Flexible Operation of Electrolysis under Local Conditions and its Impact on the Medium Voltage Grid

A Study Case of an Industrial Area in the City of Ulm

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Abstract. Various industrial processes need hydrogen (e.g. steel production), which is commonly produced by fossil energy sources and causes a high amount of greenhouse gases. Hydrogen made of sustainably generated electrical power with the Power-to-gas technology (PtG) can substitute fossil-based hydrogen.

Distributed generation (DG) of electrical power, e.g. Photovoltaic (PV), in industry areas is increasing. Due to legal requirements, industrial companies must install PV when they expand their premises. Large ground areas and roofs of this buildings result high peak power of feed-in. An increasing shortage of fossil fuels, such as natural gas because of the sanctions in the Ukraine crisis in 2022, also increases the prices and economic risk which in turn makes PV even more attractive. The high feed-in peak power of PV force distribution system operators (DSO) to reinforce the electrical grid. A smart grid approach to tackle this challenge is the active balancing of feed-in on a local level, e.g. by PtG. In Germany economic constraints impede so far the utilization of PtG as flexible load.

This contribution presents an economic comparison of the costs and the revenue of electrolysis systems coupled with an electrical grid impact analysis based on simulation results. Furthermore, balancing power at distribution grid level will be considered. Using the data of a real industrial MV grid area near the city of Ulm enable close realistic assumptions.

The analysis shows technical results by the grid simulation and economic results. A result of the simulation is detailed data for loading of assets and voltage values for grid operation. The amount and influence of grid reinforcement point quantitative out technical reserve of robust constructed electrical MV grids and set this in context of local PV potential. In comparison to that was with the simulation demonstrated that flexible load (electrolysis) can be operated to avoiding grid reinforcement. The economic analysis shows the value and allow a quantitative comparison. Thereby was the electrolysis much more profitable than grid reinforcement. Different services and benefits of flexible operated loads were point out in the conclusion, where the outlook discuss gaps in the approach and further analysis that must be taken into consideration.

Keywords: Electrolysis · Economic Conditions · Grid Simulation · Medium Voltage Grid · Industrial Area

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1 Introduction

In 1990, the first Intergovernmental Panel on Climate Change (IPCC) assessment report [1] point out a warning on manmade climate change as a problem with global consequences. This problem has deteriorated in the past 30 years since 1990 because of increasing carbon dioxide emissions [2]. Today the Paris clime agreement [3] is the political framework where nations want to fix the targets to keep the global air temperature below 1.5 °C, based on the global mean air temperature of the year 1990. The current national targets and commitments of countries are insufficient to hold the goal of the Paris agreement [4]. However, not only scientific organisations are warning policy makers. A movement based in the middle of the society walkout for activating the national governance to act against clime change. The result is that Fridays for future (FfF) [5] is now able to initiate a discussion in civil society, politics and business that did not exist before.

Because of cheap generation prizes and ubiquitous availability of wind and solar power, electricity will become the most common energy type [6, pp. 60–61]. With a well-advanced substitution of fossil energy by renewable sources, storage solution will be more and more important to balance demand and generation in the electrical sector. Hybrid energy grids and multi energy systems couple energy systems that were separated in the past. That allow first to use the heat and gas sector as a power sink for electrical surplus and second with increasing feed-in of renewable electrical power, as a storage [6, pp. 70–71].

PtG is an essential technology for long time storage in scenarios with an amount of more than 80% of renewable energy of the annual electrical consumption in Germany [6, p. 70]. Decentralised energy resources (DER) in some German regions will exceed an 80% share of renewables long bevor this will be reached in average in the whole country. Therefore, the distribution grid will be a bottleneck for transporting the local power surplus from low voltage level to the high voltage level. Urban areas in many cases include electricity, gas and heat networks for distribution, to meet demand and to accommodate generation. That makes them the optimal location to integrate decentral sector coupling points like PtG.

The industry needs hydrogen for processes of producing goods e.g. in the sectors of steel [7], oil refinery [8] and chemistry [9]. These sectors have no alternative to hydrogen and emitted in total about 95 million tons of CO_2-eq. in 2015 and 2016. There is a large reduction potential that can be targeted today. Heavy-duty transportation, on road and in ships, trains without electrification lines, long-range vehicles and working machines are sectors where the substitution of fossil energy carriers is difficult. The energy density of electrochemical storage and low capacities are not adequate to the requirements of these sectors. Hydrogen could be a promising solution in combination with fuel-cell technologies [10], [6, pp. 177–178].

All these influences also motivate German politics to discuss existing regulation for PtG from a new perspective [11]. The interest of political authorities, on federal, state and European Union level is increasing.

This paper is structured in six sections. Section 1 I presents a background to the topic based on the regulatory framework and a literature review. Section 3 describes the approaches followed to perform the analysis of this contribution. Section 4 shows the results of the performed simulations, whereas Sects. 5 and 6 focusses on the conclusions and the outlook.

2 Background

2.1 Legal Framework for PtG in Germany

PtG is a coupling technology that enable the production of hydrogen gas based on electrical energy and water. Through a further process step, methane can be produced using CO2. In general, there are various application scenarios for the use of gas, e.g. for mobility, production of goods, heat or electricity generation. In 2011, a preferential feed-in of gas (hydrogen and methane) based on renewable resources was enshrined in law, [12] §3 Nr. 10c.

In Germany for private customers the portion of taxes, levies and fees is at 51.4% (year 2021) of the total prize for electrical energy, excluded grid utilisation charge [13]. The following exemptions are possible to reduce extra costs from taxes, levies and fees for storage:

- Electrical power that was used in PtG can temporarily (20 years) be exempt from grid utilisation charge [6, p. 826]. 24.5% from extra costs [13].
- The price of renewable energy that was consumed to produce gas by PtG can be exempt to the renewable energy law (EEG) levy, if the gas will be again used to generate electrical power [6, p. 828]. Thereby it is possible to use the public gas grid for a balanced transportation. 20.4% from extra costs [13, 14].
- An exempt of the electrical tax is possible, if the electrical consumption are in close distance to the electrical generator [6, p. 831]. 6.4% from extra costs [13].
- Value added tax (VAT) will be paid by costumers and is exempt for the PtG operator. 16% from extra costs [13].

Overall, the total price of electricity consumed by PtG could be reduced to 67%, assuming residential customers and including grid utilisation charge. The price excluding taxes, levies and fees can be different for PtG. The regulation in Germany allows companies that are also operators of PtG to conclude supply contracts or to buy their electricity directly on the electricity exchange. Various products can be traded. Supply contracts guarantee stable prices over a certain period of time. On the other hand, the exchange could be more profitable, but is associated with a higher risk. Day-ahead and intraday products are available on the exchange [15]. Frequency control reserve can be traded in Germany via an online platform provided by the four transmission grid operators [16].

