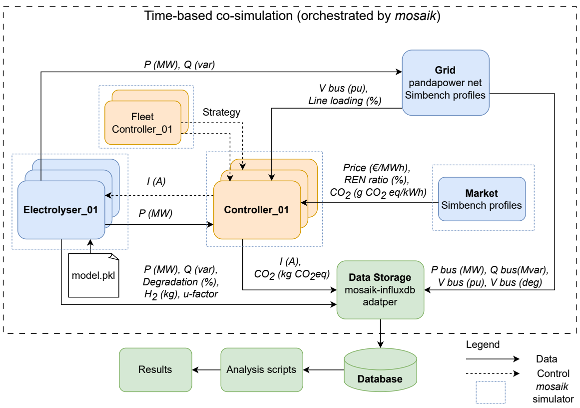

Figure 1: Components summary and data flow of the basic electrolysers co-simulation

Connections and Data Flow

In this general setup, at the initial time step, the controllers are initialised with assumed initial values for the grid bus voltages and line loadings. Each controller then calculates the initial current value I and passes it to the respective electrolyser model. The electrolyser models are then stepped by their simulator and the resulting load values P, Q are passed to the respective bus in the grid. The grid simulator will then run a power flow to calculate the grid state based on the electrolyser load as well as the generation/load profiles within the grid model. Finally, the respective results will be written to the database as shown in Fig. 1. In the next time step, the status of the grid and the market are passed to the controllers, for the controllers to calculate the operating point based on the grid and market info in combination with the fleet operation strategy. Afterwards, the flow is similar to the initial step.

Grid Simulator

The models for the German grid as provided by *SimBench* (see at https://simbench.readthedocs.io) benchmark grids are used for this setup. *SimBench* provides open-source datasets for the grid generation and load profiles as well as grid models as *pandapower* (see at https://pandapower.readthedocs.io) network objects for several scenarios (Meinecke et al. 2020, Thurner et al. 2018). In this case, the network objects can be coupled to the simulation using *mosaik*'s pandapower adaptor seamlessly. As *SimBench* provides the models at different voltage levels, it is possible to perform co-simulations on all grid levels. In this work, the impact study is demonstrated on the extra high and the medium voltage level. Other networks (here the terms grid and network are used interchangeably) can be studied using such a setup, provided that the network model is available along with its profiles, for example, for a study on the European network level.

Market simulator

The market simulator hosts the models that generate the electricity price data and the renewable energy share in the grid as well as an estimate of the CO_2 emissions values. As this work focuses on providing the tools to study the impact of electrolysis deployment, the data in this part is generated synthetically using the load/generation profiles provided by *SimBench*. The price calculation scales electricity prices based on the grid demand (loads) and renewable energy availability. It determines prices by proportionally relating loads to a maximum price ceiling while adjusting prices inversely with the availability of renewable energy sources. The CO_2 emissions associated with the generation are estimated by segregating renewable and non-renewable generation components in the *SimBench* profiles, scaling the latter to a normalised range, and computing CO_2 emissions by multiplying the scaled non-renewable energy with the maximum CO_2 intensity.

Electrolyser Simulator

The electrolyser model is based on a simplified cell model which is scaled up by the number of cells per electrolyser.
The cell model has current I as input and calculates the cell power P_{cell} and the hydrogen production rate $H2\_gen$ which are estimated as in the following equations (Järvinen et al. 2022, Carl-Jochen Winter 1988, Bessarabov et al. 2016):

$$P_{\text{cell}} = \frac{U_{\text{cell}} \cdot I \cdot \eta_{\text{eff}}}{d} \tag{1}$$

where d is a synthetic parameter applied to the power equation to simulate degradation and η_{eff} represents the cell efficiency. As the cell degrades, it is assumed that the voltage U_{cell} increases for a constant current drawn by the cell, leading to an increase in power consumption to maintain performance. The cell voltage U_{cell} is determined by the following components:

$$U_{\text{cell}} = U_{\text{ocv}} + U_{\text{ohm}} + U_{\text{act}} + U_{\text{con}} \tag{2}$$

Where U_{ocv} is the open circuit voltage, typically $1.229\,\text{V}$ for PEM cells. U_{ohm} is the over-potential caused by ohmic losses, given by $r \cdot j$, where r represents the area-specific resistance (typically $0.1\,\Omega\text{cm}^2$) and j denotes the current density ($1\,\text{A/cm}^2$ to $4\,\text{A/cm}^2$) (Järvinen et al. 2022). U_{act} represents the activation over-potential.

