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Power-to-gas in a smart city context – Influence of network restrictions and possible solutions using on-site storage and model predictive controls

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ABSTRACT

Power-to-gas (P2G or PtG) technology can provide energy storage capacity to the energy system by converting excess electrical energy into hydrogen and feeding it into the natural gas network, where it can be stored. However nowadays hydrogen feed-in has to be limited to certain percentages in order to keep the characteristics of the resulting gas mixture (i.e. heating value) within the national standards. For P2G plants in urban areas this can strongly impact the economic viability. This paper investigates the use of on-site storage and model predictive controller (MPC) to ease the negative effect of restrictions in the gas and power grid on the economics of P2G systems. Three different use-cases for P2G in an urban setting are considered: Optimal utilisation of renewable electricity produced within the boundaries of the city, optimised electricity purchase at the spot market and optimal usage of electric network. MPC is compared to an optimised rule-based control approach. Results show that both controls can be used to meet the objectives and operate the power-to-gas plant. However, the MPC approach results in a smoother operation of the plant and significantly improved economic performance in all cases and is recommended. The results indicate the beneficial effects of on-site hydrogen storage on system operation and economics. For the investigated cases a storage capacity around 6 full load hours of the electrolyser was sufficient to improve results significantly.

Introduction and motivation

For most countries decarbonisation of the energy system requires changes across all energy sectors [1,2]. In the electric sector the replacement of fossil fired power plants with renewable electricity generation leads to challenges such as balancing the fluctuations of wind and photovoltaic (PV) on different time scales. Storage will be needed to avoid curtailment during periods of high renewable electricity generation [3], to provide base-load electricity using renewable sources [4], and to support a stable operation of the electric grid [5].

Power-to-gas (P2G) systems, based on water electrolysis can convert available renewable electricity and water into hydrogen and oxygen. For this process alkaline water and proton-exchange membrane (PEM) electrolysers are commonly used [6]. The produced hydrogen can be used in different applications, such as industrial processes, mobility or electricity generation using turbines, combustion engines or fuel cells. Furthermore the generated hydrogen can be fed

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into the natural gas network directly or after a methanisation step. Feeding hydrogen into the natural gas network makes existing natural gas storage caverns accessible for seasonal storage [7–9].

Today's P2G stations show a capacity of several MW_{el} and are mainly located in the proximity of natural gas pipelines, industrial sites and wind farms. However, decentralisation of the energy system might lead to situations where P2G stations will be installed to provide storage (or more precisely flexible shifting of negative residual load from the electric sector to other sectors) in micro-grids, smart energy regions and cities or energy independent neighbourhoods. Decentralised distribution of P2G stations included into urban energy systems may be an alternative to large scale, centralised approaches.

Such a setting is investigated in this presented work, where a P2G unit is part of an urban energy network, shown in Fig. 1. The urban energy system consists of a wind array of 7.2 MW, a solar PV array of 2.5 MW, a base-load biomass plant and distributed CHP units located at industrial sites. The P2G unit is located within the city boundaries of Freiburg, Germany and connected to a natural gas line, which supplies a residential area. For this case restrictions in the electric grid and the local gas network have to be considered.

Although the electric network at this site is sufficiently strong to connect the P2G unit, operation during peak load hours is to be reduced to postpone reinforcement of the electric infrastructure. Generally transformer capacity and line capacity can limit the allowed installed capacity or the operation of a P2G unit. When operated in a grid friendly way, P2G can be used to reduce feed-in peaks of PV and Wind or provide ancillary services to the network as shown in Refs. [10,11].

In an urban setting restrictions in the gas network are an important parameter to consider when selecting a site as indicated by the results of [12]. In Germany, the operator of the gas network guarantees a stable quality of the natural gas in his network. Thus a frequent requirement - at least nowadays - is that the amount of hydrogen in the gas network may not exceed 2 vol-% [13–15]. This requirement leads to limitations in the allowed feed-in and thus the economic performance of decentralised P2G stations.

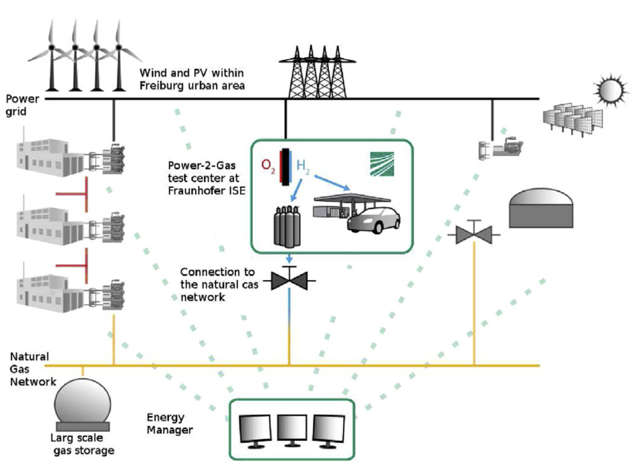

Fig. 1 – P2G stations as part of an urban energy system as will be demonstrated in the city of Freiburg, Germany.

On-site hydrogen storage can act as a buffer and provide flexibility so that the negative effect of grid restrictions to unit operation can be eased. For this purpose adjusted controls of the P2G unit are needed. This work investigates to what extend network restrictions, storage size and control strategy influence the technical and economic performance of a P2G plant in different use-cases.

The results of this study are used to select a control strategy and a preferred use-case for a real P2G unit located within the city of Freiburg, Germany.

Past work: the role and potential applications of P2G in the future energy system

Previous studies focus has been on investigating the role of P2G in the future energy system. This was done by using structural optimisation or scenario based simulation approaches.

In Ref. [7] a scenario with a 100% renewables is discussed, where electricity generated by hydrogen provided by P2G contributes up to 10% to the total supply and is considered an important storage technology in the future power system.

In Ref. [4] different scenarios for Germany 2050 are simulated. The authors show that depending on the scenario more than 20% of all fuels might be produced in a renewable way using P2G. In this scenario, the share of renewables in electricity consumption is more than 75%.

The ability of P2G-stations to integrate renewable electricity is demonstrated in Ref. [5]. This study shows, that for a 85% renewable energy scenario in Germany, up to 12 GW of P2G could be installed. The authors state that plants should be located close to wind farms for reducing power flows in the transmission grid [16].

The cost optimal structure of a fully renewable energy system of a model region in Germany is investigated in Ref. [17]. It is shown that going 100% renewable is possible with and without P2G technology. However including P2G as long term storage significantly reduces levelised cost of energy LCOE of the system. The authors highlight the importance of decentralised solutions for the energy system and sector coupling. Battery storage and power to heat (here only direct electric heating) are seen as viable parts of a storage portfolio.

Study [18] investigates the use of P2G as energy storage in a smart grid context and compares it to other storage technology using an analytical hierarchy process. The study highlights potential benefits of P2G by providing ancillary services, seasonal storage on a large scale and an efficient energy transportation infrastructure with losses around 0.001% per 1000 km.

Study [19] puts a focus on integrating P2G in urban energy systems, here highlighting the importance of the heat sector. The authors state the importance of middle and high temperature heat that can be generated by CHP units, gas-boilers and gas driven heat pumps using methanised hydrogen, which in the investigated case can be produced by surplus renewable electricity on city level.

Another stream of studies explores the use of P2G in exemplary applications in the context of providing services to the electric grid. The studies mostly are combined with economic evaluation of the investigated case.