2.2 PtG as Flexibility for Grid Integration of Renewable Energies

PtG is a technology that enables power transmission from the electrical sector to the gas sector. Gas is no final energy but it offers the function of transportation, conversion in heat and electricity as well as energy storage. Many devices for electrical and heat generation use natural gas as fuel today. These conditions make a substitute natural gas

(SNG) relatively easy to integrate in existing infrastructure. Compared to SNG, hydrogen provide a higher efficiency, is much less clime gas effective and can be used in different applications today.

There are three main hydrogen production technologies, which differ in their flexibility: Alkaline electrolysis (ALE), proton exchange membrane (PEM) electrolysis and high temperature electrolysis of steam (HTES). The most suitable technology for balancing fluctuating electricity generation from renewable energy is PEM electrolysis [6, pp. 357–359], [17]. PEM electrolysis produces hydrogen of high purity. High purity is required for many applications in the industry and medicine. PEM electrolysis is available in sizes in terms of kW to MW, e.g. [18, 19]. This power range is common in the medium voltage level of distribution grids. The efficiency of the PEM electrolysis can be increased to up to 90% if the heat loss is used to cover the heat demand. Temperatures of up to 65°C can be achieved [18]. This heat can be used for space heating and fed into many district heating networks. Due to the technical conditions, district heating is spatially limited. Therefore, it is usually available in urban areas or near a main demand.

2.3 Business Models for PtG

Due to the importance of long-term storage, PtG has been investigated in numerous research projects, papers and studies, e.g. [20]. Worldwide, a total of 56 projects (24.1 MW electric) for hydrogen production were indicated in 2019.

Several **business models** for PtG have been published. E.g.: [21] provide analyses of the impact on the economic viability when control reserve is included in the PtG business model. The results show a significant reduction of costs for methane and hydrogen production. However, the market design in Germany has been under development since October 2014 [22, 23]. In [24], the effect of an integrated value chain was analysed. All necessary resources (electricity, water and carbon dioxide) were available in the environment of an existing pulp mill. In this case financial success was achieved. Therefore, it was one recommendation that PtG markets would be in the transport sector and in the chemical industry. In general, grid services and value chain are the two major aspects of the economic viability of electrolysis and PtG.

Especially the value chain has a strong influence on which **location** PtG can be economically viable. The impact of a PtG system on the grid environment is also an issue that must be considered if a positive effect shall be achieved. In [25], an approach is presented on how large scale battery storage systems (severel hundreds kW) can be integrated into a distribution grid in a technically and economically way. A PEM electrolyser can be similar flexible operated like a battery storage, however, without generator operation. Therefore, this approach is also suitable for PEM electrolysis when grid reinforcement due to feed-in power is necessary. With an ongoing energy transition to renewable energy of the system, this condition increasingly occurs. [26] target also the impact of PtG on the electrical grid and point out the advantage of a coupled consideration in electrical and gas grid planning. In this paper, the impact of different business models on the operation of PtG is analysed. Furthermore, results of a simulated medium voltage (MV) electrical grid in an industrial area based on real data are presented.

3 Methodology

This section describes the business models studied, analytical approaches and assumptions used to conduct the analysis of this paper. The reference year for electricity demand, existing PV, rooftop potential, economic costs and legal regulations is 2020. The grid infrastructure model is based on data from 2016 because of grid data availability issues. However, most of the model data has been adjusted to current conditions based on information from the grid operator. For electrolysis, PEM development is considered until 2030. Additional technologies required for modifying output products in case of e.g. pressure or transport of gas have not been considered, excluded gas grid feed-in.

The approach of this paper combines an economic analysis and the grid simulation method. The simulation for a whole year takes seasonal effects into account and allows extrapolation of the results to the economic lifetime of the assets. The focus on the MV grid allow results on the most relevant grid in the distribution grid. The detailed economic analysis of the businesses considers all their input and output products.

3.1 Business Models

This contribution presents a fix business model combined in several installation scenarios. To point out challenges of today's regulation for electrolysis, conventional methods will be compared to a best practice approach of costs for society. Thereby all in- and out-puts of the electrolysis were involved, depicted in Fig. 1.

At one hand, consumed electrical energy consumed by electrolysis is the most important economic value. On the other hand, hydrogen as the main product is relatively easy to store. Therefore, it is possible to produce hydrogen when cheap electric power is available or even grid services are required. Based on the principle of subsidiarity, the following markets of the electric system have been prioritised. These principal priories low operation levels of the electrical system and gain resilience on higher operation levels. This enables robust operation of the overall system even if individual low levels fail in operation. The frequency containment reserve (FCR) generally balances the electrical system and is therefore a fundamental priority.

1- Frequency containment reserve (FCR): Flexible electric power will be traded at transmission grid level and balances the electrical grid on system level, EnWG §13(1), [12].

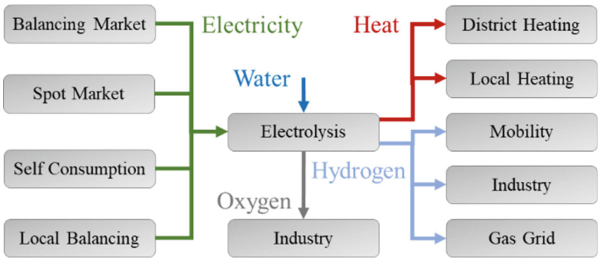

Fig. 1. In- and out-puts of the electrolysis

2- Self-consumption (SC): Targets surplus electricity in the immediate surroundings of the electrolyser, i.e. considering the feed-in of a surrounding PV and the consumption at the connection grid point of PEM. This surplus electricity will be consumed by the PEM in order to produce gas.
3- Local Balancing (LB): Targets surplus power in the distribution grid area around the electrolyser, i.e. considering the feed-in and consumption in the surrounding grid section in order to prevent local grid congestion in case of too high feed-in.
4- Spot Markets: Electric power will be traded at transmission grid level and consider a relative short time frame.

A reference scenario containing the economic costs for the grid reinforcement, as a common solution today for grid congestion, without considering flexible load management provides the basis for comparing the economic approach with a future scenario. An economically optimised operation of the electrolysis in the limits of today's regulation will not be part of this contribution, since the focus is on future scenarios.

The produced products on the output side of the electrolysis will be sold to different markets. It is assumed that there is sufficient immediate consumption and storage capacity for hydrogen, oxygen and heat. However, different markets in the three categories are available including their limitations. The prioritization was done considering the economic value and thier greenhouse gas reduction potential. The amount of the hydrogen markets at Ulm are prioritized as described hereinafter:

1- Industry: Including metal processing companies, research and crafts to 2,599.7 MWh/a [27].
2- Mobility: One installed hydrogen gas station at Ulm with demand of approximately 39.4 MWh/a [27].
3- Gas grid: The amount of hydrogen in the gas grid was assumed to be a maximum value of 5% of the annual demand and the total annual energy of natural gas consumed in Ulm in 2020 [28]. It results an amount of 125,300 MWh/a hydrogen.

