Power-to-Gas in a Virtual Power Plant

possibilities and challenges

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***Abstract*— With the growing number of distributed power producers of renewable energy, the demand for a new way of managing them is increasing. A Virtual Power Plant (VPP) can help controlling and monitoring distributed assets to ensure stabilization of the grid. This paper provides a VPP case study by outlining the possibilities and complexity of monitoring and controlling a Power-to-Gas (P2G) plant through a VPP. This Power-to-Gas project is run by Greenpeace Energy together with the German city of Haßfurt.**

Keywords: Virtual Power Plant, Power-to-Gas

I. INTRODUCTION

Power-to-Gas is the process of supplying excess renewable electricity to an electrolysis process in order to convert the energy available in the short term into hydrogen that can be fed into local natural gas network and stored in the long term. This hydrogen is either available for purposes, like mobility, or can be converted back into electrical energy by means of re-generation. The P2G plant has been deployed in Haßfurt to reduce the impact of the renewable energy surplus in the distribution network. The P2G plant operates according to the demand and availability of renewable energy fed into the local electricity grid of the municipal utility Stadtwerke Haßfurt GmbH. Aside from using the excess renewable energy, the electrolyser provides grid frequency control for the German grid operators. The plant follows the steering signal from the VPP, responds within milliseconds and provides a flexible capacity of 1.25 MW within 20 seconds. It provides all three products of German grid frequency control: primary (FCR), secondary (AFRR) and minute control power (MFRR). The P2G plant was built by a regional municipal utility and distribution network operator, Stadtwerke Haßfurt. The plant generated part of the gas required to supply end customers, using renewable energy form the wind park in the municipality. The plant was controlled by Next Kraftwerke and was integrated into their VPP.

II. THEORETICAL BACKGROUND

A. Energy market in Germany

Electricity in Germany is traded in a liberalised market. The procurement and delivery of electricity therefore takes place under free competition. There are two basic ways of procuring electricity. In direct, bilateral timetable deals with electricity producers, so-called over-the-counter deals, and via an electricity exchange. Various products are available for procurement, all of which differ in terms of duration and trading time. There is the futures market, the day-ahead market, the intraday auction and short-term intraday trading. Another important market in the German energy system is the balancing energy market, which enables the transmission system operator (TSO) to provide flexibility from a system and thus generate additional revenue. The TSO is obliged at all times to ensure a balance between electricity generation and consumption. For this purpose, the TSO uses control power of different quality, with different call-up duration, call-up principle and time activation duration. The main differentiation criterion is the speed and duration of activation. All above markets are suitable for application of P2G installation, apart from the futures market, in which electricity quantities can be procured years in advance is not suitable for procurement due to the small size of the P2G plant and the short-term nature of the predictions [1].

B. Concept of Power-to-Gas

There are different methods of electrolysis, which are Alkaline Electrolysis (AEL), Membrane Electrolysis (PEM) and High Temperature Electrolysis (HTEL). The electrolysis of water means the splitting of water into hydrogen and oxygen with the help of electrical energy. From a chemical point of view, electrolysis is a redox reaction, in which two reactants exchange electrons with each other. The donating party is oxidized, the receiving party is reduced. The reaction is an endothermic reaction; this means the reaction only takes place when energy is

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supplied. Summarized in a chemical equation, the process can be described as follows:

$$2H_2O_{(l)} \xrightarrow{Elektrolysis} 2H_{2(g)} + O_{2(g)} \quad (1)$$

$$\Delta H = +286 \frac{KJ}{mol} \quad (2)$$

The P2G studied in this project is the PEM electrolysis, characterized by a very flexible operation and thus applicable in various load ranges. In PEM the charge exchange takes place via protons (hydrogen ions) and it uses a proton-permeable membrane. This membrane is pressed directly between anode and cathode and thus forms the membrane-electrode assembly (MEA). The MEA is surrounded by a polymer electrolyte, a so-called solid polymer electrolyte (SPE) [2]. The polymer electrolyte is surrounded by the bipolar plate, which is responsible for the landing exchange between the cells. The polymer electrolyte is highly porous and enables water to reach the anode directly via grooves and crevices to execute the anode reaction.

