Real live demonstration of MPC for a power-to-gas plant

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Abstract

This paper presents the results - and the way towards them - for a field trial of a 120 kW_{el} PEM electrolyser located within the city boundaries of Freiburg, Germany. The plant is equipped with on-site hydrogen storage and connected to the local gas and electricity network. Restrictions in gas feed-in and allowed peak electricity demand apply, and limit operation of the unit. Model predictive controls have been identified in simulations as a promising control strategy for such a case. However to move from simulation into practice few things, presented in this work, should be considered.

A linear model predictive controller is successfully used in a field trial to optimise the operation of the power-to-gas unit in the presence of network restrictions and time varying electric prices. The impact of imperfect forecasts as well as deviations between the optimisation model and the real unit on controller performance are discussed. In the final part of the paper the lessons learned, improvements and potential solutions for integrating power-to-gas units into urban energy systems are presented. Additionally a modular controller design framework is introduced, which allows a rapid control development by interchanging historic time-series data with real-time values and simulation models with real components. In a separate testing sequence the power-to-gas unit is characterised regarding its dynamic properties, showing its potential for fast response, but also limitations in ramp-rates, tracking accuracy and losses due to warm stand-by.

Keywords: Power-to-Gas, Hydrogen, Smart Grid, Model Predictive Controls, Field Test,

Contents

Highlights

- Real live demonstration of MPC with power-to-gas
- Power-to-gas unit is operated in an urban setting with restrictions
- Modular controller design frame-work presented
- Urban power-to-gas research plant presented

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1. Chances and challenges for P2G in an urban setting

Power-to-gas (P2G) uses electricity to convert into hydrogen, typically using water electrolysis. As highlighted in [1] there are different pathways for using the generated hydrogen, all which start with an electrolysis process. The produced hydrogen can be directly supplied to industrial customers, used in fuel-cell cars, or fed into the natural gas network. From there it can be used for electricity generation (e.g. in a gas turbine) or used in other processes that are connected to the gas network (such as gas boilers for heating). Hydrogen can further be converted into Methane (CH_4) using a carbon source, such as CO_2, before it is supplied to the natural gas grid [2]. Using the existing natural gas infrastructure offers high energy storage potential, efficient transportation of energy over long distances as well as high energy densities compared to conventional energy storage.

But why is this needed? Rising shares of intermittent renewable electricity generation will lead to challenges in the power sector. On the one hand there will be times with an abundance of renewable electricity in the grid, while on the other hand there will be times where electricity generation from wind and PV will not be sufficient to supply the demand. The need for storage and load management is imminent. Coupling of different energy vectors, referred to as power-to-X can increase the potential flexibility and storage capacity available for operating the power system [3]. In this context P2G is seen as a technology to link the electricity sector with mobility, heat and industrial processes, thereby serving as flexible load and energy storage [4]. In Germany, the popularity of hydrogen as a long term storage solution is based on the idea that the existing gas infrastructure can be used. Which is equipped with large underground storage, as discussed in [5].

However P2G is facing challenges. High investment costs and discussion on low round-trip efficiency from electricity-to-gas-to-power (P2G2P), are two main challenges for P2G. Therefore, measures that increase efficiency and decrease total cost of hydrogen are crucial.

As indicated in [6] the transformation of the energy system towards 100 % renewables will lead a portfolio of different generation, supply and storage technologies. Furthermore the trend towards a more and more decentralised energy system can be observed. In this context energy communities, smart cities and energy independent regions play an important role. Integrating P2G into an increasingly decentralised energy infrastructure, such as urban energy systems poses challenges to system design and control. Limitations in the capacity of local energy networks can restrict the operation of P2G units. For direct hydrogen feed-in technical limitations, such as the maximum hydrogen compatibility of downstream consumers or grid components, have to be respected [7]. This can reduce the number of annual operation hours and thus the economic feasibility of a P2G project.

Furthermore, depending on the location of the plant, the electric infrastructure is operated at its maximum capacity at some instances in time during the year, which might increase in the future when electric vehicles are integrated into the power system [8]. This might limit operation and potential sites where electrolysers can be installed. However P2G could also be installed in order to provide services to the power grid and can act as an alternative to grid extension as discussed in [9] for electric grids with high a penetration of wind and PV.

Besides the limitations in operation posed by network restrictions, the operation of P2G units in a renewable energy system might become highly dynamic. Electricity generation by regional wind and PV resources, as well as fluctuations in electricity demand lead to the need for load balancing. Time variable electricity prices, energy trading on decentralised market places and the motivation of regional energy autarchy will lead to dynamically changing economic boundary conditions for the operation of P2G units. Increasing operational dynamics, changing incentives over time as well as time variant limitations in the energy networks will require advanced controls and motivate the use of on-site hydrogen storage for P2G units in a decentralised energy system. In [10] it is shown in a simulation study how on-site hydrogen storage and model predictive controls (MPC) can provide a solution to ease the negative effects of restrictions in the network and allow an optimised operation of a P2G unit in an urban setting.

As indicated changes in the energy system will lead to dynamic boundary conditions, including restrictions in the energy networks, under which P2G units will operate in the future. Thus leading to the need for improved controls, that are not only shown in simulation but are also investigated in practice. Therefore this presents the results - and in particular the way towards them - for a field trial of a P2G plant located within the city boundaries of Freiburg, Germany.

1.1. A review of academic literature

As indicated above there is an interconnection between the designated use-case of P2G and the requirements for controls, which are investigated in the following review or academic literature to provide an overview over the current state of the discussion.

1.1.1. P2G in a renewable energy system

P2G technology has been demonstrated successfully in pilot-projects worldwide. As shown in [2] those applications differ in terms of the underlying chemical processes, used catalysers and energy sources. To produce methane, sometimes referred to as synthetic natural gas (SNG), hydrogen methanisation in a Sabatier reaction can be performed. This allows using existing carbon sources such as carbon-capture from combustion plants or from bio gas generation. Hydrocarbon chemistry also allows for the generation of synthetic fuels (gas-to-liquid). An overview of realised P2G projects is provided in [11], showing that there are different approaches how to set-up P2G-plants and connect them with other energy generation and storage units as well as to the power grid.

The review of academic literature further suggests that P2G is considered a central technology for a successful transformation of the energy system towards 100% renewables. An example is [12], where a scenario, with a renewable target of 100 %

in 2030 is investigated. It is shown that reaching this target is technically possible with and without the use of P2G. Nevertheless, levelized costs of electricity (LCOE) are lower if hydrogen technologies are applied.

