Power-to-Gas - Solution of the multi-vector urban distribution system in the Smart Grid framework?

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Abstract— **Power-to-Gas can play an important role in the energy transition. Power-to-Gas primarily connects the electricity and gas grids and makes long-term, large-scale storage possible. The publication uses an example of a municipal energy suppliers to illustrate the possibility and limitation of Power-to-Gas in Switzerland. The main focus is the extension of a Power-to-Hydrogen with a methanation unit, because of limitation in operation due to hydrogen concentration limitation of the gas network. The project shows, that Power-to-Gas can play a role for urban distribution of electricity and heat and mobility concepts.**

Keywords— Power-to-Gas; urban distribution; network convergence; hydrogen

I. INTRODUCTION

The conversion of the energy supply from large central power plants to decentralised producers using renewable energy sources such as wind and sun creates major challenges. There are already many grid bottlenecks in the electricity transmission grid. In urban areas, too, the grids are partially overloaded, as the distribution grids cannot absorb the production of PV electricity at peak loads. One way of solving the problem is to expand the grid in urban areas. Another possibility is to exploit the potential of sector coupling. Sector coupling refers to the networking of players, who are energy suppliers, energy consumers or both. Traditionally, the sectors of electricity, heat supply (or cooling), transport and industry have been considered independently of each other. Sector coupling is the provision of energy from one sector to another by converting the energy into a usable form for the other sector or using unused surplus energy, e.g. recovering waste heat for another sector.

Sector coupling and integration of new units into an excisting network is a complex procedure. The units must know the needs and be able to meet them efficiently and cost-effectively. Digitization is a key factor in reducing complexity. This includes automatic control and regulation of the devices and systems that influence the energy system. An essential condition is the networking of the devices and systems with an exchange of data.

One possibility of sector coupling is converting electricity into synthetic natural gas (SNG), called Power-to-Gas (PtG). PtG will play an important systemic role by stabilizing energy supply and balancing seasonal and spatial fluctuations in power generation from renewable energy sources. Particularly in urban areas, this technology can bring the individual sectors together and create synergies.

In this publication, the PtG technology, application examples of sector coupling with PtG from municipal energy suppliers and from the STORE&GO project are presented.

II. POWER-TO-GAS

The PtG process links the power grid with the gas grid by converting (surplus) power into a grid compatible gas via a two-step process.

A. Conversion Technology

The first process of a PtG system is the electrolysis, the second process is the methanation. The electrolysis convert water (H_2O) with electrical power into hydrogen (H_2) and oxygen (O_2) (see eq. (1)). The specific reaction enthalpy (ΔH_r^0) of the endothermic reaction is +285.8 kJ/mol.

$$2\,H_2O \leftrightarrow 2H_2 + O_2 \qquad \Delta H_r^0 = +285.8\,\frac{kJ}{mol} \quad (1)$$

The main technologies are the alkaline and proton exchange membrane (PEM) electrolysis. In addition to the previously named electrolysis types, the high temperature electrolysis technology should be mentioned, due to its exceptional characteristic of high electrical efficiency. The produced hydrogen can be either injected directly in the grid or be used for producing synthetic natural gas (SNG) in the second methanation process step. The methanation is defined as the conversion of H_2 and either carbon monoxide (CO) (see eq. (2)) or carbon dioxide (CO_2) to methane (CH_4) (see eq. (3)).

$$3H_2 + CO \leftrightarrow CH_4 + H_2O \;\; \Delta H_r^0 = -206.3\,\frac{kJ}{mol} \quad (2)$$

$$4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O \;\; \Delta H_r^0 = -165.1\,\frac{kJ}{mol} \quad (3)$$

For the methanation, there are two main processes on the market and in industrial use: biological methanation with microorganisms and thermo-catalytic methanation.

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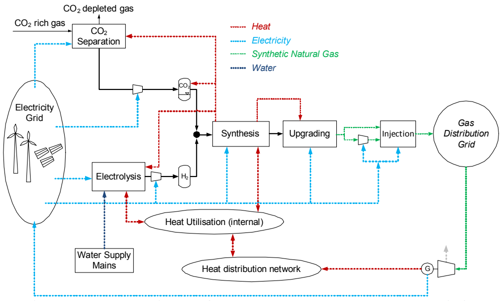

Figure 1: Overview of a Power-to-Gas system and the connections to the electricity, gas, heat distribution network.