U_{con} represents the concentration over-potential resulting from mass transport phenomena. A linear approximation of the cell voltage equation yields (Carl-Jochen Winter 1988):

$$U_{\text{cell}} = U_0 + r \cdot j \tag{3}$$

The produced hydrogen is calculated by Faraday's law of electrolysis (Järvinen et al. 2022):

$$H2\_\text{gen} = n_F \cdot \frac{j}{n_e \cdot F} \tag{4}$$

where F is Faraday's constant, n_e is the number of electrons involved in the creation of one molecule of hydrogen, n_F represents Faraday efficiency, assumed to be 0.99 for simplicity.
With this cell model and as shown in Fig 2, the scaled cell model outputs the consumed power in W DC and the generated H_2. As input, the model takes the operation current and the degradation parameter. The cell degradation is simulated by decreasing d after each step as in the following equation:

$$d(t) = d(t-1) - \gamma \tag{5}$$

where the value of $d(t)$ represents the degradation state of the cell, γ is a parameter degradation rate calculated according to the current change and the minimum and maximum γ values:

$$\gamma = \frac{|I(t) - I(t-1)|}{I_{\max} - I_{\min}} \times (\gamma_{\max} - \gamma_{\min}) + \gamma_{\min} \tag{6}$$

In this cell model, for the same current value (e.g.

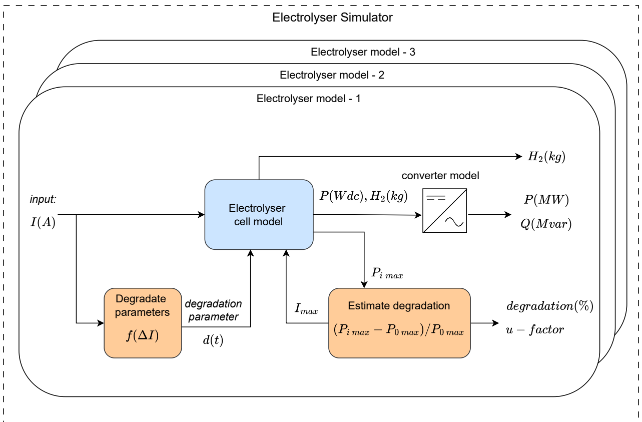

Figure 2: Electrolyser model within a *mosaik* simulator, showing the degradation estimation approach using cell models and an external parameters degradation function

I_{max}), a degraded cell will lead to an increased cell voltage and hence higher consumed power for the same I_{max} value. For calculating the degradation in per cent, the power value P_{max}, that the model produces at a time step, is compared to the initial P_{max} value to estimate the cell degradation in % as follows:

$$degradation = \frac{P_{t\_max} - P_{0\_max}}{P_{0\_max}} \times 100 \tag{7}$$

Finally, the cell utilisation factor is considered as the ratio between the operating current and the maximum current.

Controller simulators

The controller is the entity that contains the operating strategy. In the general co-simulation setup, the controller can monitor the grid status, e.g. specified lines for loading, bus voltages as well as market information. A generic operation strategy based on price or energy mix threshold is provided as in Algorithm 1.

Algorithm 1 Set I based on price/energy threshold

procedure SET_I
  Input: *point*, *threshold*, *line_loading*, I, *I_max*, *I_min*, ΔI

  if $point < threshold$ **then**
    if all *loading_value* $<$ 95 for *loading_value* in *line_loading* **then**
      if $I < I\_max$ **then**
        $I = \min(I + \Delta I, I\_max)$
      end if
    end if
  else if $point \geq threshold$ **then**
    if $I > I\_min$ **then**
      $I = \max(I - \Delta I, I\_min)$
    end if
  end if

  if any *loading_value* $\geq$ 95 for *loading_value* in *line_loading* **then**
    $I = \max(I - \Delta I, I\_min)$
  end if
end procedure

Moreover, it is possible to group a number of electrolysers in a fleet using the fleet controller, to enable more complex scenarios where several fleets of electrolysers operate with different goals/thresholds. The threshold values for line loading and the price are chosen arbitrarily and can be replaced by more reasonable values depending on the use case.