In [13] an economic optimum for P2G installations in Germany is calculated, based on a scenario, where 85 % of all electricity is generated by renewables. This leads to an installed P2G capacity between 6 and 12 GW, depending on the investment costs (the higher investment costs are, the lower optimum P2G capacities). The study further indicates the need to install P2G units in areas, where wind energy production is high in order to decrease transmission losses in the electric grid, but also to avoid curtailment of wind generation due to limitations in transmission capacity.

In [6] a study for the German energy transition is presented, showing the importance of P2G as energy carrier for the mobility sector and long term storage. The latter is supported by [14] highlighting the need of large scale energy storage in a 100 % renewable electricity supply. For the investigated case P2G and a reconversion into electricity (P2G2P) is the described solution for long-term storage. Again it is highlighted that P2G is particularly interesting in areas with a high number of wind turbines.

Reducing the curtailment of renewable energy sources is discussed in [15], where it is suggested that if the installed capacity of wind and PV power is increased, installed electrolyses power and hydrogen storage should be adapted likewise to avoid curtailment. Besides reducing curtailment it is shown in [16] that P2G can also improve the dispatch ability of wind farms. This is achieved by combining P2G with hydrogen storage and gas turbines, that enable reconversion of produced hydrogen into electricity. In this study the business-as-usual scenario favours single gas turbines as balancing systems. However, the importance of P2G supported systems rises if investment costs decrease, gas prices increase and electricity prices decrease respectively. The use of fuel cells to enable a reconversion of hydrogen into electricity is discussed in [17], where it is highlighted that applicability strongly depends on economic parameters among those the ratio of selling price and purchase price for electricity. Furthermore, the efficiency of the whole installation plays an important role, and therefore its operation close to the efficiency maximum is necessary.

From the presented review it can be concluded that P2G will play an important role in the future energy system. Critical points are the location of the plant as to avoid a) curtailment of electricity generation due to limitations in transmission capacity but also b) curtailment of hydrogen generation due to restrictions in the energy networks. Furthermore economics of P2G plants are highlighted in several studies leading to the conclusion that cost reduction and efficiency increase are crucial for the success of the technology.

1.1.2. Operation and controls of P2G plants

In the context of operating P2G in the future energy system controls play a crucial role. The way a P2G unit is integrated into the surrounding energy system and its potential application in the energy system will strongly influence the operation of the unit. Running a P2G in a dynamic environment will require tailored controls for each use-case. However, only few academic articles directly address the controls of P2G units and in particular the use of MPC in this context. Therefore the literature review was extended towards fuel-cells.

The investigated studies indicate that MPC is well suited to optimise the operation of electrolysers and fuel cells of various types. The complexity of the underlying optimal control problem formulation should be tailored to the problem. In some cases a mixed integer quadratic problem is necessary to reproduce realistic behaviour of the electrolyser or fuel cell, with respect to minimum power consumption. Additionally, a mixed-integer formulation enables a minimisation of the number of ON/OFF cycles. However, if benefits of a mixed-integer problem formulation compared to an easier linear problem formulation are insignificant or can be treated appropriately by post-processing, the control problem could be linearised.

In [18] the importance of optimised controls is pointed out. In this work, a coupled system of electrolyser, fuel cell, battery stack, and renewable electricity generation is operated as a stand-alone system. Results show that the electricity demand could be met at all times using the described energy management system and communications. In general, it seems that the more different units are used in a given system, the higher the benefit of advanced controllers. Predictive controllers potentially increase system performance for systems with high inertia and capabilities to store energy.

In [19], a detailed model of a cascade-type proton exchange membrane fuel cell (PEMFC) in combination with an overlying MPC unit is investigated. The described non-linear model, which is used to evaluate the behaviour of the given fuel cell, is linearised and simplified using a model order reduction method. The full-order-model itself was validated and compared to experimental data. Results show that the set-up, also including the MPC, was able to track the desired voltage schedules with an error of less than 10 %.

A detailed description of an MPC and the corresponding fuel cell model can also be found in [20]. MPC improves both the stability of the PEMFC and the controllability towards its set points. Mixed-Integer MPC can lead to further improvements but requires more complex problem formulations.

In [21] two case studies, dealing with an electrolyser that receives electricity directly from wind turbines (isolated system) are discussed. The electrolyser is modelled quadratically and the optimal control problem is formulated as a mixed integer quadratic problem (MIQP). The of the optimal control procedure is an optimised usage of renewable energies and a minimisation of ON/OFF cycles.

The use of a 6 MW_{el} electrolyser located in Mainz, Germany, is demonstrated in [22]. The studied cases include electricity procurement from EPEX spot market, usage of excess electricity from wind parks, and participation in the control reserve market. For electricity procurement from EPEX optimal control is used to schedule the electrolyser with respect to restrictions in total unit run-time.

The study [10] puts a focus on P2G in urban settings, where restrictions in the gas network and the electric grid apply. Detailed simulations were performed for a system of a 500 kW electrolyser and a hydrogen storage of variable size. Three use-cases are considered: Time variable electricity prices, maximisation of the use of renewable energy sources and minimisation of the grid load. It was shown that MPC is best capable of controlling the plant with respect to the varying boundary conditions.

Although a vast amount of studies show the benefits of using MPC - also for other technologies - it is hardly used in today's commercial applications in the energy sector. A down-side of MPC is clearly the need of a model representation of the underlying system, which is commonly designed by experts. Further, compared to classical rule-based controls, the design of an MPC controller seems more complex and also hardware requirements are higher, as usually some kind of numerical optimisation is used to derive the optimal trajectory. The need for predictions on prices, loads and flows makes MPC even more complex. Hence it can be said that using MPC leads to better results with an increased complexity in controller design. Therefore this work puts a focus on demonstrating MPC in a practical application and providing advice on how to implement it for P2G units.

1.2. *Contribution of this work*

A majority of the previously discussed literature puts a focus on showing (in simulations) how large units located at ideal spots will play an important role in a renewable energy system. However, those studies miss to clearly present how to control this technology.

The presented paper applies for the first time model predictive controls in a real P2G plant, located in an urban context where restrictions apply. Operating a P2G unit in such a dynamic environment poses challenges not only to the controls, but also to the dynamics of P2G unit and the feed-in system to continuously adjust electric power demand as well as hydrogen feed-in according to the requirements. The focus is on bringing the controls, that have been successfully tested in simulations [10] to a real live application in a setting where limitations in the gas network and power grid apply. The implemented linear MPC algorithm is capable of dealing with time variable restrictions and price based incentives. The algorithm was improved towards increased robustness and stable operation of the unit in a non-ideal environment where forecast errors and plant-model mismatch are part of the reality.