Thermo-catalytic methanation is defined as a conversion in the presence of a catalyst, usually nickel-based. Temperatures in the range of 240 to 300 °C and pressures from 1 to 16 bar are typical operating conditions. The advantages and challenges of thermo-catalytic methanation are described in [1]. The biological methanation uses highly specialized microorganisms (archaea or bacteria). It involves the principle of methanogenesis, a specific anaerobic metabolic pathway in which hydrogen and carbon dioxide are converted into methane [2].

For most applications, the gas quality after the methanation reactor is not sufficient and must be adapted. In most cases, the dew point, methane and hydrogen concentration must comply with certain limit values. For example, there are country-specific regulations for feeding SNG into the natural gas network [3].

In all European countries, it is important that the electricity for the H_2 generator come from renewable sources in order for the SNG to have a sustainable character. The CO_2 should come from a biological or a natural source for example the atmosphere (CO_2 capture plant). In Switzerland, the SNG will be sustainable even if the CO_2 comes from a fossil source. For example from a coal fired power plant. It is important, that the CO_2 is not produced on purpose for the methanation process but is a by-product.

The generated SNG can be injected easily into the existing European gas transportation and distribution grids or gas storage, used as Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) fuel, or can easily be utilized in all other well-established natural gas facilities.

B. *Demand and Limitation of PtG*

[4] has provided a perspective on the greening of the EU-wide gas consumption by 2030, via a scenario analysis. The main conclusion is that of the projected gas use by 2030, in the order of 400 to 450 billion m^3 per year, still a relatively limited share will be 'greened' by then. So far, the dominant source of green gas, i.e. green gas based on digestion of biomass, has succeeded in greening gas use to a level of about 4%. Most of the expected increase in 'greening' of gases will still be based on the same source. In an optimistic scenario, such green gas could comprise in the order of 10% of 2030 gas use. New technologies to generate green gases are currently under development, i.e. biomass gasification and PtG. However, it has to be pointed out that the development of the PtG technology is subject to fundamental energy and climate policy decisions.

In addition to the demand, the location is also a decisive factor for production of SNG. Especially in cities, ideal conditions for PtG and sector coupling are given. Due to the space requirements, compact and cross-sector solutions are necessary to implement the energy transition.

III. Role of PtG in a Multi-Vector Urban Distribution System

If the three energy networks gas, electricity and district heating intersect, the location has an advantage for the operation of a PtG plant. The presence of these three networks (network convergence) at one location is a decisive prerequisite and enables the various forms of energy to interact.

The PtG process links the electricity and the gas network by converting (surplus) power into a SNG. The gas can be stored on site or injected into the gas network. The waste heat from the PtG process and the heat demand during standstill makes the heat distribution network part of the multi-vector system.

The gas network is connected to the heating network via a gas boiler and a CHP unit. If there is no heat demand, the heat can be stored in a heat accumulator on site. In addition to the heat, the CHP also supplies electricity and connects the gas and the electricity network.

The integration of a PtG system into the gas and electricity grid in an urban area can be a challenging task due to specific local requirements. Legal or regulative obstacles during the planning, erection and demonstration of the plant are among other things plant location (land management), soil protection laws, water rights, noise pollution, air pollution, hazardous substances, waste management, access authorization (fencing), safety issues (fire protection), planning permission and operating permit.

The possibility to inject SNG into the gas grid and the resulting effort (technical and economical) depend mainly on the capacity of the gas grid, the operating pressure of the gas grid and the required gas quality of the gas grid. These three parameters depend strongly on the structure of the gas grid.

PtG can also be used as a storage solution for the (partial) autarky of a district. Excess energy produced on the site is stored in batteries for a short time and in the form of hydrogen or SNG for a long time. This allows seasonal separation of production and consumption and increases the degree of autarky.

IV. Technology in the Field

The Horizon 2020 project STORE&GO demonstrate the role of PtG in future energy system. In STORE&GO complementary technological, economic and societal aspects of power-to-gas with an innovation focus in methanation technologies will be implemented and tested by established private enterprises on three demonstration sites in Germany, Switzerland and Italy. In the following sections, the focus is on the Swiss plant, as the installed plant connects all distribution networks.

