FEASIBILITY ANALYSIS OF THE POWER-TO-GAS CONCEPT IN THE FUTURE SWISS POWER SYSTEM

Chan PARK
ZHAW - Switzerland
park@zhaw.ch

Rafael SEDUNDO
ZHAW - Switzerland
segu@zhaw.ch

Valerijs KNAZKINS
ZHAW - Switzerland
knaz@zhaw.ch

Petr KORBA
ZHAW - Switzerland
korb@zhaw.ch

The authors are with Zurich University of Applied Sciences (ZHAW), Switzerland

Abstract

This paper presents a qualitative and quantitative feasibility analysis of the Power-to-Gas (*PtG*) technology in the future Swiss power grid which will be characterized by a significant share of intermittent renewable energy sources. The focus is placed on establishing a resolution to effectively integrate renewable energy sources (RES) into Swiss power grid through energy storage systems including pumped hydro storage (PHS) and *PtG*, which is commonly known to offer the advantage of a long-term storage over other storage options. The resolution will be presented through the analysis of designed scenarios that reflect the current and future energy profile of Switzerland, and will utilize the strength of a model predictive controller (MPC) with respect to the optimized dispatch of storage capacity including the existing PHS and the proposed *PtG* plants in addition thereto.

Keywords: Integration of Renewable Energy Sources, Long-Term Storage, Power-to-Gas, Pumped Hydro Storage, Model Predictive Control, Excess Energy, Grid Expansion.

1 Introduction

After the disaster of the nuclear power plant in Fukushima, Japan, in 2011, the Swiss federal government decided to abandon the nuclear energy, which currently amounts to about 35% of the total electricity supply of the nation. The existing plants will be decommissioned as soon as they reach the operational limits and there will be no new installations of nuclear power plants. The deficit in the production of electricity as a result of the decision and other sweeping changes in the international energy arena will lead to major changes in the Swiss energy system. For this reason, the Swiss Federal government developed the Energy Strategy 2050 which is a long term plan based on a step-by-step guidance to reach this ambitious goal [1].

In order to fill the gap in electricity production after the phase-out of the nuclear energy, renewable energy sources represent the only possibility for Switzerland to produce self-reliant and CO_2-emission free energy. With a share of 20% of the entire electric energy consumption, which equals 11 TWh, *PV* will make up a fifth of Switzerland energy production [2]. In addition to *PV*, wind power will fill up the energy gap with a share of 4.3 TWh. The share of renewable energy sources (RES) will increase to make up 24.2 TWh by 2050, which amounts to be about 40% of the gross electricity production.

An important aspect of the RES to be considered—mainly energy from solar and wind—is their intermittency and unpredictability. Also they are not quite aligned with the load most of the time. There are hours when the generation clearly exceeds demand and there are also periods in which RES generation is not sufficient to cover the load [3]. High share of the excess energy, which is defined as the generated energy, can add a considerable uncertainty to the supply of electricity which could threaten the power balance and thus the stability and reliability of the Swiss electric power system [4]. For excess energy production due to *PV* and wind, there are three possible options for balancing the power grid, including:

1. Storing the excess energy in storage systems such as batteries, pumped hydro storage (PHS), batteries, *PtG* or thermal storages;
2. Curtailing energy production;
3. Exporting the excess energy.

Focus of the effort of this paper is to investigate how *PtG* technology might be able to contribute to integrating renewables in the future Swiss power system by providing additional storage capacity along with active power curtailment.

The structure of the paper is as follows. Section 2 introduces the principal concept of *PtG* and Swiss power system and PHS. Section 3 presents simulations, in which *PtG* serves as an additional storage in the Swiss power grid in future. Section 4 describes results of the simulation and discussion surrounding *PtG* as an additional storage. Then Section 5 summarizes the results of this paper and discusses ideas for future research.