The amount of heat markets is assumed and prioritised as described below:

1- Local heating: this quantity is to be assumed for each individual consumer in the vicinity of an electrolysis, which was localised during the network simulation.
2- District heating: The amount of heat that was consumed in district heating grid at the city of Ulm is around 700,000 MWh/a, published by two grid operators [29, 30].

The amount of oxygen was assumed to be 315,135 Nm^3 in 2018 based on information from a large consumer of oxygen in Ulm [31]. No prioritisation was necessary.

3.2 Modelling and Assumptions of the Economic Analysis

Based on the previous subsections, business models were combined in the future scenario. The flow chart, depicted in Fig. 2, couples the consumed energy of the electrolysis in the different markets. This allows considering multiple markets and operation of the electrolysis. The Table 1 give a description of the shortcuts in Fig. 2, which run for the total number (n) of the every single electrolysis (x) and time steps (t) during the period (p).

Table 1. Shortcut description of Fig. 3

	Description
$E_{H2,max}$	Energy that can be maximal consumed over the time step (t) by an electrolysis system (x).
E_{PV}	Energy that was produced by a PV system.
$E_{H2,SC}$	Energy consumed by an electrolysis in a close area to a PV.
E_{load}	Energy of the load of a consumer that is close to a PV operator.
F	Factor that represents the normalized blocked power of the electrolysis for frequency containment reserve (FCR).
$E_{H2,LB}$	Energy that might be consumed under the conditions of local balancing by the electrolysis (x). Conditions are the normalised voltage (u) and asset stress (C).
$E_{H2,FCR}$	Energy that might be consumed under the conditions of FCR by the electrolysis (x). Conditions are the grid frequency (f) [32].
$E_{H2,SM}$	Energy that might be consumed under the conditions of spot market by the electrolysis (x).
u	Normalized voltage. Operation voltage divided by nominal Voltage.
C	Line and transformer stress. Operation power divided by nominal power.

For the comparison of the economic results of the scenarios, the net present value (NPV) method was chosen in this paper [33]. In cooperation with a municipal grid operator the database of this analysis was prepared as realistically as possible. The assumptions for calculating the economic models are summarised below.

The general economic assumptions for the future and the reference scenario, which are necessary to calculate the NPV, are listed in Table 2 WACC (weighted average cost of capital) is the assumed factor for the calculation of the cost of capital to investors in PEM electrolysis.

The **reference scenario** considers grid reinforcement of all assets operated under critical conditions in the area in case of all potential PV is installed. The reference includes PV potential. This includes costs for cable and transformer stations. A cost assessment was carried out taking into account various sources [34, 35] which have been evaluated in an interview with a distribution grid operator held in December 2019. This allows the specific CAPEX to be used for the area under study. The cost of installation of an MV cable in sealed urban areas is assumed to be 215 €/m. The price for transformer is assumed based on [35]. The economic lifetime for all grid assets is assumed to be 30 years. The OPEX for MV cable and MV/LV transformer have been assumed based on an interview with the local distribution grid operator held in April 2020. DSO generates revenue through reversals in grid reinforcement and return on equity. This is set by the German grid agency at 6.91%.

Spot markets were represented by data from the day-ahead market. The data was provided by the German grid agency (dt. Bundesnetzagentur (BNetzA)) for the year 2020 [36]. The price is given in €/MWh in a time resolution of one hour. There, the energy

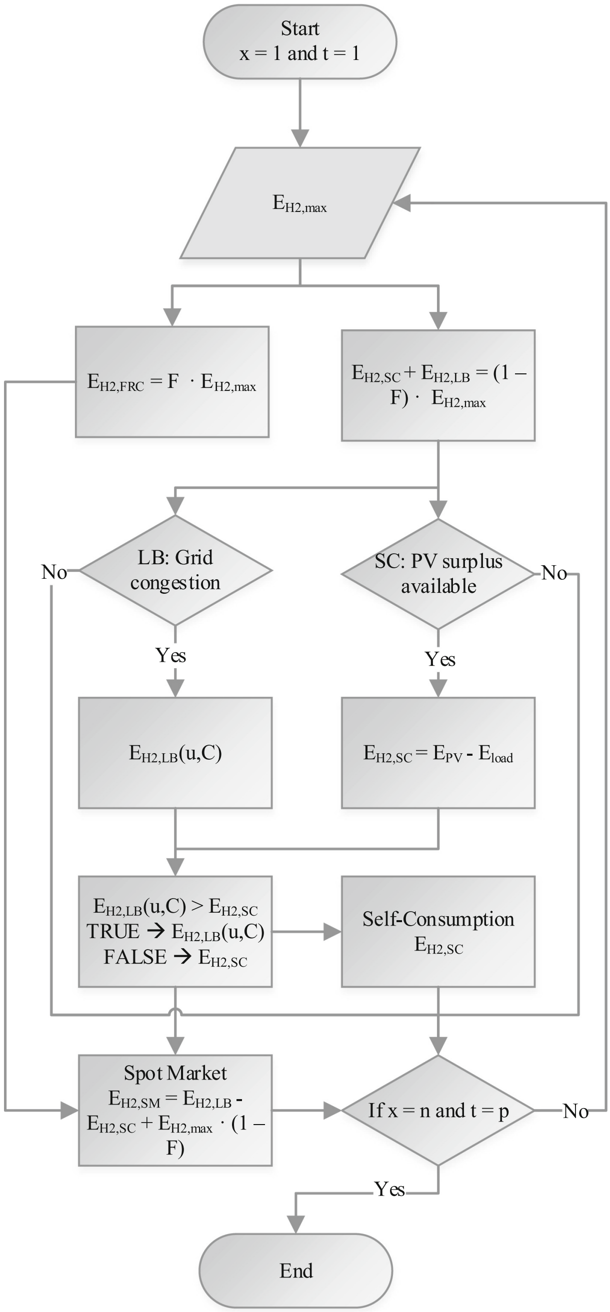

Fig. 2. Flowchart for prioritized business models

Table 2. General economic assumptions for the future scenario

Scenario	Credit interest rate [%]	WACC [%]	Credit for CAPEX [%]	Credit repayment per year [%]
Future	3	4.5	90	4.5
Reference	3	4.5	100	3.33

Table 3. Economic assumptions regarding PEM electrolysis

CAPEX [€/kW]	OPEX [€/kW/]	Total lifetime of cell stack[h]
811.26 [20, p. 175]	11.31 [20, p. 44]	60666 [20, p. 41]

consumed is remunerated, in the case of FCR and local balancing (LB). In addition to the market price, various additional costs are required, which are considered [13]:

- Concession fee: 0.0166 €/kWh
- Offshore liability levy § 17 f EnWG, special consumer levy §19 StromNEV, levy for disconnected loads §18 AbLaV and CHP (combined heat and power) levy: 0.00109 €/kWh

The transmission system operator will require the **Frequency containment reserve (FCR)** to balance frequency in the electrical system. The price will be determined by a merit order of the offered prices and required control reserve. This mechanism as well as the prequalification is not modelled in detail in the paper. 15% of the nominal power of the PEM was blocked to ensure the availability of FCR. The PEM was operated with 15% to ensure flexibility only in negative direction and will be able to produce relative constant output. Positive FCR will be provided by other electrical generation devices in the FCR operator's pool, e.g., fuel cells, CHP or gas turbines, which have not been modelled in detail in this paper, too. The electrical energy that was consumed to provide power for FCR will be traded with the price of the spot market. Historical price data for FCR was provided by the transmission grid operators [16]. The prices are given in €/MW and for the time slice. In the second half of 2020, the time slice for bidding was changed from 24 h to 4 h. This significantly reduces the specific price per slice. For the analysis in this paper, a specific price per 15 min was calculated based on linear interpolation.