A. *Swiss Demo Site*

The Swiss demonstration site at Zuchwil (Solothurn) represents a municipal area with considerable PV and hydro production capacities. The hybrid plant connects the grids electricity, gas, district heating and water. In the hybrid plant, electricity, gas, district heating and water can be converted from one form of energy (e.g. electricity) to another (e.g. hydrogen) by means of converter components (e.g. electrolyser). The newly created form of energy can then be temporarily stored on site in storage components (e.g. hydrogen storage) or fed directly into the respective energy grid.

Currently, the Aarmatt hybrid plant consists of three energy converter components: a gas boiler with 6MW heat output, two electrolyser with a total hourly hydrogen production of max. 60 m^3 and a combined heat and Power plant (CHP) with approx. 1.2 MW electrical and thermal output and two associated storage components: a hydrogen storage tank with a storage capacity of 360 m^3 and a heat storage tank with a storage capacity of 16 MWh. In addition, a heat recovery system, a hydrogen and a methane injection station, connected to the gas network, a heat injection device

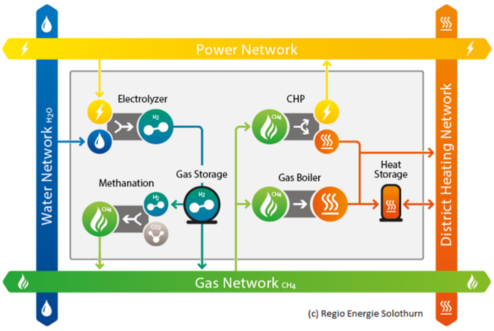

Figure 2: Interaction of the hybrid plant Aarmatt in Solothurn (Switzerland) with the municipal supply utilities for water (blue), electricity (yellow), gas (green) and heat (red). © Regio Energie Solothurn

for feeding heat into the district heating network and a transformer station with a medium-voltage switchgear are installed. All components are connected to a minimum of two networks and to each other so that energy can be converted, stored or fed directly into the grid flexibly and as required.

Summarized the demonstration plant is embedded between the electricity and gas grid and production infrastructure of the utility. It essentially consists of three energy converter components and two associated storage components.

B. Extension of the Power-to-Gas Plant to solve problems

The hydrogen part of the PtG plant has three units. H_2 generation via electrolysis, H_2 storage and a H_2 grid injection. Due to the current framework conditions, there is no commercial use for the operation of electrolysis. In addition, the feeding of hydrogen into the natural gas grid is limited to 2 % by volume of the gas mixture in the grid. In particular, if the customer structure after the injection point is predominantly for heating applications (private customers), then the gas consumption in summer is very low and the injection is restricted. In summer, however, PV and (surplus) hydroelectric power can be used to generate hydrogen at attractive electricity prices, if the electrolyser is except from grid fees. In order to be prepared for the future, with adapted framework conditions, several ideas for preventing the interruption of injection, due to the 2 % by volume limit were discussed.

One possibility is to optimize the consumer structure by adjusting the gas flow in the natural gas network. Industrial consumers with a high minimum consumption throughout the year are needed. Then the hydrogen feed into the natural gas grid can process higher production capacities of the electrolysis, always depending on the currently possible feed quantity. In the hybrid plant, it was shown that a constant industrial consumer allows more hydrogen to be added immediately to the natural gas and that the need for hydrogen storage has been greatly reduced.

Another option is the installation of a hydrogen compressor and the use of the pressure band of the existing 200 bar storage tanks. The hydrogen storage tanks are currently operated with the maximum output pressure of the electrolysis of 30 bar. This option makes sense if the hydrogen is marketed directly as a pure substance or can be used for a hydrogen filling station.

The conversion of hydrogen into synthetic methane was also considered as an option. This means that at high conversion rates from CO_2 and H_2 to CH_4, the injection can be done without limitation. The gas network can be used as a long-term and large-scale buffer storage.

This option was implemented. Today the PtG plant consists of five main units. CO_2 supply, H_2 generation and storage, methanation reactor, injection and utility connection for heat recovery. The biological methanation reactor is designed to convert H_2 and CO_2 gas to CH_4 using archaea microorganisms as a biological catalyst. The CO_2 source for the biological methanation process is a byproduct coming from the waste water treatment plant where biogas is produced. The CO_2 is separated from the raw gas by membranes, leaving a stream of CH_4, which is fed into the gas grid. The hydrogen comes from the existing electrolysis and can be stored in the hydrogen storage tank if the operation of the methanation is not simultaneous with the electrolyser operation.