Furthermore this work presents a modular framework to design and test controllers in simulation and field test. The framework allows replacing inputs and simulation models by real sensor values and the plant. Furthermore, the lessons learned during this field trial are discussed to allow other researchers and engineers to directly start where we have ended.

2. From simulation to reality

The main steps and ideas needed to move from the simulation study presented in [10] towards a real live demonstration are explained in this section.

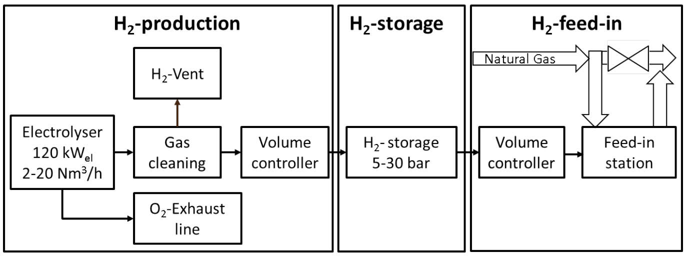


Figure 1: System description of the P2G test site at Fraunhofer ISE in Freiburg.

2.1. *Description of the P2G facility*

The investigated P2G plant is part of the lab infrastructure of the hydrogen facilities at Fraunhofer Institute for Solar Energy Systems ISE, located in the city of Freiburg, Germany. It consists of a hydrogen-production unit, a hydrogen gas storage and the hydrogen feed-in-plant. The general set-up is shown in Figure 1.

2.1.1. *Electrolyser*

For this P2G plant a commercially available 120 kW_{el} PEM water electrolyser (Proton Onsite C20) is used. It features a differential pressure electrolysis stack (see Figure 2(a)) enabling a pressure of 30 bar on the hydrogen side and near-ambient pressure for oxygen, which is currently not used.

Typical impurities of the produced hydrogen are water vapour and oxygen. The electrolyser therefore features a gas cleaning unit (pressure swing adsorption), which reduces impurities of the generated hydrogen down to less than 2 ppm of water vapour and oxygen. This exceeds hydrogen quality requirements of the local gas grid (up to 200 mg/m^3 water and 3 Vol-% of oxygen possible according to [23]) but is necessary for the second use case of the electrolyser - the supply of the local hydrogen infrastructure at Fraunhofer ISE.

The overall efficiency of the plant is 58 % based on the higher heating value (HHV) of the produced hydrogen. This is equivalent to a power consumption of 6.0 kWh_{el} per standard cubic metre of produced hydrogen and includes all hydrogen losses and energy losses needed to generate high purity hydrogen at 30 bar. It should be noted, that its efficiency cannot compete with larger plants, as the described unit is comparably small.

This specific electrolyser has been designed for pressure controlled on-site-supply of hydrogen and therefore does not follow a control signal but instead produces hydrogen according to demand: If there is hydrogen demand on the application side, the back-pressure of the electrolyser is reduced and the PLC of the electrolyser increases the hydrogen production until pressure stabilizes or the maximum production capacity is reached.

In order to be able to control the hydrogen production independently of the feed-in, a flow controller is installed directly behind the electrolyser and ahead of the storage. Another flow controller is installed in the feed-in station. These low level controllers enable the mid level controller to control hydrogen generation and feed-in. Another two flow meters are integrated in the gas grid (see Figure 2(c)) to measure gas flow in the gas grid.

2.1.2. *On-site hydrogen storage*

The produced hydrogen is fed into the bottled-storage, shown in Figure 2(b), which has a capacity of 1.8 m^3 and a maximum allowed pressure of 200 bar. The storage is operated in the range between 5 bar (minimum pressure needed for the hydrogen feed-in-plant) and 30 bar (maximum operating pressure of the electrolysis unit) which allows the storage of about two hours of hydrogen production at nominal load.

2.1.3. *Hydrogen feed-in*

Hydrogen is fed into the local natural gas network via the feed-in station shown in Figure 2(c). The feed-in station is connected to a 4 bar natural gas pipeline exclusively supplying Gundelfingen - a small district on the outskirts of Freiburg - and some industrial customers. Down-stream consumers therefore consist mostly of domestic heating applications as well as small-scale CHP plants and some industrial customers. This results in low flow rates in the gas grid (about 3,000 Nm^3/h max.) compared to interregional high pressure pipeline. Demand of natural gas, and consequently flow rates in the gas grid, is strongly reduced during summer (down to 750 Nm^3/h).

The down-stream consumers and present regulations allow a feed-in of up to 9 Vol-% of hydrogen in this specific case. But in order to avoid the necessity of creating a new accounting grid for a non-commercial research project the maximum allowed hydrogen content is limited to 2 % for the time being. In order to account for fast fluctuations in the gas grid and limited response times of the flow controller the maximum hydrogen content had to be lowered to 1.9 Vol-% in order to avoid shutdowns and might be lowered further if necessary.

The restrictions in hydrogen feed-in are one of the main limitations to the operation of the plant and are considered at all control levels. Especially in summer, when flow rates are low, an efficient observation of feed-in rates is essential.

2.1.4. *Operation states of the P2G plant*

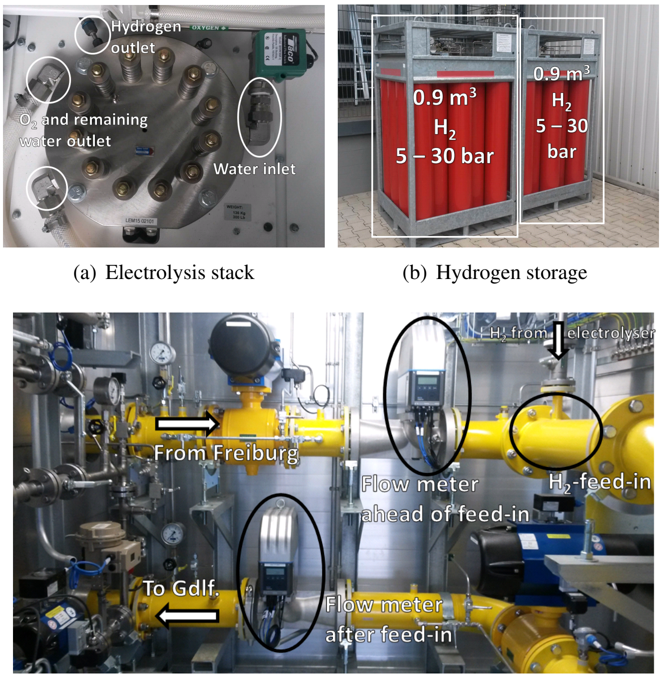
The plant operates in five different states:

1. *Cold start*: After being switched on, it takes about three minutes until the electrolyser reaches warm standby-mode. During this time, all controllers are started, interior cleaning is done, system testing routines are run and pressure is built up.