SHOWCASE I: ANALYSIS OF ELECTROLYSERS INTEGRATION INTO THE GERMAN EHV GRID

In this showcase, the analysis of the impact of deploying large electrolysis capacity on the German EHV grid congestion situation is demonstrated. The generic setup and the various components described before are used to create multiple scenarios for the analysis. *SimBench* future scenarios 1 and 2 (for the years 2024 and 2035) were assumed to represent the grid model and its profiles. In short, scenario 2 (the year 2035) represents the EHV grid profile with higher renewable integration compared to scenario 1 (the year 2024), the EHV lines are the same in both scenarios. An electrolyser unit is assumed to have 2600 cells and hence around 80 MW capacity. A fleet of 152 electrolysers is assumed and distributed over the grid to represent around 12 GW of electrolysis capacity. The electrolysers are distributed along the grid buses, whereas two different spatial distributions are assumed here: near the H_2 backbone and near renewable energy sources (RENs). In “near H_2 backbone”, electrolysers are distributed to buses near the projected H_2 grid as in the European Hydrogen Backbone (EHB) initiative plan (EHB 2023). In “near RENs”, they are distributed to buses that have the most renewable generation in the grid.

Two electrolyser operating strategies are assumed: renewable-driven and price-driven. In the renewable-driven strategy, the electrolysers operate to produce greener H_2, ramping up to their maximum current when the renewable share in the grid is over 50% (renewables threshold) according to algorithm 1. Furthermore, the electrolysers’ controllers receive the line loading of the lines directly connected to the electrolyser bus, to ramp the electrolyser down whenever there is an overload on these lines. A similar operating strategy is used according to a price threshold, with a price threshold of 70 €/MWh. Finally, two reference scenarios are used to represent the boundary cases: the electrolysers running at their maximum current, and a simulation without electrolysers. Table 1 lists the scenarios of this showcase.

Table 1: Showcase I scenarios summary

Scenario	Year	Strategy	Distribution
1.1	2024	RENs driven	near H2
1.2	2024	price driven	near H2
1.3	2024	max. current	near H2
2.1	2024	RENs driven	near RENs
2.2	2024	price driven	near RENs
2.3	2024	max. current	near RENs
3.1	2035	RENs driven	near H2
3.2	2035	price driven	near H2
3.3	2035	max. current	near H2
4.1	2035	RENs driven	near RENs
4.2	2035	price driven	near RENs
4.3	2035	max. current	near RENs

The scenarios in table 1 are run for 1 year, with a time resolution of 15 minutes. The results are analysed regarding the impact on the grid and the electrolysers for each scenario. For example, the increase in line loading in % caused by the electrolysers can be examined to identify lines with high congestion and determine which units are causing that. Furthermore, the unit operation strategy can be modified to mitigate congestion. Fig. 3 shows the line loading overview (change in line loading %) for scenario 1.1 as an example. line-100 in the scenario shown in Fig. 3 experiences high overload caused by the electrolysers. A closer look at the simulation results shows that this overload is caused by electrolysers no 45 and 46, which are connected to bus 1316 and 1317. The operating strategy for these electrolysers needs to be investigated further to figure out if they can be kept at this location.