The conversion in the methanation reactor releases heat, which requires a cooling system. The cooling system consists of an internal coil in the reactor and an external air cooler. Water is circulated through the system thus dissipating the heat. This heat could be fed to the existing heat recovery system, if the experience collected during operation would prove this to be beneficial for the overall efficiency. The produced CH_4 can be injected in the local distribution grid and used for various application.

The application of the PtG plant and the combined heat and power plant (CHP) of the hybrid plant demonstrate the contribution to network convergence. Electricity grid services can be provided by both sub-systems. Through the combination and communication via smart meters, an optimized provision of positive and negative balancing power and control reserve can be achieved, see . This operating strategy enables the stabilisation of the electricity supply and the storage of surpluses to compensate for undersupply.

	CHP	PtG
Power Generation • futures marketing • self-consumption • interday marketing • spot marketing	✓	
Balancing Power • + positive • - negative	✓	✓
Control Reserve • +/- secondary • +/- tertiary	✓	✓
Peak Shaving	✓	
Gas Production • renewable		✓
Heat Production	✓	✓

Figure 3: Provided products and services of the CHP and PtG plant of the hybrid plant.

C. *Results*

The methanation plant has been installed and the commissioning of the plant is in progress. The expectations could not yet be verified in real operation as commissioning is ongoing. Two scenarios are possible. On the one hand, methanisation achieves a gas quality that contains less than 2% hydrogen and a minimum of 96% of methane. In this case the gas can be unlimitedly fed into the grid, as the 2% hydrogen in the natural gas network will not be exceeded, as long as there is no hydrogen from previous feeds or from the source in the pipeline. On the other hand, it is possible that the feed gases are not completely converted and a hydrogen concentration greater than 2% is measured. Then the situation has improved compared to pure hydrogen, but the injection is still limited. The latter is a minor problem if the consumer structure after injection has a high natural gas consumption throughout the year.

In addition to the feed-in, the operating costs and investment costs are analysed and optimisation proposals are presented. The techno-economic optimization of the power-to-gas system has a strong focus on reduction of investment costs through experience curves, learning effects and economies of scale. The influence on the investment costs is expected to be different for each main component. In general, learning curves and economies of scale are strongly influenced by the global market in terms of an overall application of the system or its technology compounds.

Techno-economic optimization also considers optimal system integration and additional benefits through utilization of byproducts such as heat or oxygen, which can increase the overall efficiency significantly. The techno-economical optimization studies have a clear impact on the selection of priorities for future development efforts.

D. *Other Projects*

In Italy a STORE&GO demonstration plant in the region of Puglia is realized. In this region high PV production capacities are available representing the South European RES situation. The innovative concept at this demo site consists of adsorptive $CO2$ enrichment from the atmosphere and a modular micro-reactor based methanation concept. This plant delivers liquefied synthetic natural gas (LNG) and offers the direct utilization of the produced SNG in the transport sector.

The overall objective of the German STORE&GO demonstration plant is to prove successful operation of an integrated innovative Power-to-Methane plant, suitable for large scale energy storage. It comprises a 1 MW PtG plant, interconnection to the high pressure transport gas grid, intelligent interconnection to the transmission electricity grid and potential thermal energy integration with local industrial facilities, in order to further increase the overall efficiency and economy.

The world's first power-to-gas plant in an existing residential complex was recently commissioned in Augsburg [5]. The intelligent, forward-looking energy management system controls the supply of electricity and heat according to demand and the storage of excess energy as SNG. If required, the stored methane can be converted into electricity and heat in a CHP. According to the manufacturer, this results in a degree of utilisation of around 90 percent of the energy generated by the company itself.

In another project, hydrogen is used to store excess solar power from an apartment building [6]. The solar energy is temporarily stored in daily and medium-term battery storages (two to three days) for use in the building. For long-term storage, electricity is converted into hydrogen. The hydrogen is temporarily stored and converted into electrical and thermal energy via a fuel cell if required.

V. Conclusion

At the European level, power-to-gas technology is already seen as an important opportunity. Not only to store energy on a large scale, but also to optimize local energy production and distribution with the help of smart grids and artificial intelligence. As part of the STORE&GO research project, Power to Gas technology is being tested and developed on an industrial scale at three locations in Italy, Germany and Switzerland. With its infrastructure, the hybrid plant in Switzerland offers an interesting platform for applied research and development in urban and industrial environments.

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