2. *Warm start*: The unit is ready for operation. Hydrogen production is enabled and reaction to set-point changes are possible. Its activation can be done quickly via a remote signal (see the dynamic characterisation in Section 3).

3. *Operation*: In the normal operation mode set-points are received and followed. Operation is limited by the dynamics properties of the unit, storage content and feed-in restrictions in the gas network. A three step procedure now starts:

    (a) *Calculation of set-points*: The high level controller calculates the optimal set-point schedule using MPC for the given the system state and forecasts. This process is triggered every 15 minutes.



(a) Electrolysis stack (b) Hydrogen storage

(c) Feed-in station (*Gdlf.* refers to the municipality of *Gundelfingen*)

Figure 2: Units of the power-to-gas station.

    (b) *Transmission of set-points*: For the next 15 minutes the schedule is used and the set-points are sent to the P2G unit.

    (c) *Reset of set-points*: All set-points are set to zero after the time window has exceeded 15 minutes and no new optimisation was performed. This is a safety feature in case the optimisation should crash for an unexpected reason.

4. *Shut down*: The electrolyser is switched off, pressure is released and control systems are on stand-by.

2.2. *Controls and communication*

The control of the P2G plant is hierarchical and consists of three layers.

High level controller Generates set-points for hydrogen generation and feed-in. This is done using measurements of the system state (e.g. pressure in the storage) but also by using predictions of gas-flow, state of the electric grid and prices for electricity and gas.

Mid level controller Operates the P2G plant to meet the set-points. The local grid control centre is connected to this control level and is able to block the feed-in of hydrogen into the gas network.

Low level controller Each component of the P2G unit has their dedicated low level controls. Those are in charge for safety critical features and the operation of individual parts such as valves and pumps.

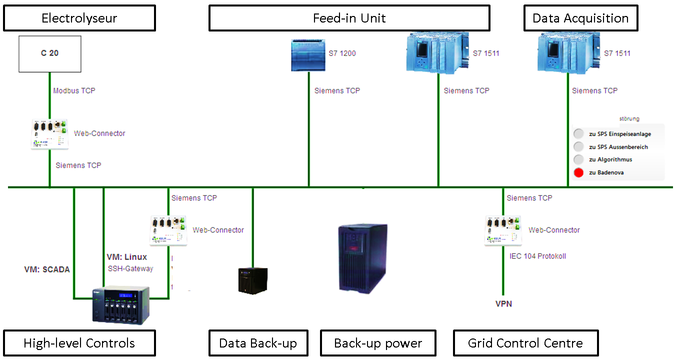


Figure 3: IT set-up for the P2G unit.

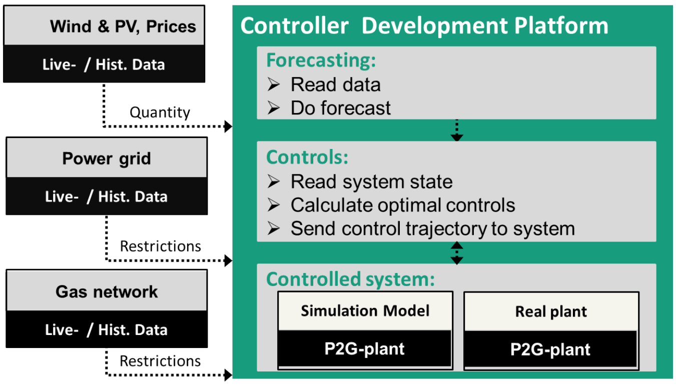


Figure 4: Controller development and simulation platform

Figure 3 shows the individual components of the different control levels and the data acquisition. The high level controller, which is implemented in python programming language, is operated on an embedded system running a Linux Virtual Machine. The mid-level controls are implemented on a Siemens S7 PLC. Optimisation is done using *cvxopt* [24]. The connection of the electrolyser and the high level controller is established through a Modbus-TCP-Server, whose registers can be written and read from both sides. The server is implemented using the *pymodbus* library [25]. Sensor values, measurements and set-points are communicated between the high level controller and the P2G unit every 3 seconds. Every 15 minutes a new optimal control schedule for the next 24 hours is calculated by the high level controller. The P2G plant is connected to the grid control centre of the local gas and electricity grid operator via a VPN-tunnel using a IEC104 protocol. Electricity prices are obtained every 24 hours for the next day from EPEX via a web API.

2.2.1. *Controller development and simulation platform*

A modular approach has been chosen to develop and test the high level controllers for the P2G plant. Figure 4 shows the controller development and simulation platform. The platform consists of three parts:

1. Forecasting
2. Calculation of control schedule
3. Interaction with the controlled system

The idea is that every component of the framework can be replaced by a real component. Input data can be replaced by real data, acquired on-line. The P2G system can be either simulated or the real unit is used. This set-up allows a rapid development and iterative improvement of controls and models.

2.2.2. *High level controls*

The model predictive controller (MPC) presented in [10] is used to generate set-points for electricity consumption and hydrogen feed-in. The MPC takes into account the current system state, and predictions about restrictions in the gas network, the electric grid and a prices for electricity and gas.