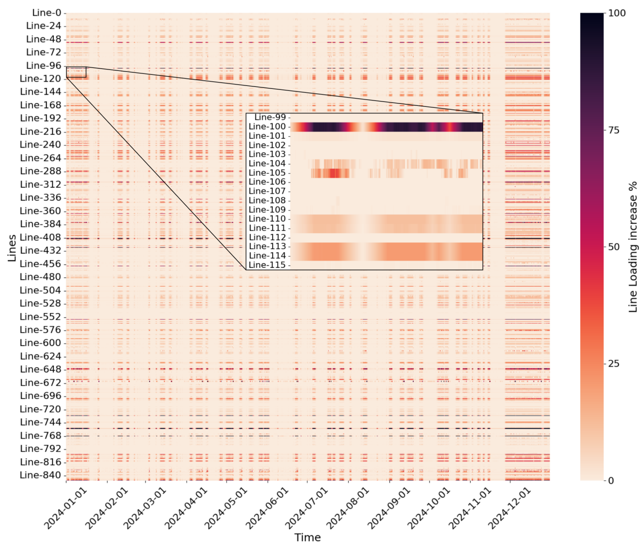

Figure 3: Overview of the fleet impact on the grid for scenario 1.1: the increase of lines’ loading due to electrolysers, identifying line 100 as an example of a highly affected line.

Fig. 4 shows the total number of overload incidents for the 12 scenarios. It can be noticed that the price-driven scenarios have a higher impact on the grid than the renewable-driven scenarios. The distribution of electrolysers near renewables causes fewer overload incidents than near the H_2 backbone, and the incidents in the year 2035 are less than in 2024, which can be explained by the higher renewable integration in the year 2035 scenarios.

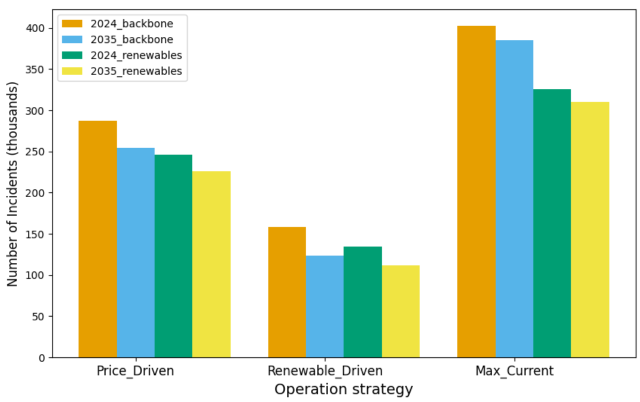

Figure 4: Grid impact Summary: Number of overload incidents for the 12 scenarios

Fig. 5 shows an overview of the electrolysers' ageing over the simulation year for scenario 1.1. Whereas most of the electrolysers reach around 25% ageing by the end of the year, some of the electrolysers do not age fast. The utilisation factor results of these electrolysers show that they also do not ramp up, hence their adjacent line loading needs to be investigated further. This can lead to relocating these electrolysers or other measures to ensure the effective utilisation of these units. Fig. 6

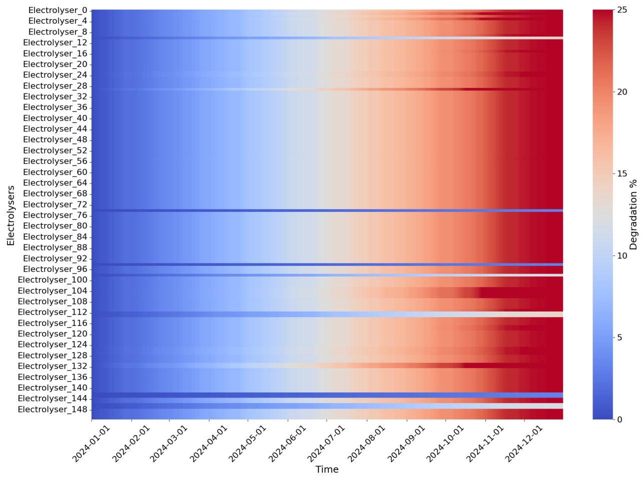

Figure 5: Overview of the electrolysers ageing over the year for scenario 1.1

shows an example of one electrolyser's ageing development over the simulation year along with the utilisation factor. Fig. 7 compares the average electrolyser