2 Technology Analysis

2.1 Power-to-Gas

The principal concept of *PtG* is to transform electrical energy via electrolysis into gases, which in turn can be stored in gaseous chemical storages. The electrical energy is used

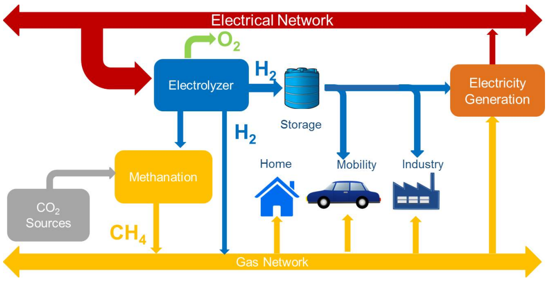


Fig. 1: Concept of Power-to-Gas.

to produce hydrogen (H_2) and oxygen (O_2) from water. The concept can be expanded with an optional process step—the methanation process—which needs a source of carbon dioxide (CO_2) to produce methane (CH_4) out of H_2 and CO_2. The produced H_2 or CH_4 has various areas which it can be used such as: Mobility sector and chemistry industry or it can be used to feed directly into the gas network [5]. Figure 1 displays the concept of *PtG* with all the different stages to produce H_2 or CH_4. The produced H_2 will be stored in tanks. However, the H_2 storage tank would rather serve as a buffer, and the stored H_2 will be delivered to the consumers in an appropriate time.

2.2 Power system and PHS in Switzerland

Switzerland's current energy system has many features that put it in a comfortable position from an energy storage perspective. Most notably, the country has a large installed base of hydropower and pumped hydro storage facilities: Approximately 59% Switzerland's current energy production comes from hydropower.

Pumped hydro storage (PHS) is currently the most established technology for providing control energy in the electric power system. Electricity is converted to potential energy by pumping water to higher altitudes. When electricity is needed, the water is released from the reservoir, and the potential energy is again converted to electricity by hydro turbines. The efficiency of this storage technology ranges between 70-85% which is comparatively high [6].

As far as energy storage technologies in Switzerland are concerned, PHS is a well-developed and widely applied technology, with its use limited by site limitations. The existing pumped power capacity and storage capacity in Switzerland in 2010 are 1.8 GW and 50 GWh, respectively [4]. Up to 4GW of additional pumped power capacity is planned to be added by the time-period of 2020-25 [7] and the pumped storage capacity is estimated to be 200 GWh [8].

3 Simulation of Power-to-Gas as an Additional Storage

3.1 Approach

The goal of this simulation is to illustrate the extent of the excess energy in light of one of the BFE scenarios [2] and the possible role of Power-to-Gas technology with respect to the excess energy. To evaluate the role of *PtG* plants in the Swiss power grid, a simulation will be constructed by treating the Swiss power grid as a single node, consisting of power generators including hydropower generation, conventional generation, and RES, energy storages including PHS and *PtG* plants, and consumers, as shown in Figure 2.

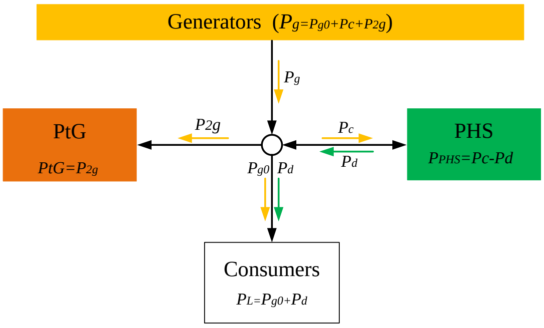


Fig. 2: Swiss power grid represented as a single node.

3.2 Simulations

In order to demonstrate the feasibility of *PtG* for integrating the renewable energy generation through *PtG* technology at the Swiss grid level, three scenarios are established for simulation. For the simulations Switzerland is treated as a single node as shown in Figure 2.

3.3 Scenario 1

For this simulation, the energy model of Switzerland in the year 2050 was constructed based on Swiss Federal Office of Energy (BFE) Energy Strategy 2050 report, conducted by the consultancy Prognos [2], especially in accordance with BFE New Energy Policy (NEP) scenario, Option NEP C/E. As shown in Figure 3, input data was constructed with the statistical data compiled and provided by BFE in [9]. Also *PV* and wind data are reconstructed based on measurement data from MeteoSwiss [10]. In accordance with BFE New Energy Policy (NEP) scenario, Option NEP C/E [2], the parameters of electricity production and consumption are as follows: Total

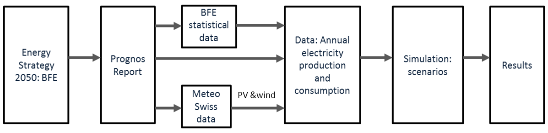
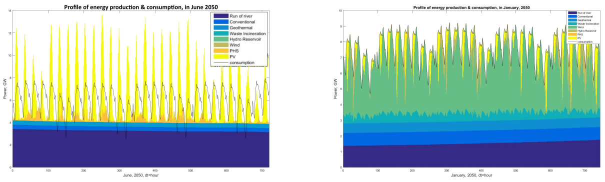


Fig. 3: Data flow of *PtG*feasibility simulation.



