Applied Energy 228 (2018) 833–842

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

David Fischer*, Florian Kaufmann, Raphael Hollinger, Christopher Voglstätter

Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany

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.

ARTICLE INFO

Keywords:
Power-to-gas
Hydrogen
Smart grid
Model predictive controls
Field test

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.

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.

* Corresponding author.
E-mail address: David.Fischer@ise.fraunhofer.de (D. Fischer).

https://doi.org/10.1016/j.apenergy.2018.06.144
Received 27 February 2018; Received in revised form 22 June 2018; Accepted 30 June 2018

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