$$2H_2O_{(l)} \xrightarrow{Oxidation} O_{2(g)} + 4H^+ + 4\,e^- \quad (3)$$

The electrons are conducted through the polymer electrolyte from the bipolar plate to the anode. The oxygen produced during oxidation is removed by the polymer electrolyte. The protons or hydrogen ions ($4H^+$) released during the oxidation process pass through the PEM to the cathode, where the cathode reaction takes place with the electron provided by the polymer electrolyte:

$$2H^+ + 2e^- \xrightarrow{Reduktion} H_{2\,(g)} \quad (4)$$

The resulting hydrogen is very pure and free of contamination because theoretically no liquid occurs in the half-cell of the cathode. Nevertheless, a certain amount of moisture often occurs in practical operation, which still has to be removed from the gas. The polymer electrolyte must be characterized by high conductivity to transport the charge carriers and to ensure a high and homogeneously distributed current density as well as high permeability to ensure a uniform flushing of the anode with water and the removal of the resulting oxygen or hydrogen (on the cathode side).

There are several options for further use of the hydrogen produced in the electrolysis process. Firstly, on-site storage of the hydrogen for subsequent reuse in a hydrogen CHP or fuel cell. Secondly, utilization as a fuel in a hydrogen filling station or as a raw material for the chemical industry. To avoid development of costly hydrogen infrastructure, the hydrogen can be fed into the existing natural gas infrastructure, either unchanged or after undergoing a methanisation process of transforming hydrogen to methane using CO_2. In the case of direct injection, the amount of hydrogen that can be fed into the grid is restricted to 2-10% hydrogen content and therefore severely limits the amounts of hydrogen that can be stored or transported in the existing natural gas infrastructure, which is a crucial restriction for this research project.

Another critical aspect of implementation of P2G system to store excess of the renewable energy is the efficiency of the overall process - one of the main criticisms of the technology. [3] and [4] compared the different electrolysis methods with regard to their degrees of effectiveness.

C. Importance of Power-to-Gas for the energy transition

The energy sector faces the challenge of integrating supply-dependent and volatile renewable electricity, mainly produced by photovoltaics and wind, into the energy system without endangering security of supply. In order to guarantee successful system integration, the use of storage technologies with long storage periods is integral, especially during longer winter periods with little wind, so-called dark lulls [5]. The P2G technology can additionally support heat, industry and transport sectors in phasing out fossil fuels by making use of excess renewable electricity to power an electrolysis process. The hydrogen used as a substitute fuel in the heat and mobility sectors, advancing the energy transition in these sectors. Alternatively, the hydrogen obtained in this manner can be stored in the natural gas network. Alternatively, hydrogen undergoes a downstream methanisation process and is transformed into natural gas that can then be stored in the gas network and converted back into electricity in flexible gas-fired power plants in case of no renewable energy available. Several studies have been carried out in recent years on the feasibility and economic viability of the energy system transformation, in which, among other things, the effects and use of P2G in future energy system scenarios have been investigated. [6] simulated the transition of entire energy industry to renewable energy sources by 2040. The study follows a holistic approach and considers the sectors of electricity, heat and mobility. It recommends a rapid and comprehensive expansion of P2G. [5] conducted a comprehensive overview of studies on the necessity of power-to-gas for energy system transformation, which compared four scenarios for emission-free energy systems. All scenarios assume an installed power-to-gas capacity between 8-23 GW and prove that a future energy system with P2G technology is cost-effective that without it.