(a) June **(b)** January

Fig. 4: Profile of energy production and consumption in June and January, 2050.

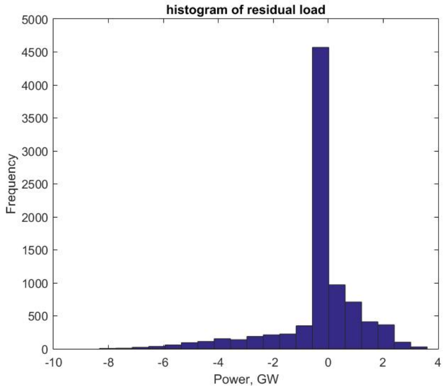


Fig. 5: Histogram of the residual load.

consumption (57.56 TWh), total generation consists of Hydro Run of river (19.8 TWh), Hydro reservoir (14.3 TWh), Conventional (6.0 TWh), and RES (24.42 TWh) For RES, there will be generation from *PV* (11.12 TWh), wind (4.26 TWh), geothermal (4.33 TWh), Biomass (1.24 TWh), and waste incineration (1.33 TWh). It is to be noted that the electricity production from the nuclear power plants will have been zero from the year 2035 on. Subsequent energy gap will be filled up by RES including 11.2 TWh from *PV* energy, which amounts to 20% of the entire electric energy consumption in Switzerland, 4.3 TWh from wind energy and others. As a result, the profile of energy production and consumption in June and January, 2050 are shown in Figure 4a and Figure 4b, respectively. In Figure 4, it is to be noted that there exists energy gap each day. As demonstrated in the next scenario, PHS will operate to store the excess energy whenever available and then to discharge a certain amount of energy to fill up the gap. For the current production and consumption data, Figure 5 shows residual load, which describes what is left of the current power consumption after the production is being subtracted from the consumption. The negative residual load indicates that there exists the excess power, which is maximum power of 8 GW in this case.

3.4 Scenario 2

In this scenario, a model predictive controller (MPC) is used to optimally fill the energy gap with the excess energy. Also the excess energy is more than the existing storage, which is the PHS, in this case, the energy will be stored in the *PtG* plants. It is to be noted that all the losses are neglected for this simulation. For this scenario, the energy flow model as shown in Figure 2 is established as follows:

a. The generations (P_g) supply energy to the consumers (P_L), contribute to charge the PHS (P_c) and transform energy into hydrogen (P_{2g}):

$$P_g(i) = P_{g0}(i) + P_c(i) + P_{2g}(i), \tag{1}$$

where $P_{g0}(i)$ consists of all the energies produced according to the parameters defined in the Scenario 1, at time instant $i = 1, 2, \ldots, 35040$.

b. The PHS absorbs power from the generation (P_c) and provides power to the consumers (P_d):

$$P_{PHS}(i) = P_c(i) - P_d(i) \tag{2}$$

c. The total power consumption (P_L) is equal to the contribution from the generation (P_g) and the power stored on the PHS system (P_d):

$$P_L(i) = P_{g0}(i) + P_d(i) \tag{3}$$

d. By Kirchoff's law, the sum of currents (and thus the sum of active powers) injected in a node has to be equal to zero:

$$0 = P_g(i) + P_{PHS}(i)P_L(i) - P_{PtG}(i) \tag{4}$$

e. When the energy production is greater than the consumption, the excess power is present:

$$P_{ex}(i) = P_g(i) - P_L(i) > 0 \tag{5}$$

f. If the excess energy is less than or equal to an epsilon ($\epsilon = 5$GW in this case), the power will be absorbed by the PHS. If the excess power exceeds this value the power will be absorbed by the *PtG* plant:

$$\begin{align} P_{ex}(i) &\leq \epsilon \text{ and } Pc(i) \leq P_{ex}(i) \tag{6} \\ P_{ex}(i) &> \epsilon \text{ and } P_{PtG}(i) \leq P_{ex}(i) \tag{7} \end{align}$$

The results are shown in Figure 6, where (a) shows the yearly profile of energy production and consumption; (b) shows charge and discharge of energy in PHS, and excess energy to be stored in *PtG*; in (c) sum of Excess energy stored in *PtG* and the state of charge (SOC) of PHS are depicted. The excess energy captured by the *PtG* amounts to 1.63 TWh. It is also calculated that the runtime of the *PtG* plant is 606 hours over the whole year.