To calculate the optimal control schedule, a cost function is minimised. The result is a schedule for power consumption of the electrolyser and feed-in for each time step. As no costs aside from power consumption are considered (i.e. CAPEX, OPEX, costs for start-up processes) the stage cost l at each step depends on electricity costs c_{el} and gas price c_{gas} as well as the current electric demand P_{el} and hydrogen feed-in $P_{\mathrm{th,feed}}$. The stage cost function is defined as follows:

$$\begin{aligned} l(k, P_{\mathrm{el}}, P_{\mathrm{th,feed}}) = {} & c_{\mathrm{el,k}} \cdot P_{\mathrm{el,k}} \\ & - c_{\mathrm{gas,k}} \cdot P_{\mathrm{th,feed,k}} \end{aligned} \quad [\mathrm{EUR}] \qquad (1)$$

In the optimisation problem the sum of the stage costs l for every discrete point in time k is minimised over the prediction horizon N_p. A prediction horizon of 24 h is used and the step-width is 15 minutes leading to 96 time steps ($N_p = 96$). The objective function J is the sum over all stage costs for the entire prediction horizon:

$$\min_{P_{\mathrm{el}}, P_{\mathrm{th,feed}}} J(k, P_{\mathrm{el}}, P_{\mathrm{th,feed}}) = \sum_{k=0}^{N_p - 1} l(k, P_{\mathrm{el,k}}, P_{\mathrm{th,feed,k}}) \qquad (2)$$

Gas prices might be fluctuating slightly (i.e. NCG Spotmarket prices in Germany for January 2018 were between 17.4 and 19.5 Euro per MWh), but are assumed as constant throughout the 24 h time window. The electricity price is changing with time. The high level controller solves the presented optimal control problem repeatedly and delivers a schedule with set values for power consumption and feed-in rates for the next N_p time steps [26]. This schedule is sent to the mid level controls via a modbus connection.

In order to get physically correct and technically feasible solutions several boundary conditions have to be considered. This results in a constraint optimisation problem.

Storage equation. The storage content at the beginning of the upcoming time step $W_{\mathrm{sto,k+1}}$ is a function of hydrogen feed-in $P_{\mathrm{th,feed,k}}$ and hydrogen production. It is described with the following equation:

$$\begin{aligned} W_{\mathrm{sto,k+1}} = {} & (\eta_{\mathrm{ely}} \cdot P_{\mathrm{el,k}} - P_{\mathrm{th,feed,k}}) \Delta t \\ & + W_{\mathrm{sto,k}} \end{aligned} \quad [\mathrm{J}] \qquad (3)$$

where η_{ely} is the efficiency of the electrolyser and $W_{sto,k}$ the storage content in terms of stored chemical energy at the current time-step k.

Storable energy. The maximum and minimum storable energy, defined as $W_{sto,min,k}$ and $W_{sto,max,k}$ have to be respected at any time:

$$W_{sto,min,k} \leq W_{sto,k} \leq W_{sto,max,k} \qquad [J] \quad (4)$$

Maximum hydrogen feed-in. The maximum allowed hydrogen feed-in at the gas network $P_{th,grid,max}$ has to be respected at any time:

$$0 \leq P_{th,feed,k} \leq P_{th,grid,max,k} \qquad [W] \quad (5)$$

Electrical consumption. The limit in electrical power of the electrolyser $P_{el,ely,max}$ must not be violated. In addition to this the maximum power, defined by the current state of the power grid $P_{el,grid,max,k}$, has to be respected at any time:

$$0 \leq P_{el,ely,k} \leq \min(P_{el,ely,max},\, P_{el,grid,max,k}) \quad [W] \quad (6)$$

2.3. Increasing the robustness for operation with the real plant

To move from using simulation towards controlling the real unit, few adjustments had to be made. As errors in sensor reading or deviations of optimisation model from the real unit, as well as unexpected events can lead to values that are outside the allowed boundaries of the optimal control problem formulation. In this case the optimisation algorithm can not solve as the optimisation problem is infeasible from the start. To avoid this, values outside the allowed boundaries are replaced by the closest allowed value. This allows a feasible operation at all times. In addition error handling has been extended to allow operation even in the case of unforeseen errors that might lead to problems in the high level controller.

2.4. Forecasting

To calculate an optimal control schedule the MPC requires forecasts of electricity prices and gas flow.

For the electricity price the day-ahead prices from EPEX spot-market auction are used and obtained on-line, via a web interface.

Gas flow is predicted based on on-line measured data using a one day persistence forecast ("yesterday-is-today"). This forecast is an internal method and does not need any additional external data (such as weather predictions). In future research other forecasting methods, that allow for a better prediction will be developed.

3. Results

The system test of the P2G plant is done in two steps. In a first step a dynamic characterisation of the P2G unit and its controller is performed. This is done to evaluate the ability of the plant to operate in a context where electricity consumption has to be dynamically adjusted according to the needs in the power system.

In a second step the use of MPC to operate the P2G plant under dynamic boundary conditions is evaluated. For this purpose the unit is operated continuously for three days in different use-cases, using the developed MPC. A more simple on-off control approach is used for comparison.

3.1. Dynamic characterisation

To evaluate the ability of the plant to operate in a context where electricity consumption has to be dynamically adjusted according to the needs in the power system a dynamic system test is performed. For this purpose, time varying set-points are transmitted to the unit and the ability to follow the set-points is evaluated. The signals used to characterise the dynamics of the system and the corresponding response are shown in Figure 6.

The characterisation procedure tests for different response types. The ability to offer a fast and r response is required to provide operation reserve. The ability to continuously adjust the power is required to balance fluctuating electricity generation from wind or PV. Therefore three different test sequences have been performed:

1. Double-pulse: Two rectangular steps of equal hight, duration and pause time. This corresponds to the pre-qualification requirements for electricity consumers and producers to take part in the German market for operating reserve [27]. The chosen sequence is for secondary reserve and allows a delay up to 5 minutes to reach the set-point.

2. Steps with decreasing pause times: For quantifying the dynamic properties and their limits, rectangular-shaped signals with equal height decreasing durations are applied as set-points. Each signal is followed by a pause of the same length. The duration of the steps and pause times between the steps are decreased steadily.

3. Ramps with increasing speed: Ramps with different steepness are applied as power set-points. This can be interesting if e.g. the changing production of renewable energy has to be tracked. Starting from 50 % part-load the unit is ramped-up to 100 %, down to 0 % and than back to 50 %. This sequence is repeated with increased ramp-rates.

The results of the test sequences are shown in Figure 6 and 5. It can be seen from Figure 5 that the dynamics of the plant are sufficient to pass the pre-qualification needed for participation in the secondary reserve market. The electrolyser responds almost instantaneously towards the changed set-point. During the steady state operation phases, small fluctuations around the set-point are observed. Those are attributed to the interaction between pressure driven internal electrolysis control and our subsequent flow controller. It can be further observed that electricity consumption is not zero at the intended times, as the unit is put in warm-standby to respond quickly to set-point changes.