D. Possibilities for integrating power-to-gas into the energy system

According to political plans, by the year 2050 the share of renewable energies in electricity generation in Germany should amount to at least 80%, largely covered by fluctuating electricity feed-in from wind and PV plants. To cover the electricity demand at any time and to enable the integration of the volatile plants into the power grid, flexible consumers will be necessary. They can provide load management, meaning shifting the consumption to times with high renewable energy feed-in or times with low or negative wholesale electricity prices. Alternatively, they can store the excess energy that could not have been consumed at that moment [7], offer balancing services or participate in minimising the infrastructure problems in the electricity networks. From the point of view of the electricity market, a P2G system is an electricity consumer that has no operation restrictions and can be controlled very flexibly. It produces gas from renewable sources, which is a fuel for the heating industry, a fuel for the transport sector or an important raw material for the chemical industry. P2G technology is also suitable for advancing the energy transition and decarbonisation in these sectors and reducing Germany's dependence on imports of foreign natural gas. In practice, P2G system would be activated in times of surplus of electricity supply - whether on the market side or on the grid side. In this way, it aligns the consumption side with the production side, and uses the excess energy to generate storable hydrogen or methane. First, P2G in combination with the gas network with its entire storage capacity it offers a can operate as energy storage facility. This solution is not economical under current market conditions, mainly because of system's low overall efficiency of 35%. At current gas prices of 0.03 €/kWh [8], renewably generated gas at electricity prices of 0.2-0.4 €/kWh with a conversion efficiency of 50% is already 0.4 €/kWh more expensive than natural gas. This calculation does not include charges for electricity procurement such as grid fees or subsidies [7]. On the other hand, P2G as a power storage device is particularly convincing due to its low costs for long-term storage. While an additional kWh of storage capacity for battery storage, for example, costs around €1000, the cost for cavern storage is only €0.1. Another argument in favour of P2G as a long-term storage facility is the low self-discharge rates due to diffusion of natural gas. There arguments prove that P2G is a very suitable technology to implementing storage cycles over a period of more than a week up to months or years [5]. To improve the financial viability, P2G system can generate additional revenue from provision of flexibility in energy use and balancing services. The electrolysis unit is flexible and quickly controllable, requires high electrical power and are usually independent of downstream processes that could limit the operation of the plant. Therefore, they are very well suited for the provision of e.g. balancing power [7], which are three control energy products, primary control power (FCR), secondary control power (AFRR) and minute reserve (MFRR). They are tendered by the transmission system operators (TSOs) and is used as a flexible reserve to compensate for schedule deviations or power plant failures. Additionally, P2G systems integrated into weakly developed distribution networks with very high renewable energy feed-in, deter the necessary network expansion in such a distribution network. The plant would be activated in times of an threatening grid bottleneck due to high renewable feed-in, in order to prevent shutdown measures and to route the surplus electricity causing the grid bottleneck to the consumers via the gas grid with subsequent retrogeneration. From the point of view of the TSOs, such a measure could also be justified as a replacement for the expansion of the transmission grid between the windy northern Germany and the high-consumption industrial locations in the south and southwest of Germany.

III. IMPLEMENTATION OF THE POWER-TO-GAS PLANT IN HAßFURT

Greenpeace Energy eG. has recognized the importance of P2G for energy system transformation and offers its customers its own gas tariff per wind gas to promote this key technology [9]. Stadtwerk Haßfurt is responsible for the technical management of the P2G plant, construction planning and implementation. Next Kraftwerke was chosen as the partner for the timetable control and power supply of the plant. Next Kraftwerke integrates the plant into their VK Next Pool. This makes it possible to optimize the plant in a quarter of an hour and provide control energy. In the course of the present work the integration of the plant into the Next Pool was accompanied, the timetable logic was implemented and the operational operation of the timetable optimisation was realised.

A. The electricity and gas sector of the city of Haßfurt

In the Haßfurt distribution network, the local consumption is largely covered by renewables. The electricity consumption of the city of Haßfurt, which is between four and a maximum of 13 MW, is offset by a supply-dependent, renewables-based generation of almost 50 MW. According to Stadtwerke Haßfurt, this leads to large local surpluses in the distribution network. So far, the surplus electricity has been fed into the upstream transmission grid. The basic idea behind the project is to use this "green" surplus electricity in a P2G plant by producing synthetic hydrogen. By activating the plant the local consumption would be increased and the outflow into the transmission grid would be reduced. The hydrogen produced in the plant is to be fed into the gas network of the city of Haßfurt so that it can be added to the gas supply of the local industry. Greenpeace Energy provides its customers with renewably produced hydrogen and thus offers environmentally conscious customers the opportunity to support the project via special tariff. As a result, these customers receive natural gas enriched to a certain extent with green hydrogen.