To evaluate the value of **local balancing (LB)** this contribution considers costs for conventional grid reinforcement (reference scenario). Only reinforcement that can be avoided by local balancing gain value. Gained value will be allocate as a compensation on the total number (n) of electrolysis (x). The allocation was calculated based on energy and power of the PEM during the time-period (p). This approach was general described in Eq. (1).

$$C_{LB}(x,n) = C_{LB,annual} \cdot \left(0.5 \cdot \frac{E_{H2}(x)}{E_{H2,tot}(n)} + 0.5 \cdot \frac{\overline{P}_{H2}(x)}{\overline{P}_{H2,tot}(n)}\right) \quad (1)$$

- C_{LB}, is the compensation that will be paid to the operator of an electrolyser that provide local balancing grid services.
- $C_{LB,annual}$ is the sum of all costs for grid reinforcement that has to be avoided in the area per year. The total investment costs for grid reinforcement were split in equal pieces using annuities under condition as outlined in the bullet point "reference scenario" in chapter B Business Models.
- E_{H2} is the sum of electrical energy that was consumed by the electrolyser (x) during the year.
- $E_{H2,tot}$ is the sum of electrical energy that was consumed by the total number electrolyser (n) during the year.
- $\overline{P}_{H2}$ is the annual mean power that was consumed by the electrolyser (x).
- $\overline{P}_{H2,tot}$ is the sum of the mean electrical power that was provided by the total number electrolyser (n).

Nonetheless, the consumed electrical energy of the electrolyser must be paid in a regular way at the spot markets.

The price of the PV surplus for **self-consumption (SC)** by the electrolyser will be determine based on the feed-in-tariff. The German grid agency (BNetzA) provides data of the feed-in-tariff for different power levels, in monthly time resolution [37]. The price was assumed based on the current level (07/2022) for PV from 40 to 750 kWp (0.051362 €/kWh). Extra costs were calculated as described in the section of the spot market.

Additional to electrical power, **water** is needed to run a PEM electrolysis. Water is available from the water grid at Ulm. The price has two parts: a base- and an amount-price. The base price depends on the coupling diameter of the pipe and is assumed to be 107.03 €/a. The amount-price depends on the consumed cubic meters of water and is 1.82 €/m^3 (including taxes) [38].

PEM **electrolysis** technology is not very common in the energy system up to now. Based on [12, 20, 21], scenarios of the technological development for today, 2030, 2050 and different power levels (1 MW, 10 MW and 100 MW) are available. In this contribution the electrolyser will be represented by the values for 1 MW and the estimated technological progress of year 2030. The economic lifetime will be calculated by the number of full load hours of the year and the total lifetime in hours. Divide the annual consumed energy by the nominal power of the electrolysis, it results the full load hours.

The price for heat at the **district heating grid** was researched at an interview held in December 2019, with a distribution grid operator to 20–38 €/MWh. In this contribution a price of 0,025 €/kWh was assumed. In addition, a price for grid coupling is necessary. This price is the same one that heat consumers have to pay and depends on the thermal power [12].

Local heat from the electrolysis will enable to substitute fossil-based heating of buildings in the direct neighborhood. The price of heating energy will be assumed to the price of substituted natural gas offered by the local distribution system operator (DSO). There are two parts of the price, an energy- and a base-price, which are 0.0542 €/kWh and 154.68 €/a, respectively [39].

The price for **hydrogen** used in **mobility** is fixed to 0.1815 €/kWh in Germany, based on a voluntary agreement of gas station operators, e.g. [40].

A price for **hydrogen** in the **industry** sector is difficult to assume. There can be a wide spread of the price, depending on different factors, like distance for delivery, amount of take, gas quality and type of delivery (e.g. gas bottles, tank). For this contribution a survey in December 2019 was started. The result was a number of answers from gas dealers and hydrogen using companies. None of them wants to be named in public for the prices. Based on this information, a price of 0.2 €/kWh was assumed in this contribution. That includes a delivery distance of 250 km, delivery in tanks, technical quality and a draw-off of 2000 Nm^3 per month.

For feed-in of **hydrogen** at the **gas grid** a specific price of 0,0542 €/kWh as substitute for natural gas was assumed [39].

Prices for **Oxygen** are similarly difficult to be assumed like hydrogen. There is no common energy related usage today. Main applications are in chemical industry processes and medicine sectors. There are similar price-influencing factors like in the field of hydrogen. An interview, held in February 2020 with a number of local consumers in the fields of research and medicine, results in an oxygen price of 0,1495 €/Nm^3 for storage in tanks [31].

3.3 Modelling and Assumptions of Grid Impact Analysis

Considering the economic boundaries and the operation for technical grid services for PEM electrolysers, the grid impact analysis was done. The setups and assumptions for the simulations are summarized hereinafter.

A quasi-dynamic simulation was conducted using the software PowerFactory and considering a time resolution of 15 min. The current existing PV led to no surplus power for usage at electrolysis. The results were conducted for the reference and future scenarios described above, in Sect. 3.2

The grid simulation was performed using real medium voltage (MV) grid data for an industrial area at Ulm (i.e. Donautal). The grid is fed by HV/MV transformers and has a ring network characteristic. The MV-grid is connected to 100 MV/LV transformer stations (TS) including 174 transformers and it has 76.5 km of underground cable lines.

The characteristic of existing load and feed-in profiles were gained by registered load measurement (RLM) as well as scaled standard load profiles (SLP) for the year 2020. The annual energy amount of the analysed meter profiles is classified in 15.2% of SLP and 84.8% of RLM. If the annual energy of potential PV were taken into consideration, the part of RLM decrease to 18.7%. Twelve different SLP types were used. At TS were four main group located, load and DER with SLP and RLM. In addition, the SLP were split in subgroups per SLP type. The allocation of the DER and load data to the TS was done with the approach of the shortest distance of the load and DER to the TS (i.e. nearest neighbour approach).

Potential of future **PV** were assumed with data of the ground area of the buildings in the industrial area (A) usage factor (A_{PV}/A_{roof}) of 0.55 [41] and a module efficiency of 5 m^2/kWp. The annual energy production of the potential PV was calculated to 911 kWh/kWp based on meter data of 2282 existing PV in the city of Ulm and the year 2020. The characteristic was calculated in the same way as SLP of existing PV. The allocation of the PV to the TS was also done with the nearest neighbor approach. There were in total 221 PV systems with a nominal module power of 65.4 MWp included in the simulation model. Figure 3 visualizes the additional potential PV power.