The same characteristics are observed for single pulses, even when the speed of the pulses is increased, as seen in Figure 6(a). The unit reaches the set-point after approximately 20 seconds, with an initial dead time of 4 seconds. Below a pulse length of

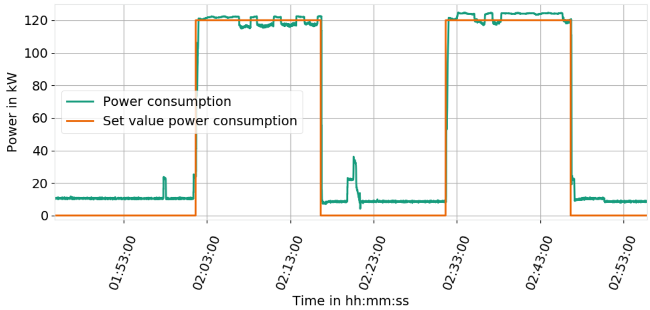


Figure 5: Pre-qualification procedure.

20 seconds the dynamics and the delay in the control cycle do not allow faster response (see zoomed in Figure 6(b)).

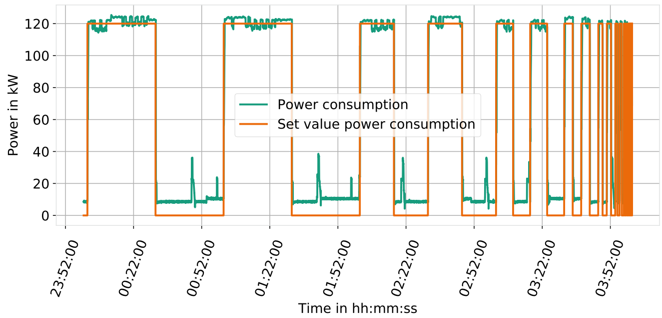
Figure 6(c) shows the complete results for the ramping sequence. Figure 6(d) shows a section of this sequence where higher ramping rates are applied. It can be seen that the power consumption of the electrolyser is able to follow the set-points for ramps with a ramp rate less than 1 %/s of the nominal power. It can be observed that power consumption oscillates around the set-point. This is due to the dead band controller implemented in the electrolyser unit. As seen in the pre-qualification time series, values below 8 kW_{el} cannot be reached without shutting down the electrolyser. When ramping upwards from the minimum value the system "swings" upwards directly after starting and then comes back to the set-point (see Figure 6(c) and 6(d)). This is not due to a pressure build-up in the system as one might believe, but due to instabilities of the flow controller. The shown sequences clearly indicate the limitations in control accuracy, dynamic response and tracking accuracy of a pressure-controlled system with a flow control unit for applications in the power system. Nevertheless, the dynamic characterisation procedure shows that the dynamic properties of the unit allow for the intended application as part of an urban energy system. Dynamics of the investigated site are suited for balancing on a 20 second times scale, which is sufficient for most applications. However fast changes that might occur in PV electricity generation due to sudden cloud covering and the provision of primary reserve might be not suitable for this P2G unit.

3.2. *Long term operation*

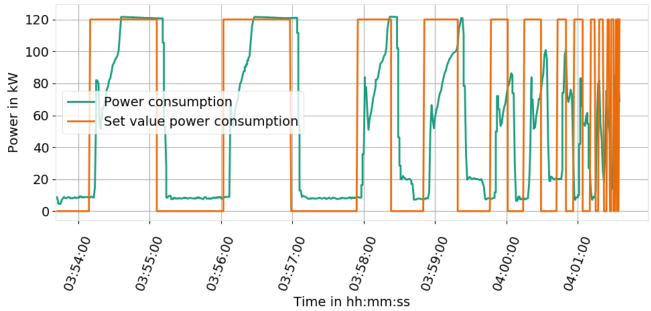
In a second step, the MPC controller is demonstrated live for several days with the real P2G unit. For a better interpretation of the dynamic abilities of MPC, the P2G unit is also operated using an on-off controller.

3.2.1. *ON-OFF controller*

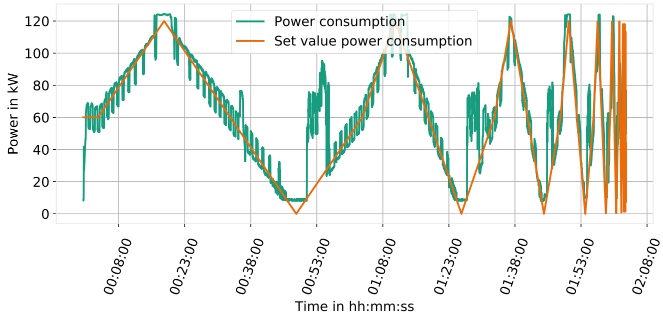
In this case the power demand of the electrolyser depends on the state of charge of the hydrogen storage. The electrolyser is started, whenever the storage state of charge (SoC) is below a certain value. Full load production of hydrogen then continues until the storage is fully charged and the electrolyser is switched off. Hydrogen is fed into the gas network at the maximum allowed feed-in rate at all times. Hence the duration of one ON-OFF cycle primarily depends on the prevailing flow



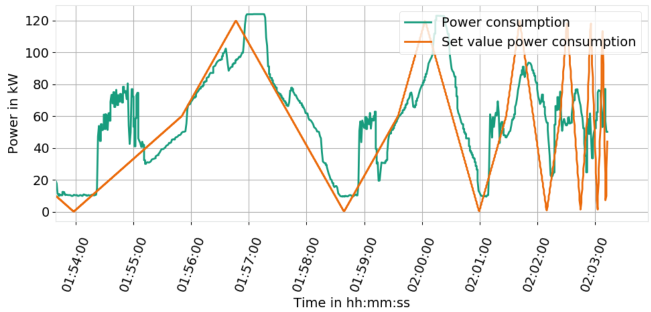
(a) Steps with decreasing duration and pause times.



(b) Steps with decreasing duration and pause times (zoomed in).



(c) Ramps with increasing slope.



(d) Ramps with increasing slope (zoomed in).

Figure 6: Dynamic characterisation of the electrolyser unit.

Used test	Description	Value
Pre-qualification	Time to reach nominal power	≈ 20 s
	Average deviation from set value	≈ 2.5 %
	Offset	10 kW
	Average slope	5.5 kW/s
Rectangular signals	Dead time	≈ 4 s
	Time to reach nominal power	≈ 20 s
Ramps	Maximum possible ramp	≈ 1.2 kW/s (≈ 1 %/s)

Table 1: Results of the dynamic characterisation procedure

in the natural gas network. Using the ON-OFF controller, the unit is operated to allow long run-times at nominal load.