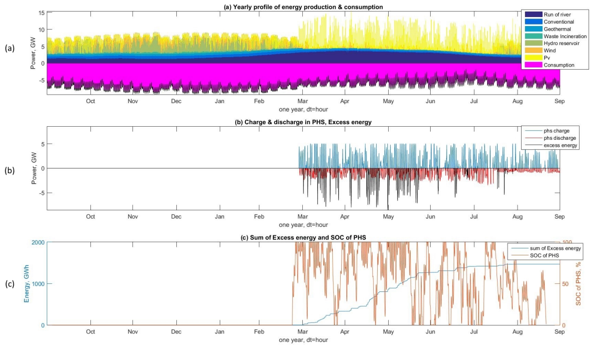


Fig. 6: Results of simulation No. 2: (a) Yearly profile of energy production and consumption; (b) change & discharge of energy in PHS, and excess energy to be stored in PtG; (c) sum of excess energy stored in PtG and SOC of PHS.

3.5 Scenario 3

In this simulation, the MPC model in the scenario 2 will be repeated with curtailed *PV* production. In other words, the *PV* was curtailed to see its influence on the grid and the implemented *PtG* plant. The *PV* curtailment was set at 35%, resulting in 5% loss of the annual *PV* energy yield. The results show that the excess energy captured by the *PtG* amounts to 1.26 TWh. It is also calculated that the runtime of the *PtG* plant is 495 hours over the whole year.

4 Results and Discussion

4.1 *PtG* for Integrating excess energy

As indicated in the above simulation, additional storage capacity might be required due to the amount of the excess energy expected in year 2050. However, building new pumped hydropower plants or even increasing the capacity of the existing plants will probably be politically difficult. *PtG* plants can contribute to solving this problem. One major advantage of the power-to-gas technology is that it needs less space than a pumped hydro storage plant to store energy [6].

In Scenario 2 of the above simulation, the excess energy, which is not integrated into grid, amounts to be about 1.63 TWh, which can be converted to hydrogen or methane. According to the average efficiency of electrolysis of 65.5% and methanation of 49.5% [11], the produced hydrogen and methane amount to 1050 GWh and 792 GWh, respectively. Based on the lower heating values of hydrogen, 33.33 kWh/kg, and methane, 13.9 kWh/kg [12], 3.14×10^7 kg of hydrogen and 5.7×10^7 kg of methane are produced, respectively. In scenario 3, the excess energy is 1.26TWh, for which the produced hydrogen and methane amount to 825 GWh (or 2.47×10^7 kg) and 624 GWh (4.49×10^7 kg), respectively.

4.2 PHS for integrating the excess energy

The simulations executed above indicate that additional storage is required to integrate the excess energy projected in 2050. This might create difficulties in the Swiss grid. First, although PHS is a well-developed and widely applied technology, the erection of new PHS facilities is generally difficult due to commonly low public acceptance of infrastructure projects affecting the overall appearance of the landscape [6]. Second, most of the *PV* generation will be connected to the local distribution grids (Grid level 7). If the *PV* energy is stored in PHS plants, which are connected to Grid level 1, the energy has to be transported via all the grid levels. This may result in the need for grid expansions. If the *PV* energy is stored near the site of generation, grid losses can be reduced and investments for grid expansions can be avoided [8].