PEM electrolysis at the position of a critical TS is connected to the low voltage (LV) bus bar of the TS for self-consumption. This avoids local transformer reinforcement. On the MV bus bar of the TS an additional power is connected, to consume feed-in power, which potentially overload MV lines from previous TS and FCR. The total nominal power of electrolysis is calculated from the maximum power at the TS (MV + LV) during the period. The resulting characteristic of the electrolysis was rounded to full 100 kW and were also considered for the economic modelling [20]. Table 4 list an overview for operational data of the electrolyser. The fast and flexible operation is the base for dynamic grid services. The efficiency was used to calculate the hydrogen and oxygen production.

The **positioning** of the PEM electrolyser was done based of the analysis of the current grid, taken the PV potential into consideration. The analysis of this contribution focuses on the MV grid. Therefore, in the reference and the future scenario only TS were considered, which were also connected to MV lines that are overloaded. In addition to Fig. 2, the approach of modelling power consumption for the PEM electrolysis is in detail described for SC, LB and FCR hereinafter.

Self consumption (SC) will be triggered in cases of surplus nearby the PEM electrolysis. This was done by taking the potential PV (E_{PV}) and load (E_{Load}) with the nearest neighbour method at critical TS into account. Equation (2) show this approach.

$$E(x,t)_{SC} = \begin{cases} E(t)_{PV} - E_{Load} & if\ E_{Load} < E(t)_{PV} \\ 0 & otherwise \end{cases} \quad (2)$$

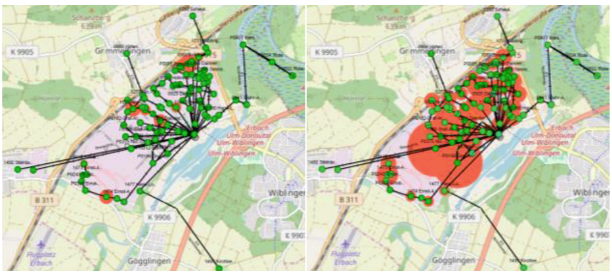

Fig. 3. Maps for visualization of current PV power (left) and additional potential PV (right) as red circles. Gray area is the industrial area of Donautal.

Table 4. Technical assumptions regarding PEM electrolysis

Nominal hydrogen efficiency [4]	62% (4.8 kWhel./Nm^3)
Dynamic range [20]	< 5% - 100%
Warm start time [20]	0.33 min
Cold start time [20]	4.3 min

Local Balancing (LB) of the PEM electrolyser was added to the model based on the grid simulation including the PV potential. The necessary load flow, to avoid overloading of current lines and TS, were fundamental to avoid local grid reinforcement. To ensure availability of LB for every time step, the higher value from self-consumption or local balancing was used in the calculation.

The regulation mechanism of frequency containment reserve **FCR** is modelled based on the regulatory framework [42]. The time resolution for the grid simulation is 15 min. Therefore, FRC ramps and mechanism below 15 min will not be considered in this model. Transmission system operators (TSO) provide measured data for the frequency (f) in a resolution with one second [43]. Missing values in the raw data were linear interpolated. To use the data in combination with the resolution of the grid simulation the mean of 15 min for positive and negative FCR separate was calculated, considering boundary limits of the linear regulation. This ensures that the integral of the 15 min time slice is still equal to the one-second frame in 15 min. Equation (3) represents the ramp of the normalized FCR power (F_{FCR}). The FCR power was subtracted with the blocked power. This results in the total FRC operation power.

$$F(x,t)_{FCR} = \begin{cases} 1 & if\, f(t) < 49.8Hz \\ \frac{f(t)-49.99}{0.19} & if\ 49.99Hz > f(t) > 49.8Hz \\ 0 & if\, f(t) > 49.99Hz \end{cases} \tag{3}$$

4 Results

4.1 Grid Impact Analysis

A first simulation of the recent grid showed that the grid must be updated. This will be necessary because of PV installations and loads from the period from the year 2016 to 2021. The grid was modelled based on data from the year 2016. It was necessary to add at 5 TS, 9 additional transformers. A standard transformer with a nominal apparent power of 630 kVA was included. Adding the potential PV to the updated status quo in the area, it results that 23 TS must be updated with additional 74 transformer. In sum, 3 km lines are overloaded or have critical voltage levels. Lines were reinforced by multiply their number in parallel.

In the reference scenario 2 TS were identified and in sum 3 transformer and 3 km lines were reinforced. In the future scenario 2 PEM at this 2 TS were included, which avoid the grid reinforcement from the reference scenario. The PEM electrolysis has a nominal power of:

– PEM1: 5,900 kW
– PEM2: 3,700 kW

The so located TS fix also the position for PV surplus and heat demand that was considered for SC and local heat.

The grid analysis reveals the total power that was fed-in to MV grid at the general calculation element of the grid simulation model (slack element). The comparison of the future and the reference scenario showed a reduction of 19% (9.0 MW) of the max reverse power during the year. The feed-in power increases up to 23% (2.3 MW). These are important indicators for the TSO, which must deal with an increasing number of MV grid areas reverse powers during times with high PV generation. Figure 4 depicts the total load flow.

The comparison of the mean day of the year of the total power shows, that the maximum power was reduced mainly during the noon of the day. Almost all the time the load flow switches with a relative constant value to consumption. This is illustrated in Fig. 5.

The grid was analysed through simulations, considering a max permissible voltage deviation of $\pm$ 3%. The rest of the voltage tolerance band (i.e. 10%) is for the transmission grid and other distribution voltage levels. The comparison of the analysis of the two scenarios for the maximum and minimum voltage at the simulated MV grid show a different characteristic. Figure 6 depicts the future scenario which alternates around 1.018 p.u. for maximal and 0.985 p.u. for minimal voltage during the year. The maximal voltage at the reference scenario is relative constant at 1.022 p.u. with strong voltage fluctuation during days with PV feed-in which result to higher maximal values of 1.029 p.u.. The Ref. Scenario has a narrow range for voltage changes, since grid reinforcement reduces the grid impedances, and thus reduces the sensitivity to power changes during the year. However, the PEM can also lint the voltage deviation, when it has the right control strategy.