Figure 7 shows the operation of the P2G unit using the ON-OFF controller. The dead-band characteristics are clearly visible. The storage is charged and discharged cyclically, leading to approx. four cycles a day for the given sequence. Furthermore it shows that the plant follows the power set-point in an accurate way. As already visible in the pre-qualification sequence, the unit is operated in warm stand-by mode and not completely shut down, which leads to a base-load electric demand of eight kW at times where the set-point is zero. Regarding the hydrogen feed-in it can be seen that the set-points for hydrogen feed-in are followed with a small time delay.

3.2.2. *Model predictive controller*

The performance of the MPC is investigated with the real plant for a use-case where time variable electricity prices are applied. The target of operation is to optimally use the existing hydrogen generation and storage capacity, in the presence of time electricity prices, with respect to the limitations in the natural gas grid.

The results for an exemplary two day operation sequence are shown in Figure 8. It can be seen that the MPC operates the real unit successfully and the generated schedule for set-points is tracked by the plant. MPC optimises the operation of the P2G unit towards the changing electricity prices. This leads to a more dynamic operation compared to the on-off case. During low price periods the unit is operated mostly at full load and the hydrogen storage is charged. During times with high prices the electrolyser is switched off. The storage is used dynamically with respect to the current situation, which in this case leads to more cycles and more variation in the charge and discharge rates of the storage. The ability of MPC to respect time varying constraints can be seen when investigating the time series for feed-in, storage SOC and power demand, shown in Figure 8. The system is operated within the allowed boundaries at all times. Hydrogen feed-in is adjusted dynamically and mostly follows the allowed maximum rate. Furthermore the MPC makes use of the full range of operation possibilities. Leading to times where the unit is operated in part load, as can be seen during 08.12. 20:00 to 24:00.

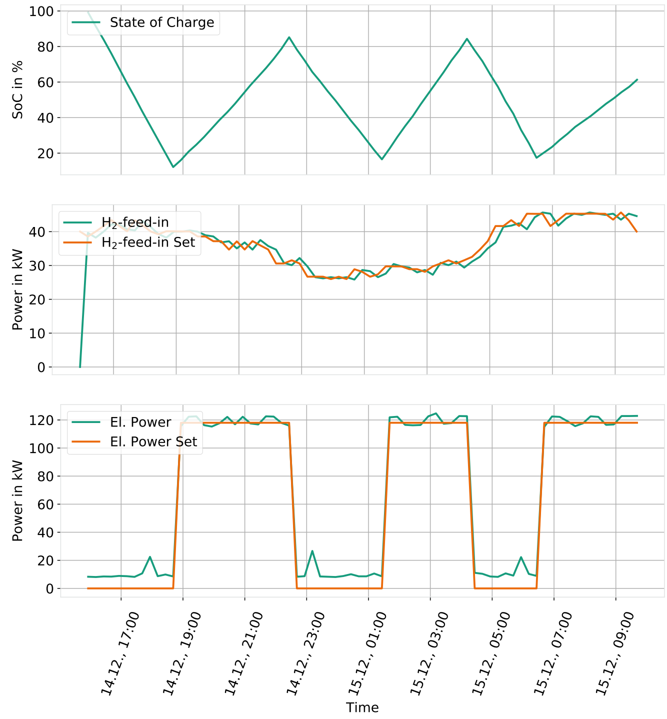


Figure 7: Exemplary sequence of 18 hours using the ON-OFF controller in live operation.

There are a series of observations, that can be made using the test sequence, to highlight the differences between simulation and practice. As already seen during the dynamic characterisation procedure there are tracking inaccuracies rooted in the low level controller, which lead to oscillations of the real value around the set-points. Furthermore it can be seen that the real unit does not properly respect the zero set-point and switches to warm stand-by instead, which leads to a mismatch between the linear optimal control model and reality. However, as it can be seen, this mismatch does not seem to have negative impact on the operation as hydrogen generation during this periods is still zero as assumed by the controller. At 8.12. 10:00 and 15:00 the set-point resulting from the high level controller is below the minimum value possible for the flow controller. In this case the set-point is set to zero, leading to a difference between calculated and actual feed-in and hence storage content. At 9.12. 21:00 the storage is empty ahead of schedule and the feed in is put to zero by the mid level controller. In case that the calculated feed-in exceeds the allowed, the plant follows the maximum allowed feed-in.

It can be seen from this sequence that simulated and observed behaviour of the P2G differs, which can negatively influence the performance of the controller. A potential reason for the observed deviations between set-points and real system states are imperfect forecasts for the gas-flow and hence the maximum allowed feed-in. Also, minimum technically possible feed-in rates contribute to this mismatch. This may either result in too low feed-in rates, although higher rates were possible, or, as

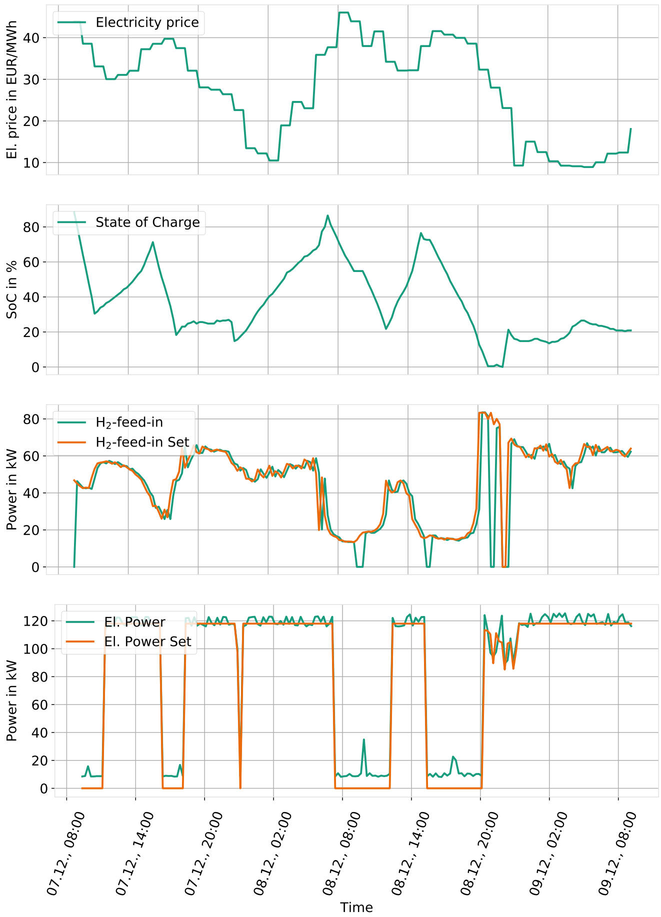


Figure 8: Exemplary sequence of three days using the MPC controller to operate the unit with respect to time varying electricity prices, in live operation.

seen, lead to a switch off of the hydrogen feed-in. Both cases lead to reduced operating hours and therefore decrease the economic feasibility of the plant. Furthermore, unforeseen events such as manual override, maintenance, or events in the gas grid can lead to deviations from the planned operation. These errors are compensated by restarting the optimisation, updating the current system state, represented by the storage content, and using it to calculate the next step (closed loop controls).