4.3 *PtG* as long-term storage

In references including [4], Power-to-Gas is categorized as a large scale storage, which maintains power capacity ranges from 100 to 1,000 MW for durations of up to months. It is commonly known that methane can be stored in the natural gas network for months at a time, including pipeline and gas storage. In case of Switzerland, the gas network consists of 16,591 km of pipeline, including transport network (2,220 km) and distribution network (14,371 km), and 116 public filling stations offering natural gas [13]. This gas network could be utilized to transport the *PtG* produced gas and to store it to a certain extent. When it comes to storing the gas, especially on a long-term basis, however, there is a storage capacity of about 4.8 million cubic meters in Switzerland [14]. In comparison, there are 48 underground storage facilities in Germany with a total volume of 20 billion cubic meters, which can be classified into 26 storage caverns and 22 pore storage reservoirs. The pore reservoirs are used to cover a basic load. The cavern storages are used to compensate the peak loads of gas consumption [15].
Considering the fact that the annual gas demand in Switzerland is 3,682 million cubic meter [16], which is equivalent to about 10 million cubic meter per day, the Switzerland gas storage capacity can sustain its demand for about a half day long. The natural gas demand is expected to be reduced until year 2050 in accordance with the scenario NEP, option C/E in 2050 [2]. Therefore, significant amount of investment is expected to be made in the natural gas storage in order to establish a long-term storage in its own premises in relation to the Power-to-Gas technology.

5 Summary and outlook

Through simulations based on the data and scenarios set forth in light of Energy Strategy 2050, which was initiated by the Swiss Federal government, this paper illustrated that *PtG* will play a significant role in the effective integration of RES into the future Swiss power grid. This paper estimated the amount of the projected excess energy in future by treating Switzerland as a single node. Then a *PtG* plant was demonstrated in combination with PHS in handling the excess energy. The paper also established the requirements for implementing *PtG* as a long-term storage in Switzerland. The authors plan to further investigate feasibility of *PtG* concept in Switzerland, which will be treated as multi-node system, thereby placing the focus on sizing and siting of the *PtG* plants.

Acknowledgements

This work was supported in part by Swiss Competence Center for Energy Research (SCCER), the Swiss Federal Office of Energy within the CCEM RENERG2 project, and Elektrizitätswerk der Stadt Zürich (ewz).

References

[1] Bundesamt für Energie (BFE), “Botschaft zum ersten Massnahmenpaket der Energiestrategie 2050”, September 2013.

[2] Prognos AG, “Die Energieperspektiven fr die Schweiz bis 2050 Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 - 2050”, 2012.

[3] C. Baumann, D. Siegler, and A. Moser, “Utilization of Natural Gas Infrastructure as Long-Term Energy Storage”. IEEE PES General Meeting, 2014.

[4] Prognos AG, ”Energiespeicher in der Schweiz: Bedarf, Wirtschaftlichkeit und Rahmenbedingungen im Kontext der Energiestrategie 2050,” September 2012.

[5] M. Lehner, R. Tichler, H. Steinmller, M. Koppe, “Power-to-Gas: Technology and Business Models”, Springer, 2014.

[6] Y. Domigall, “Impact of power-to-gas storage on the integration of photovoltaic electricity into the grid”, Springer-Verlag Berlin Heidelberg 2014.

[7] F. Comaty, A. Ulbig, G. Andersson, ”Ist das geplante Stromsystem der Schweiz fr die Umsetzung der Energiestrategie 2050 aus technischer Sicht geeignet?” Swiss Energy Strategy 2050 and the Consequences for Electricity Grid Operation, July 2014.

[8] H. Vollenweider, “Grid Integration of *PV* Systems and Local Storage in Distribution Networks”. Master Thesis, Swiss Federal Institute of Technology (ETH) Zurich, September 2014.

[9] Swiss Federal Office of Energy, ”Schweizerische Statistik der erneuerbaren Energien,” 2010-2014

[10] Online resource. URL: http://gate.meteoswiss.ch, [Accessed: 01-Nov-2015]

[11] L. Grond, P. Schulze and J. Holstein, “Systems Analyses Power to Gas”, June 2013.

[12] Online resource. URL: http://www.h2data.de/, [Accessed: 01-Nov-2015]

[13] Switzerland Energy Statistics, 2013

[14] Der Schweizerische Verein des Gas- und Wasserfaches (SVGW), Jahrbuch 2015, Gas und Wasser.

[15] N. Moskalenko, P. Lombardi and P. Komarnicki, “Multi-Criteria Optimization for Determining Installation Locations for the Power-to-Gas Technologies”. IEEE PES General Meeting, 2014.

[16] International Energy Agency (IEA), Oil and Gas Security in Switzerland, 2012.