The economy in Haßfurt is characterised by small trade and commerce. The electricity consumption is mainly driven by household and commercial customers as well as the municipal utility itself consuming electricity to power larger water pumps, which are used in the city's water supply system. There are no large industrial enterprises with distinctive individual power consumption patterns. On the other hand, the gas demand in the municipality is mainly driven by ordinary household and commercial customers as well as a big malt house. Household and commercial customers mainly use the purchased natural gas taken from the gas network for normal household applications such as cooking, heating or hot water supply. In the gas network supplying the households, it is possible to add up to five percent hydrogen to natural gas. Under the given circumstances, this is possible because the feed-in point of the P2G plant is located in a different network branch than the natural gas filling station, for which only a hydrogen admixture rate of two percent would be permitted. The household gas consumption varies between 100 m^3/h in summer and about 1000 m^3/h at peak consumption times in winter. On the other hand, the malting plant requires large amounts of heat to dry the malted grain. The process heat is provided by several cogeneration units, which are operated with natural gas. These cogeneration units are compatible with the hydrogen content in the natural gas up to 10 percent. The gas consumption of the malt house is very regular and has almost the same structure every day of the year.

B. Configuration of the Power-to-Gas system

The P2G plant in Haßfurt consists of an electrolysis unit combined with a gas storage facility and two grid feed-in facilities, one for the gas grid and one for the malting plant. The P2G system is connected to the medium-voltage level of the distribution network. The installed capacity of 1.25 MW peak corresponds to about 10 % of the peak load of the total electricity consumption of the city of Haßfurt. The electricity from the medium voltage level is used to split water into hydrogen and oxygen in the electrolysis unit. The resulting hydrogen is fed into the gas storage tank where it is temporarily stored. A continuous volume flow is fed from the storage into the gas network of the city of Haßfurt or to the industrial customer.

The selected electrolyser is particularly suitable for this application as the electrolysis can be controlled very flexibly and without restrictions. Any operating point can be reached within twenty seconds. This results in a load change gradient of 4 - 6 MW/min. With a peak output of 1.25 MW, the plant produces 225 m³/h of hydrogen. With a calorific value of the hydrogen of 3.54 kWh/m³, this results in an efficiency of about 70 percent. It would also be possible to feed fluctuating generation from wind or PV directly into the plant with this type of plant. The hydrogen produced has a high purity and is therefore suitable for feeding into the public gas grid. The water required for electrolysis is taken from the public water supply. This water is purified and treated before it is fed to the electrolyser. To produce one cubic meter of hydrogen, 1.5 litres of water are needed. At full load the electrolyser needs 340 litres/h. In order to prevent possible failures of the water treatment, a buffer tank between water treatment and electrolyser is installed. Heat losses occurring during operation of the plant, at the efficiency of about 70 percent at a full load of 1250 kW, result in a thermal output of 375 kW. Now, this waste heat is dissipated to the surrounding because practical use of the waste heat is not yet possible due to the low process temperatures.

Between the electrolyser and the device feeding the hydrogen into the gas network, a buffer storage tank is installed that enables a flexible operation of the plant. The hydrogen produced is first fed into the gas storage tank and from there independently fed into the gas injection devices. The gas storage tank has a volume of 50m³ and can be operated with a pressure of up to 35 bar. This results in a gas storage of 1750m³. Once the gas volume reaches the upper limit of storage tank, the electrolysis process stops automatically. In case of emergency, meaning exceeding of the upper storage limit, the pressure relief valve of gas storage tank releases hydrogen. Hydrogen is continuously discharged from the gas storage of the P2G plant. The gas network and the local industrial consumer, the malting plant, are supplied separately due to the different hydrogen tolerances - 10 percent for the malt house, only 5 percent for the public gas network. Since the P2G plant is located in the immediate proximity of the malting plant, it was possible to build a direct gas pipeline from the P2G plant at low cost. The feed-in device continuously measures the natural gas volume flows in the pipelines of the public gas network and the malt house, because it influences the feed-in capacity of the hydrogen to the gas network and the malt house.