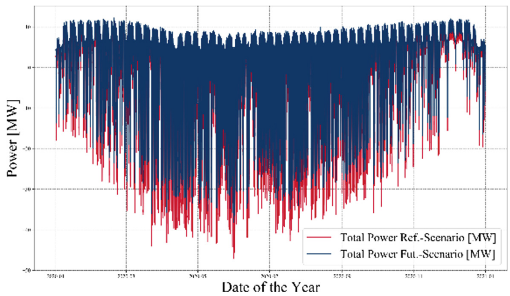

Fig. 4. Simulated annual total load flow at the slack element (i.e. HV/MV TS)

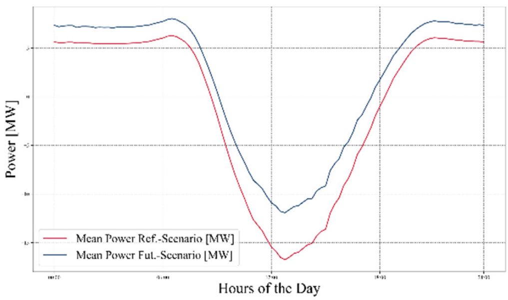

Fig. 5. Simulated total load flow as average day of the year at the slack element (i.e. HV/MV TS)

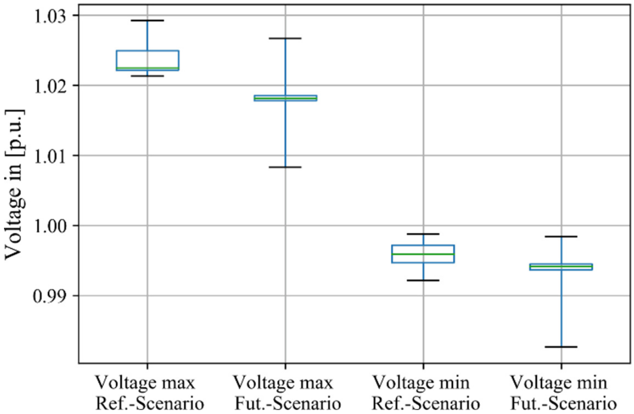

Fig. 6. Box-plot of the maximum and minimum voltage for the reference and fututre scenario

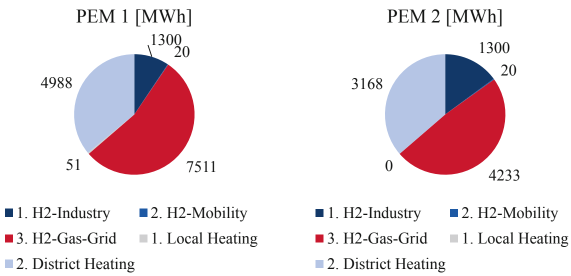

Fig. 7. Comparison of the output energy per market

The amount of energy that was provided at the different markets of the 2 PEM electrolyser is depicted in Fig. 7. The number of PEM split the total energy amount of the market for industrial hydrogen. It reveals in detail, that PEM 2 delivers greater portions of hydrogen to the industry. H2-mobility and local heating has no significant part. For both, it depends on the small market amount in relation to the other market.

The electricity generated by the PV that was consumed by the PEM electrolyser due to SC and LB is credited (46%) as green hydrogen. Electricity that comes from the German electricity mix and is consumed due to FCR (54%) is allocated to yellow hydrogen.

4.2 Economic Analysis

For the reference scenario the number of additional transformer and lines economic were rated using the approach described in Sect. 2.3

Taking into account the operating time of the cell stacks, 25 years of operation were calculated. The grid assets at the reference scenario are assumed with an economic lifetime of 30 years. An analysis of the cumulated cash flow, depicted in Fig. 8, show the outcome for PEM1 and PEM2 that represent the electrolysis at the future scenario and

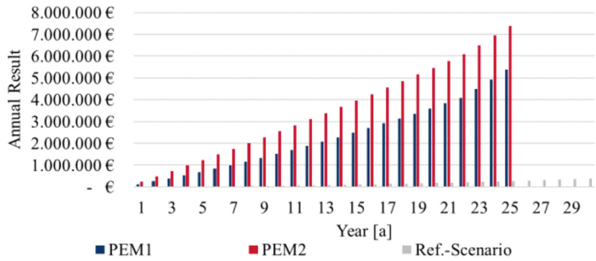

Fig. 8. Comparison of cumulated cash flow of electrolysis

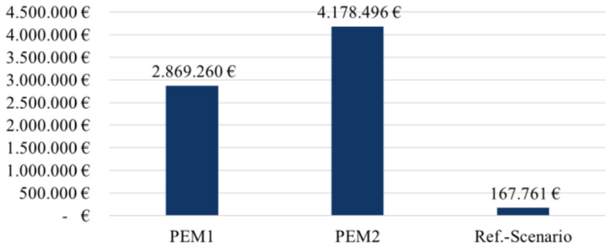

Fig. 9. Net present value (NPV) for the electrolysis of the future scenario and the reference scenario

the grid reinforcement of the reference scenario. Starting in year one all scenarios gain positive cashflow. PEM2 gain the highest values per year. This leads also to the highest NPV over lifetime. This can be explained with the large share of industrial hydrogen by PEM1. Industrial hydrogen gains the highest specific value per kWh of the output products. Hydrogen feed-in to the gas grid gain much less value. The reference scenario profit from the longer lifetime but achieve a much lower result than PEM1 and PEM2.

Considering the WACC for the net present value the results depicted in Fig. 9 was calculated. The electrolysis achieves a very positive result, while the reference scenario achieves a just positive result.

An analysis of the power that was not in operation during the year by the electrolysis show, that it was able to provide also positive FRC (increase operation power). If that power could be used, it will lead to addition hydrogen production, without additional flexible power. This can makes the electrolysis even more profitable.

5 Conclusions

This contribution analyses the profitability of a business case for PEM electrolysis, which consider different markets. It points out that the amount of regional markets and the value of the output products and prices for input goods has a strong influence on the economic success. Based on the research and assumed prices the studied systems can be economically viable compared to reference solutions.

The electrolysis consumes the surplus power of PV locally, whereas grid reinforcement enables the transport of power to higher voltage levels. If many distribution grid areas will do that, the surplus power accumulate at the transmission grid level up to critical values and additional grid reinforcement in the transmission grid would be necessary later. That make power balancing direct at distribution grid level more effective.

On the other hand, the risk of operation of electrolysis is during lifetime much higher than for grid reinforcement. Many different influences (e.g. price for output produces, electrical prices or disturbance during operation) can affect the economic viability of the system. In comparison, the business of grid reinforcement is very reliable and gain constant income for DSOs.

Many markets that have taken into consideration at this contribution are under strong influences of global trends today (2022). Gas and electrical prices increase more and more were development of electrolysis effect CAPEX and efficiency positive.

Today, local balancing is affected by a price increase for grid reinforcement and a less availability of assets (e.g. cable and transformer) at market. This makes it even more important to use alternative approaches, like flexible operated electrolysis, to tackle an ongoing installation process of generation units at distribution grids.

FCR is good to increase operation hours of the electrolysis. This is possible if only negative power is provided. This makes it necessary to gain a well-balanced pool of technical units that can also provide flexible generation for positive operation, e.g. CHP. Finally, units and devices gain value during active operation and lose value when they are in idle operation. Blocking such resources only for a few hours per year is not effective and can be very expensive. Flexible operation of a pool of demand and generation units need a smart operation to ensure an efficient dealing with resources. For example, it makes no sense to reduce electrical generation of PV and wind power while combustion generation units runs consuming fossil fuels. The fuel, which was used in combustion units, should be produced based on surplus power of PV and wind power, such as the gas generated by electrolysis.