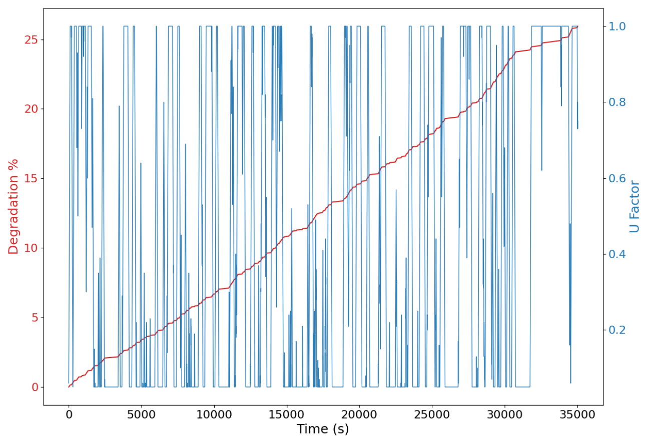

Figure 6: Single electrolyser ageing profile (electrolyser-0) along with the utilisation for scenario 1.1

degradation at the end of the simulated period for each scenario. The results show that the operating strategy is the main factor for degradation. Comparing the price-driven strategy with the renewable one, the price-driven strategy has a larger negative impact on ageing. The maximum current reference strategy shows the least ageing, as the electrolyser ageing is largely affected by the change in current, this can be noticed in Fig. 6 as well. Overall, the rate of degradation is only minimally affected by the spatial distribution of the electrolysers or the scenario.

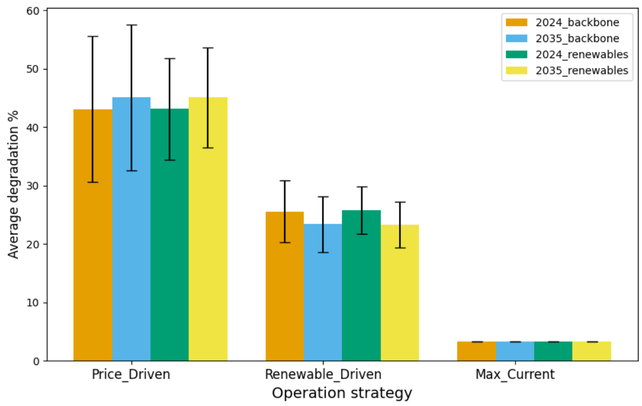

Figure 7: Impact on Electrolysers Summary: Average fleet degradation in % at the end of the simulation year for the 12 scenarios.

SHOWCASE II: ELECTROLYSERS INTEGRATION INTO A GERMAN MV GRID

In lower grid voltage levels, for example, HV or MV levels, connecting large electrolysers might affect the voltage stability. Furthermore, it might cause the bus voltage to drop below its operation limits. The provided co-simulation setup can also be used to simulate scenarios for such use cases. As a showcase, a German MV grid is chosen to connect one large electrolyser and study the impact on its limits, namely the urban MV network *1-MV-urban–0-sw* from *SimBench* is used for this purpose.

As a first step, to identify the feasibility of connecting a large electrolyser of 60 MW in terms of steady-state voltage stability, the steady-state stability limits of the buses in the network were found by incrementally increasing the load of the bus until the power flow calculation does not converge anymore (see Prabha 1994; chap. 2). Buses that do not have enough margin to connect the electrolyser were excluded. Fig. 8 shows the voltage stability margin for possible buses on a branch where the electrolyser is chosen to be connected.

A scenario of the MV grid without an electrolyser is run as a reference. Next, a scenario with the electrolyser connected to bus 81 is run over the year, in this case with maximum current operation strategy. Fig. 9 shows the bus voltage profiles of the two scenarios for one week. The results show that the bus voltages did not drop below the 0.9 pu limit after connecting the electrolysers. However, lines 69 and 70 in the highlighted branch in Fig. 9 experienced severe overload (around

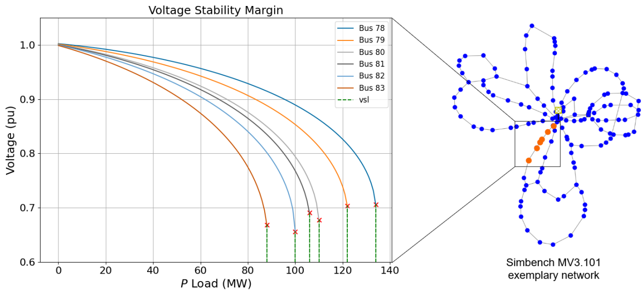

Figure 8: Estimating the voltage stability margin for selected buses in an urban MV grid

700%). Hence, the limitation of integrating the electrolyser in this case is identified to be the lines' capacity. Such analysis might be utilised further in a similar real-world use case to investigate the limitations and how they can be mitigated. For example, integrating more renewables at that bus, battery storage or even increasing the line capacity.