C. *Input data for optimisation of operation*

The plant is continuously optimized in every quarter of an hour. The following routine is carried out: First, the information about the status of the distribution network in Haßfurt is updated every 15 minutes to verify the amount of available excess electricity. This is calculated, taking into consideration the forecast of consumption as well as generation of wind and PV. With these three load curves, the next 36 hours are forecasted in 15-minute resolution, according to following formula:

$$\begin{aligned}\boldsymbol{Generation_{Wind} + Generation_{PV} - Consumption_{Haßfurt}} \\ \boldsymbol{= Forecasted\ surplus}\end{aligned} \tag{5}$$

The wind forecast has a special significance for the forecast of the surplus electricity, as the generation from wind power plant in the municipality of Haßfurt has the greatest influence on accessible electricity to power the electrolysis. As soon as the wind power plant reaches 30% of its maximum capacity production, it exceeds the average consumption of the city, which means that the excess renewably generated electricity is available for the P2G plant. To precisely predict the available electricity, Next Kraftwerke has used short and medium-term forecasts. Short-term forecasts help determine the wind feed-in for the last tradable product of the intraday. On the other hand, the medium-term forecasts attempt to foresee the wind generation in time horizon of 3-36 hours. It was prepared under the assumption that there is a correlation between the wind feed-in in Germany and the wind feed-in in the distribution grid Haßfurt. The forecasts of PV generation were prepared with data published by Stadtwerke Haßfurt providing live values of the current PV feed-in in the entire distribution network. These data include the feed-in from smaller roof systems as well as the feed-in from the four large open space installations. Although there were minor forecasts errors occurring in the predictions, they could have been neglected due to the fact that the PV generation has less significant influence on the amount of available excess electricity to power the P2G system. This happens because the PV feed-in is much smaller in terms of quantity and also in terms of installed capacity than the wind generation in the municipality. Secondly, the structure of the PV feed-in corresponds very well with the consumption load curve, which means that the PV feed-in can be more efficiently consumed locally. The third important optimization parameter was the electricity consumption in Haßfurt, that could not be directly measured. Therefore, the measured parameters were bidirectional power flow between the transmission grid and the distribution grid and renewable generation, together with known parameter of power consumption by the electrolyser. Due to the fact that one grid transfer point to the higher grid level, the following grid equation served to calculate the electricity consumption:

$$\begin{aligned}\boldsymbol{Generation_{Wind} + Generation_{PV} - Consumption_{Haßfurt}} \\ \boldsymbol{- Consumption_{Electrolyser} = 0}\end{aligned} \tag{6}$$

Thus the power consumption can be determined. This method is subject to several inaccuracies and errors that need to be considered. The grid equation is a simplified assumption and was made on the basis of the available data. In addition to household and commercial customers, the distribution network contains several larger, individually controlled consumers, such as groundwater pumps, whose consumption were not reported to the forecast provider. The consumption values considered here were therefore not exclusively standard load profile customers, making the creation of reliable forecasts more complicated. The forecasts are recalculated iteratively every 15 minutes and are used to re-evaluate and optimize the timetable of the plant. The new timetable is checked and transmitted to the plant. The reliability and degree of automation were given special consideration when setting up the timetable optimisation. From an economic point of view, the size of the plant does not permit intensive manual control of the plant.