Increasing prices for natural gas makes it more attractive to feed-in hydrogen to the gas grid as substitute. Prices for PV are mainly influenced by CAPEX. Therefore, electricity generation costs are not affected by price increase of fuels (e.g. natural gas) like combustion units. This trend affect the economic success of electrolyser in general.

Hydrogen, which was fed-in to the gas grid, can be used at other areas to provide fuel for power generating units. These units are flexible in operation and can provide additional power in times with less feed-in from PV and wind power.

Additional invest could be necessary to sell hydrogen at the different markets as the ones considered in this paper. Industrial requirements of hydrogen can be different from the assumptions that has made in this paper. For example, hydrogen in the field of mobility need gas stations to be refuel to vehicles. Therefore, at this point no final conclusion can be made to evaluate the economic environment of hydrogen. Furthermore, more economic details has to be taken into account.

6 Outlook

Some assumption in this contribution were researched during interviews held the year 2020. The pandemic makes it difficult to making progress during this time. Given the current situation and the impact on the economics of electrolysis, further analysis is needed.

Hydrogen has become even more under the focus by companies and governance in the last years. More and more electrolysers were installed in development projects by companies in Germany, transmission system operator (TSO) develop roadmaps for a hydrogen-backbone and negotiations were held with North African countries to supply hydrogen at Southern Europe. This trend will be considered in further analysis of the topic of this paper.

The data of grid model will be updated based on actual data of the DSO. Further analysis will use a nearest path approach, instead of nearest neighbour, to include meter data at the MV grid model. These both updates will increase the quality of the analysis significantly.

The updated grid model will be used to analyse additional trends like electro mobility and battery storage. Because of large parking spaces at industrial areas, electro mobility has a strong effect on load flow. In addition, PV in combination with local batteries can strongly affect the load flow.

A sensitivity analysis of the business cases to analyse the profitability of the different markets can be the base to optimise the economic operation of the electrolysis. Such analysis should be conducted later.

Grid reinforcement will be analysed with the consideration of the local situation and take e.g. space for additional TS into account. Actual and less blanket prices of assets will enable a more realistic base for the economic calculation of the reference scenario. In addition, the details of the regulated market for grid operators will be considered in further analysis.

Not least, markets on research level will be taken into consideration. Local markets for flexibility were developed during research projects (e.g. C/sells). Block-chain and Peer-to-Peer are trends that allow direct trade between operators of generation units and consumer of electric power. These new markets and approaches enable more subsidiarity in the electrical energy system and can strengthen people's encouragement for the energy transmutation toward renewable energy.

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References

1. 'Clima Change - The IPCC Scientific Assessment', Cambridge, 1990. Accessed: Jul. 25, 2022. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_I_full_report.pdf
2. 'International Panel on Clima Change- IPCC', Data Distribution Centre, Jul. 25, 2022. https://www.ipcc-data.org/observ/ddc_co2.html
3. 'United Nations - Clima Change', The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed Jul. 25, 2022).

4. 'Global Energy Transformation: A Roadmap to 2050 (2019 Edition)', International Renewable Energy Agency (IRENA), 2019. Accessed: Jul. 25, 2022. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf?la=en&hash=D3AF0A4437104F4815731C932729A699A8CF753F
5. 'UNSERE FORDERUNGENFÜR DEN KLIMASCHUTZ', Fridays for Future, 2019. Accessed: Jul. 25, 2022. [Online]. Available: https://fridaysforfuture.de/wp-content/uploads/2019/04/Forderungen-min.pdf
6. M. Sterner and I. Stadler, Energiespeicher - Bedarf, Technologien, Integration, 2., Korrigierte und ergänzte Auflage. 2017. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014. https://doi.org/10.1007/978-3-642-37380-0.
7. 'Einsatzgebiete für Power Fuels - Stahlproduktion', Deutsche Energie-Agentur GmbH (dena). Accessed: Jul. 25, 2022. [Online]. Available: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/Factsheet_PowerFuels_Stahlproduktion_Industrielle_Prozesswaerme.pdf
8. 'Einsatzgebiete für Power Fuels - Erdölraffinerie', Deutsche Energie-Agentur GmbH (dena). Accessed: Jul. 25, 2022. [Online]. Available: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/Factsheet_PowerFuels_Erdoelraffinerie.pdf
9. 'Einsatzgebiete für Power Fuels - Grundstoffe für die chemische Industrie', Deutsche Energie-Agentur GmbH (dena). Accessed: Jul. 25, 2022. [Online]. Available: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/Factsheet_PowerFuels_Chemische_Industrie.pdf
10. Dennitsa Nozharova and Werner Diwald, 'H2-Industrie Potenzialstudie Brandenburg', Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V., Jul. 2019. Accessed: Jul. 25, 2022. [Online]. Available: https://mwae.brandenburg.de/media/bb1.a.3814.de/Wasserstoff_Industrie_Potenzialstudie_Brandenburg.pdf
11. 'pv magazine', Bundestag soll Rücknahme der Netzentgelte für Power-to-Gas-Anlagen beschließen, Jul. 27, 2019. https://www.pv-magazine.de/2019/06/27/bundestag-soll-ruecknahme-der-netzentgelte-fuer-power-to-gas-anlagen-beschliessen/ (accessed Jul. 25, 2022).
12. Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - EnWG). 2005. [Online]. Available: http://www.gesetze-im-internet.de/enwg_2005/EnWG.pdf
13. 'Strom-Report', Strompreiszusammensetzung 2022 in Deutschland. https://strom-report.de/strompreise/strompreis-zusammensetzung/ (accessed Jul. 25, 2022).
14. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2021). 2014. Accessed: Jul. 25, 2022. [Online]. Available: https://www.gesetze-im-internet.de/eeg_2014/BJNR106610014.html
15. 'epexspot', Trading & Services. https://www.epexspot.com/en (accessed Jul. 25, 2022).
16. 'regelleistung.net - Internetplattform zur Vergabe von Regelleistung'. https://www.regelleistung.net/ext/?lang=en (accessed Jul. 25, 2022).
17. A. S. Aricò, S. Siracusano, N. Briguglio, V. Baglio, A. Di Blasi, and V. Antonucci, 'Polymer electrolyte membrane water electrolysis: status of technologies and potential applications in combination with renewable power sources', J. Appl. Electrochem., vol. 43, no. 2, pp. 107–118, Feb. 2013, https://doi.org/10.1007/s10800-012-0490-5.
18. 'H-TEC SYSTEMS', H-TEC SYSTEMS Hochleistungs- Elektrolyseure: Ready. Set. Supply. https://www.h-tec.com/produkte/ (accessed Jul. 25, 2022).
19. 'Siemens Energy', Hydrogen Solutions. https://www.siemens-energy.com/global/en/offerings/renewable-energy/hydrogen-solutions.html (accessed Jul. 25, 2022).
20. T. Smolinka, 'Studie: IndWEDe Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und -Wärme', NOW GmbH Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie, Berlin, Sep. 2018. Accessed: Jul. 25, 2022. [Online]. Available: https://www.ipa.fraunhofer.de/content/dam/ipa/de/documents/Publikationen/Studien/Studie-IndWEDe.pdf