4. Discussion

The results of the live test confirm the findings obtained by simulations, presented in [10]. The controller will be used for future operation of the P2G plant and is by February 2018 running in stable operation for over 10 weeks. During the test and design period of the P2G plant a series of lessons have been learned and potential improvements identified, that are discussed in the following.

4.1. Potential improvements

Improved forecasts could be applied. The accuracy and availability of predictions for gas flow, feed-in of renewables, and grid load contributes to the quality of the operation of the plant. Forecast accuracy plays an important role when the system is operated close to its limits. This is the case when hydrogen feed-in is low, which limits the operation and therefore strongly influences the optimal control decision. More sophisticated forecasting methods could help to improve accuracy and thus system operation.

Secondly, it showed that the plant was not always tracking the calculated set-points. An improvement could be to formulate the optimal control problem as a linear mixed-integer optimisation problem. By this the optimal control model could be adjusted to respect hybrid system characteristics instead of treating set-points that are not feasible with post-processing. This potentially improves the control accuracy at points where the linear approach results in low part-load operation or low feed-in rates, which are not traceable by the unit. However, this comes at the cost of increased computational complexity and thus computation time and hardware requirements. Generally it should be said that although using MPC offers benefits in operation it comes with additional complexity. MPC requires more time and resources during the design process as a system model and the forecasting algorithms are required. Additionally the requirements for computation are higher compared to simple rule-based controllers

Thirdly, increasing the storage capacity can improve operation. Increasing storage capacity increases the flexibility of the system and allows an improved operation of the unit. In summer, when gas network restrictions are dominant, hydrogen production can be increased significantly at hours with low prices when storage capacity is increased. Furthermore, tests in simulations showed that the presence of sufficient on-site hydrogen storage reduces the negative effect of plant-model mismatch [10].

Finally, the stand-by controls of the P2G unit could be improved. In the shown sequences, the electrolyser is always operated in a warm stand-by mode which allows fast reaction rates on set-point changes on the one hand, but also increases the overall power consumption without any further benefits. 8 kW_{el}, about 7 % of the nominal power, are consumed in this mode without contributing to any hydrogen production. An improved adapted control should recognize long sequences where hydrogen production is set to zero in order to switch off the plant, including cooling and ventilation, completely. This could improve the overall efficiency of the plant significantly, especially in summer, when hydrogen production is low.

4.2. A word on P2G in urban contexts

P2G in combination with on-site storage and the presented MPC can be used for a variety of applications in decentralised energy systems. It was demonstrated that MPC is well suitable for operating such plants in the presence of restrictions in the energy networks and changing boundary conditions such as time variable electricity prices. On the way setting up the controls as well as the test site the following lessons have been learned and can contribute to successfully integrate P2G in a decentralised energy system:

If connected to a gas network which could limit feed-in, on-site hydrogen storage is recommended. The stricter network restrictions are, the larger storage devices should be. As demonstrated in this paper, adapted controls are capable of optimised storage management. The potential of such a control increases with increasing storage capacity [10].

Operating electrolyser and feed-in-plant according to quickly changing set-values requires a high dynamic of the controlled system. Especially in areas where load and production can change quickly due to consumer variability and fluctuating electricity generation from renewables, system dynamics may limit the usability of P2G-stations. Even though the overall system was not built towards fast reaction time (indirect control of electrolyser power, three level controller set-up with transaction delays between the levels) the investigated electrolyser showed sufficiently fast dynamic behaviour and all set-values could be reached within seconds. A more direct control set-up might even improve reaction times. Nonetheless the potential use-case should be considered beforehand and dynamics of the P2G plant and the selected control strategy should match the requirements.

On the system level an increased hydrogen tolerance in the gas network could ease the restrictions. At the given location a relatively low upper limit of only 2 Vol-% of fluctuating hydrogen applied. Nonetheless, as gas grid applications prefer a rather constant heating value and therefore a rather constant share of hydrogen in the gas grid, constant hydrogen percentages in the gas grid could be introduced as a secondary optimization goal to account for that preference.

Furthermore, when optimising the operation of a P2G unit towards objectives coming from the power system, as it was done in the presented research, hydrogen content in the gas grid will vary. In commercial applications, the gas grid has to be balanced by the balance group responsible and their respective gas producers. In most commercial P2G plants this is solved by producing gas according to the demands of the balance group at least part of the time. Taking into consideration the accounting period and the delivery commitments as an optimisation goal could improve commercial viability of P2G plants.

5. Conclusion

Power-to-gas stations are likely to play an important role in the transition of the energy system. With an increased decentralisation of the energy system, those units could be located even at sites where restriction in the gas network or the electric grid apply. When actively integrated into the power system P2G stations have to respond dynamically to changing requirements in the electric power grid and the gas network.

In this paper a real electrolysis plant, located within the city of Freiburg, Germany is characterised with respect to its dynamic properties. The application of a model predictive control (MPC) approach is successfully demonstrated. It is shown that the controls are capable of optimising operation with respect to time variable electricity prices, while operating within the limitations in the gas network and the electric grid. The controller optimises the operation of the P2G unit and the on-site storage, which confirms the simulation results presented in [10].

It is shown that imperfect forecasts and a mismatch between the optimisation model and the real unit led to a set-point schedule that could not always be tracked by the plant, which leaves room for further improvements. However, as the controller is implemented in a closed-loop way those errors are indirectly corrected by updated measurements of the system state and the operation of the system is robust. The findings of the real live demonstration lead to the suggestion that P2G plants should be operated using advanced controls - as the one presented. This particularly holds true when on-site storage, limitations in the energy networks and time varying incentives are present.

The presented modular set-up of the controller development platform allows for a rapid development and testing of controllers and will be used for other applications such as integrating different energy units like heat pumps, CHP and electrical storage.

The presented demonstration plant is capable of testing various operation algorithms and components and will be used as research platform for further studies concerning integration of P2G units and testing of P2G components.

6. Acknowledgements

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