Apart from the available energy to power the P2G system, the limits of hydrogen production were forecasted. Because natural gas and hydrogen consumption limits the permitted production of hydrogen. The forecast of gas consumption in the municipality took into consideration the residential users in the city as well as the big industrial user. Apart from gas consumption and the storage capacities in the natural gas network, the production plan of P2G system was based on the predicted periods, during which the installation could be used to provide balancing services to the grid operator. Due to the organisation of balancing market in Germany, it required creation of forecasts for 13 days ahead, including weather forecasts and forecasts of ambient temperature strongly influencing the gas consumption of the residential users. This forecast was very difficult to obtain because historical gas consumption data were only available from the main node in the gas network, meaning from the entire city of Haßfurt. For this reason, first the approximation a data basis was created used as the basis for the forecast. The gas load curve data show a strong annual seasonality or temperature dependency as well as a strong daily pattern. Additionally, slight weekend or holiday pattern can be observed. The natural gas is mainly used for heating purposes A regression analysis of the daily mean values of gas consumption with respect to the mean daytime temperature shows that gas consumption is linearly dependent on the outside temperature. On the other hand, the forecast of gas consumption in the CHP unit of the malt house was based on high quality historical data showing a very regular gas consumption. The load profile follows a classic daily pattern. It rises daily from base load between 7:30 and 8:00 a.m. and increases over the course of the day up to midnight. It then drops rapidly and reaches the baseline in the early morning hours. Apart of distinctive daily pattern, it has a specific weekly pattern, repeating regularly during whole year. The two gas consumption patterns combined with the current gas filling level and the fixed schedules of the electrolyser were used to forecast the available level of gas storage capacity. Additionally, the forecast respected the limits of the hydrogen absorption in the gas network that were calculated according to following formulas:

$$\dot{V}_{H_2\,gas\,network,max} = \dot{V}_{CH_4\,gas\,network} * \boldsymbol{admixture\ limit}_{gas\,network} \tag{7}$$

$$\dot{V}_{H_2\,Maelzerei,max} = \dot{V}_{CH_4\,malt\,house} * \boldsymbol{admixture\ limit}_{malt\,house} \tag{8}$$

$$\textbf{admixture limit}_{gas\,network} = \textbf{5\%} \tag{9}$$

$$\textbf{admixture limit}_{malt\,house} = \textbf{10\%} \tag{10}$$

In the next step, the actual values of gas production of the electrolyze was calculated on the basis of the efficiency characteristic curve. The efficiency of the electrolyser varies depending on the power range, reaching maximum in the medium power range and lowest values in minimum load (125kW) or maximum load (1250kW). Key data points of the efficiency curve were recorded and used to create approximation formula. Thus it is possible to assign a hydrogen production quantity to each power value. The performance schedule of the plant was converted into specific quantities of hydrogen production using the transfer function. These data were used to forecast change of the gas filling level of the gas storage, according to the following equation:

$$\Delta V_{gas\,storage} = (\dot{V}_{H_2\,electrolyser} - \dot{V}_{H_2\,gas\,network} - \dot{V}_{H_2\,malt\,house}) * t \tag{11}$$

The change in the gas storage level results from the volume flow of hydrogen produced by the electrolyser, minus the outflows of hydrogen to the malting plant and the gas network. Initially, the current filling level of the gas storage tank is used to calculate the gas storage tank filling level for the next quarter of an hour with the predicted hydrogen flows. With the help of the forecast of excess electricity and the predicted available volume of gas storage, the system was optimized to take advantage of hourly price differences in the intraday market. The electricity powering the P2G system is procured in the intraday market due to short-term nature and the short duration of events in which the excess electricity is available. Therefore, it was crucial to optimise the production timetable to map the load curve of the plant as accurately as possible to the available electricity as well as low prices on the wholesale market. The aim of the optimisation is to generate a maximum amount of regenerative gas at the lowest possible cost.