21. M. Götz et al., 'Renewable Power-to-Gas: A technological and economic review', Renew. Energy, vol. 85, pp. 1371–1390, Jan. 2016, https://doi.org/10.1016/j.renene.2015.07.066.
22. 'Ein Strommarkt für die Energiewende', Bundesministerium für Wirtschaft und Energie (BMWi), Berlin, Oct. 2014. Accessed: Jul. 25, 2022. [Online]. Available: https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/gruenbuch.pdf?__blob=publicationFile&v=19
23. 'Bundesministerium für Wirtschaft und Klimaschutz', Strommarkt der Zukunft. https://www.bmwi.de/Navigation/DE/Themen/themen.html?cl2Categories_LeadKeyword=strommarkt-der-zukunft (accessed Jul. 25, 2022).
24. C. Breyer, E. Tsupari, V. Tikka, and P. Vainikka, 'Power-to-Gas as an Emerging Profitable Business Through Creating an Integrated Value Chain', Energy Procedia, vol. 73, pp. 182–189, Jun. 2015, https://doi.org/10.1016/j.egypro.2015.07.668.
25. M. Resch, J. Bühler, H. Huyskens, and A. Sumper, 'Optimale Positionierung von Großbatterien in Verteilnetzen', p. 36.
26. Albert Moser, Markus Zdrallek, Hartmut Krause, and Frank Graf, 'Studie Nutzen von Smart-Grid-Konzepten unter Berücksichtigung der Power-to-Gas-Technologie', DVGW Deutscher Verein des Gas- und Wasserfachs e.V., Bonn, Mar. 2014. Accessed: Jul. 25, 2022. [Online]. Available: https://www.dvgw.de/medien/dvgw/forschung/berichte/g3_03_12.pdf
27. U. Balzow, M. Jenne, L. Jörissen, G. Schlumberger, and S. Schwarz, 'Regionale, netzunabhängige Nutzung Erneuerbarer Energien', Ulm, Dec. 2017. Accessed: Jul. 25, 2022. [Online]. Available: https://pudi.lubw.de/detailseite/-/publication/54773-RENEE.pdf
28. 'Stadtwerke Ulm/Neu-Ulm Netze GmbH', Downloads. https://www.ulm-netze.de/online-services/downloads (accessed Jul. 25, 2022).
29. 'FUG fernwärme Ulm', Downloads Vertrieb. https://www.fernwaerme-ulm.de/service/downloads/vertrieb/ (accessed Jul. 25, 2022).
30. 'Zahlenspiegel 2020', SWU, Ulm, 2019. Accessed: Jul. 25, 2022. [Online]. Available: https://www.swu.de/fileadmin/content/unternehmen/SWU-Zahlenspiegel-2020.pdf
31. 'Universitätsklinikum Ulm, Abteilung für Materialwirtschaft', Apr. 01, 2020.
32. 'Technische Anforderungen an die automatische Frequenzentlastung', Forum Netztechnik/Netzbetrieb im VDE (FNN), Berlin, Jun. 2012. Accessed: Jul. 25, 2022. [Online]. Available: https://www.regelleistung.net/ext/download/ablaAnforderungenFnn
33. B. Idlbi, D. Stakic, M. Casel, D. Graeber, G. Heilscher, and M. Fiedler, 'Business Models and Grid Impact of Energy Storages and Controllable Loads for PV-Self-Consumption at Prosumer Level', in Proceedings of the 13th International Renewable Energy Storage Conference 2019 (IRES 2019), Düsseldorf, Germany, 2019. https://doi.org/10.2991/ires-19.2019.3.
34. 'dena-Verteilnetzstudie - Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030', Deutsche Energie-Agentur GmbH (dena), Berlin, Dec. 2012. Accessed: Jul. 25, 2022. [Online]. Available: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9100_dena-Verteilnetzstudie_Abschlussbericht.pdf
35. Benjamin Schott et al., 'Optimierung der Systemintegration fluktuierender Stromerzeugung aus erneuerbaren Energien am Beispiel der Photovoltaik auf Niederspannungsebene - Untersuchungen zu Möglichkeiten und Potenzialen zukünftiger Energieversorgungsstrukturen -', Stuttgart, Dec. 2014. Accessed: Jul. 25, 2022. [Online]. Available: https://www.ulm-netze.de/fileadmin/content/downloadcenter/Allgemeines/Smart_Grids/SYSPV-NS-Schlussbericht-Energieversorgungsstrukturen.pdf
36. 'SMARD Strommarktdaten', Marktdaten. https://www.smard.de/home/downloadcenter/download-marktdaten#!?downloadAttributes=%7B%22selectedCategory%22:false,%22selectedSubCategory%22:false,%22selectedRegion%22:false,%22from%22:1625781600000,%22to%22:1626731999999,%22selectedFileType%22:false%7D (accessed Jul. 25, 2022).

37. ‘Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen’, Erneuerbare Energien / Kraft-Wärme-Kopplung. https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/ArchivDatenMeldgn/ArchivDatenMeldgn_node.html (accessed Jul. 25, 2022).
38. ‘SWU’, Preise für Trinkwasser und Abwasser. https://www.swu.de/privatkunden/produkte-leistungen/trinkwasser/preise/ (accessed Jul. 25, 2022).
39. ‘SWU’, Unsere Gasprodukte. https://www.swu.de/geschaeftskunden/produkte-leistungen/gas/?tx_swuproductfinder_piproductfinder%5Baction%5D=list&tx_swuproductfinder_piproductfinder%5Bcontroller%5D=TariffData&cHash=9f35d7800eadf9be4641920e0a617e36 (accessed Jul. 25, 2022).
40. ‘H2 MOBILITY Deutschland GmbH & Co. KG’, Häufige Fragen. https://h2.live/faq (accessed Jul. 25, 2022).
41. M. Lödl, G. Kerber, D. R. Witzmann, D. C. Hoffmann, and D. M. Metzger, ‘Abschätzung des Photovoltaik-Potentials auf Dachflächen in Deutschland’, Graz/Austria, Feb. 2010, p. 14.
42. ENTSO-E, ‘P1 – Policy 1: Load-Frequency Control and Performance [C]’. Mar. 19, 2009. Accessed: Aug. 29, 2022. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/Policy_1_final.pdf
43. ‘Transnet BW’, Regelenergie Bedarf + Abruf. https://www.transnetbw.de/de/strommarkt/systemdienstleistungen/regelenergie-bedarf-und-abruf#netzf2018 (accessed Jul. 25, 2022).