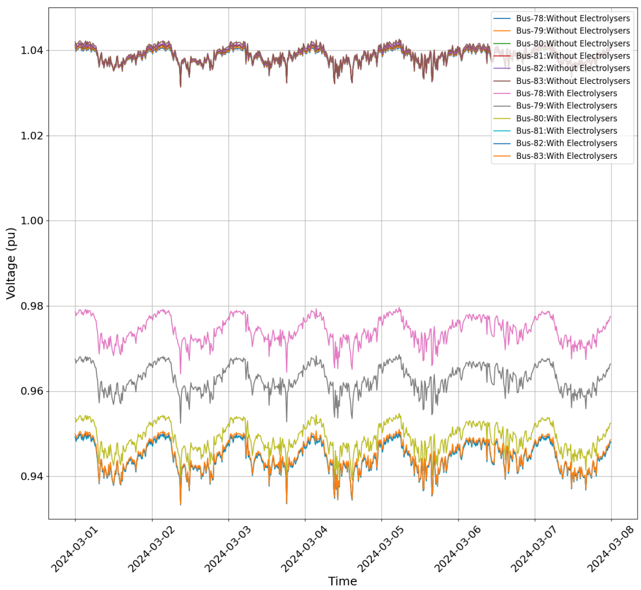

Figure 9: Network bus voltage profiles in pu showing buses 78-83 with and without the electrolyser

CONCLUSION

In this paper, we present an open-source co-simulation-based toolbox that provides tools for analysing the integration of large-scale electrolysers into electricity grids. In the context of assessing the potential of H_2 as an energy carrier, the presented tool allows for the examination of various deployment scenarios and operational strategies, thereby ensuring grid stability and efficient electrolyser utilisation. The basic structure of the tool, as well as the data flow is explained in this work, along with a simplified electrolyser model that can be used in such simulations. In addition, further open models for the electricity grid are assumed and used for scenario creation, with the possibility to easily replace them for other use cases. In this way, the proposed toolbox provides more flexibility, modularity and adaptability for researchers, enabling them to tailor the simulations to different use cases and environments more easily. To demonstrate the use of co-simulation scenarios, two showcases were provided and their results were analysed, showing which insights can be explored in each showcase. In the first use case, the impact of deploying around 12 GW of electrolysers in the grid showed that the operating strategy of the electrolysers highly affected the grid, whereas a price-driven strategy led to higher overload incidents compared to a strategy that is driven by the renewable energy share. The spatial distribution of the electrolysers was found to decrease the total overload incidents when the electrolysers were moved to buses with larger renewable generation. In contrast, the electrolysers degradation is minimally affected by the location of the electrolysers, but highly affected by the operating strategy. In a second showcase, the study of integrating individual electrolysers in lower-level grids is demonstrated. In an urban German MV grid, the results show that some of the buses did not have enough margin in terms of steady-state voltage stability to accommodate a large electrolyser. However, for an example of a bus with enough stability margin, the line capacity is the limiting factor for integrating the electrolysers and the bus voltage drop is within the limit.

In future work, the simulations can be extended to incorporate other grid stability and security aspects. For example dynamic simulations for studying more detailed impact within shorter simulation periods. Harmonic analysis along with the incorporation of detailed models for the converters can be used to study the ability to conform with grid requirements, for example providing low-voltage ride-through (LVRT) support. Furthermore, the use of the electrolysers as a flexibility source within a flexibility market can be further investigated, considering the electrolysers' ageing costs as against remuneration.

ACKNOWLEDGEMENT

This work is part of the project SEGIWA (Serienproduktion von Elektrolyseuren im Gigawatt-Bereich) funded by the BMBF under reference number 03HY121F.

CODE AND DATA AVAILABILITY

The code for the toolbox described in this work, along with the showcase results and analysis are provided under the public repository at https://gitlab.com/mosaik/examples/electrolysers-grid-scenarios

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