D. Optimisation logic

The optimisation consists of two components: on the one hand a base load consumption and on the other hand controlled peak consumption in surplus scenarios. The electricity needed to satisfy the base load band is procured in the day-ahead auction. Whenever a quantity has been procured for the system, the corresponding schedule is sent to the Next Box of the P2G system. This guarantees that there are no discrepancies between the plant schedule and the quantities traded. To create the timetable, a linear optimization problem is created and solved. The main assumptions are that hydrogen production of the electrolyser increases filling level of the gas storage tank. Hydrogen intake from the gas network and malt house reduces it. The achievable production of hydrogen in oversupply scenarios is greater than the consumption capacity of the gas network and the malt house. Therefore, it is not only possible but also necessary to optimize the amount of hydrogen produced with regard to the absorption capacities of the gas network and the malting plant and the filling level of the gas storage tank.

Slightly different logic leads optimisation of the P2G system to provide balancing services. In this case, it is necessary to keep storage capacity free. The free availability of storage capacity is only necessary for the provision of negative balancing energy. In order to provide negative balancing energy, the P2G facility increases its power consumption and produces more hydrogen. According to prequalification criteria, no energy may be wasted for the provision of balancing energy. It is therefore necessary to keep sufficient storage capacity available so that all the hydrogen additionally generated by the control energy demand can be temporarily stored in the storage facility. On the other hand, no storage capacity is required for the provision of positive balancing energy. In this case, the electrolyser reduces the output, produces less hydrogen and the storage tank empties. Depending on the type of control, different storage capacities are required. For the provision of AFRR, required storage capacity must be available for three hours of production.

The optimization problem has the following structure: First, all target values are converted into the unit cubic meter of hydrogen. With help of approximation function calculates the amount of hydrogen the electrolyser can generate in the respective quarter of an hour that was forecasted as the quarter of an hour with the available quantity of excess renewable electricity. In each quarter of an hour of the optimization period, a certain amount of "excess gas" between zero cubic meters and a maximum of 56.25 m³ is available. The absorption capacity of hydrogen results from the sum of the absorption capacities of the malting plant and the gas network. The absorption capacity therefore permits a maximum hydrogen production of the electrolyser of about 60 m³/h in base load operation, which corresponds to a reference power of 330 kW. The absorption capacity of the gas network is therefore not sufficient to store the entire excess flow in the form of hydrogen in the event of a prolonged availability of excess renewable electricity. The optimisation choses favourable quarters of an hour aim to produce hydrogen in the case of large surplus quantities. For this purpose, a matrix with the quarter-hour values for the hydrogen absorption capacity of the malting plant and gas network, "excess gas", the initial gas storage forecast and the forecast electricity prices is created. The optimisation function solves the optimisation problem and returns a timetable that provides a maximum of hydrogen at minimum cost. The optimization tries to produce as much hydrogen as possible within the given optimization horizon, usually all quarter hours available in the intraday market, and to fill the gas storage as much as possible.

IV. RESULTS OF THE OPTIMISATION

The successful optimization implemented in production schedule and control of the P2G system without any major problems was proved by monthly issued reports verifying the quality of forecasts and the control system. The gas storage of the plant was filled during favourable quarter hours. Over the entire optimisation period, in many quarter hours, the renewable electricity generation exceeded the consumption of Haßfurt, which means that operation of the system made use of excess electricity in all available quarter hours. At the beginning of the optimization, however, the prices were relatively high. The optimisation therefore only selected individual favourable quarter-hours in order to make full use of the absorption capacity of the gas network. During the favourable night hours, the system worked at full capacity and filled about half of the gas storage tank. On the following day, the PV feed-in in Germany was very high and led to favourable prices in the midday hours. The optimization algorithm made use of them and filled the gas storage in the noon hours at low prices. Following the initial intraday auction, the timetable is further optimised in continuous intraday operation. For this purpose, the previous schedule of the plant is transferred to the optimization. In contrast to initial optimization, continuous intraday optimization determines the timetable based on supply and demand prices (bid and ask prices).

V. CONCLUSIONS AND DISCUSSION

Although, the P2G plant in Haßfurt was a pilot project, it can compete on the market under economic conditions as one of the very first projects of this kind. The practical implementation of its integration into the virtual power plant was successful in terms of both control technology and operation without any major complications. However, some aspect of its operation and the technological process behind the P2G systems require critics and discussion. Firstly, the efficiency of conversion of electricity to hydrogen in the electrolysis is around 65%. The remaining 35% of waste heat is extracted at relatively low temperatures, can no longer be used for further energetic purposes and must be dissipated to the environment. The hydrogen obtained in the process powers CHP unit of the malt house that generates electricity with an electrical efficiency of 35% and the remaining 65% of energy is used for heat application. On the other hand, the hydrogen injected into the gas network of the city is used for heat applications by household and commercial customers. The efficiency of this process is lower than use of gas heaters delivering heat at an efficiency of 90%. In these circumstances, it would have been possible to use more efficient and cheaper power-to-heat plant, which converts electricity directly with an efficiency of 95% into heat at any temperature level. However, the intention of this project was to promote and further develop P2G technology delivering value to more vast set of stakeholders, meaning transmission and distribution network operators, industrial users and residential users. From this point of view, this project must be seen as a research project that successfully demonstrated the functionality of the technology, its value proposition to an energy industry and provided experience valuable in design of future energy scenarios.

VI. PRACTICAL IMPLICATIONS

The plant in Haßfurt is already economically successful in the optimization and is controlled and operated according to the customer's wishes. The P2G plant works under almost no restrictions, apart from the limited absorption capacity of the gas network. Therefore, it delivered not only balancing services and the reduction of local surpluses, but also proved useful in peak shaving and management of balancing groups. This modi of operation can be replicated to other P2G installations. First, it can be used to limit power transfers to the transmission network. It would be conceivable to use the plant specifically to cut the peaks in exports of electricity from the distribution network in Haßfurt to the transmission network. This approach reduces costs for the operation of the distribution network, which depend on the maximum capacity requested via a connection point between the distribution network and transmission network.

Another possibility would be use of the P2G plant for balancing group management using the unexpected surplus of renewable energy. This approach minimizes the risks connected with deviations between the forecasts of the energy production and the actual delivery of the energy. In this case, the P2G plant would activate not to deliver traded electricity, but to ensure balance in the balancing group.

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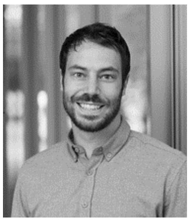
BIOGRAPHICAL INFORMATION

Aleksandra Radwanska received the B.Sc. at Warsaw University of Technology, Poland in power engineering in 2017. She graduated in 2019 from double degree M.Sc. in innovation sciences and sustainable energy technologies at Universitat Politecnica de Catalunya, Spain and Eindhoven University of Technology, the Netherlands. Her research topics included energy access in developing countries, democratization of energy provision, energy flexibility and decentralization of energy system supported by energy communities.

As a student, she has been working at international companies such as Transition Technologies, General Electric and InnoEnergy in Poland and Spain as well as in a start-up Thermovault in Belgium. Currently, she is International Business Development Manager at Next Kraftwerke in Cologne, Germany. Aleksandra is a member of Young Leaders in Energy and Leader at Community by InnoEnergy.

Maximilian Fuhrmann has received the B.Sc. in renewable energy technology at Regensburg University of Applied Sciences and M.Sc. at FH Aachen University of Applied Sciences in energy economics and computer science.

He connects his areas of research in professional career. He works as Analyst in Energy Trading Department at Next Kraftwerke and supports clients in developing strategies to increase the profitability of their renewable energy generating installations.



Felix Jedamzik has received the B.Sc. in the business economics The Berlin School of Economics and Law and the M.Sc. in industrial engineer at Bergische Universität Wuppertal, Germany.

He has started the career at Berliner Volksbank eG. He has continued the career in the energy sector at Next Kraftwerke, initially as Key-Account-Manager and currently as International Business Development Manager. He supports Next Kraftwerke's VPP-as-a-service partners to kick off their VPP business. Additionally, he works with clients developing systems supporting the consumer-side flexibility in the electricity market.