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

Chan PARK
ZHAW - Switzerland
park@zhaw.ch

Felix BIGLER
ZHAW - Switzerland
f.bigler@gmx.net

Valerijs KNAZKINS
ZHAW - Switzerland
knaz@zhaw.ch

Florian KIENZLE
EWZ-Switzerland
florian.kienzle @ewz.ch

Petr KORBA
ZHAW - Switzerland
korb@zhaw.ch

ABSTRACT

This paper presents qualitative and quantitative feasibility analysis of the Power-to-Gas (PtG) technology in the future Swiss low voltage (LV) grid, which will be characterized by a significant share of intermittent renewable energy sources (RES). For this purpose, a model of producing hydrogen or methane with Photovoltaics (PV) excess energy and additional energy from the grid is established. Data and results from a load flow analysis of a previous study serve as the basis for the analysis. Impact of the PtG technology is demonstrated through nine different operating scenarios established. The input energy source to the PtG plant comprises the excess PV energy and the energy from the grid. Economic values, such as levelized cost of energy (LCOE) and levelized value of electricity (LVOE), are calculated to assess the economic feasibility. Moreover, sensitivity analysis is conducted to identify the parameters having the strongest impact on the electricity cost.

INTRODUCTION

After the disaster of the nuclear power plant in Fukushima, Japan, in 2011, the Swiss federal government decided to progressively abandon the nuclear energy which currently amounts to about 35% of the total electricity supply of the nation. The deficit in the production of electricity as a result of the decision will lead to major changes in the Swiss energy system such as *Energy Strategy 2050* which is a long term plan based on a step-by-step guidance to reach this ambitious goal [1]. Under the *Strategy,* 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. Of the total RES, PV will make up 11.2 TWh, which is a fifth of Switzerland energy production [2].

PV is a fluctuating energy source due to its innate dependency on diurnal, seasonal, and meteorological variations. These characteristics are anticipated to cause significant challenges to the existing electricity network. A previous study [3] was performed to illustrate the impact of the increased PV production in the low voltage grid in a Zürich area comprising 213 houses by simulating the load flow. The considered area is characterized by maximum active power load (0.675 MW), yearly load energy consumption (2.95 GWh), maximum PV power (2.096 MWp), and yearly PV energy production (2.453 GWh).

The result of the load flow analysis of the study is illustrated in Figure 1, in which the reverse power flow is anticipated beyond the maximum 630 kVA, causing problems characterized as voltage violation, line and transformer overloading, and N-1 violation.

In order to protect the existing electricity network form such violations, energy storage systems (ESS) will play an important role in the future. To operate the transformers in a safe range, for example, the previous study [3] indicated that a Battery Energy Storage System (BESS) is required to have a nominal power of 1 MW and a nominal capacity of 6.5 MWh, which seems unrealistic to implement, considering the fact that it is nine times larger than the largest one that exists currently in Switzerland, in order to resolve an issue at such a low voltage level.

Alternatively, Power-to-Gas (PtG) technology is another suitable storage solution for absorbing the excess PV energy production in the LV grid in future. Therefore, the goal of the study presented in this paper is to analyze the feasibility of a PtG plant in light of the previous study [3]. The results of the simulations shall give the insights concerning the technical as well as economic feasibility of the integration of PtG into the existing electricity low voltage grid.

TECHNOLOGY ANALYSIS: POWER-TO-GAS

The principal concept of PtG is to transform electrical energy via electrolysis into gas which in turn can be stored in a gaseous chemical storage. The electrical energy is used 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 application areas such as, mobility sector and chemistry industry. Alternatively, it can be used to feed directly into the gas network [4].

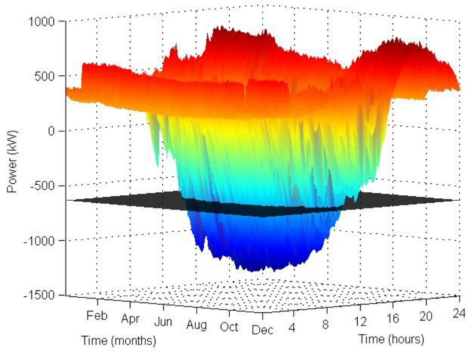

Figure 1: A 3-dimensional plot of a transformer power flow of the case under consideration. For the z axis values, the area below the black plane indicates the excess reverse power flow.

SIMULATION OF POWER-TO-GAS

PtG involves many sectors including electricity, gas, mobility, waste, biogas, etc., to make PtG a technical and economically viable option for the future energy plan. Based on the results of the previous work [5], the goal of this study, therefore, is to further investigate the feasibility of the PtG plant with extended value sources, including production of hydrogen or methane as a main product, production of oxygen and heat as by-products, and provision of services such as biogas upgrading, and frequency regulation in order to make the PtG system economically viable. The PV excess energy calculated in study [3] was used to operate the electrolyzer in study [5] and is also used to operate the electrolyzer in this study.

The research questions of this study are summarized as follows:

- *How economically profitable will be the PtG system under different operating scenarios?*
- *Which is the most suitable operating scenario?*
- *What are the most influential cost drivers?*
- *What value sources are available, respectively what measures have to be taken to make the PtG most profitable?*

Approach

Overall the analysis is performed in 4 steps. Every step is built up from the previous step and is dependent upon the previous output results. The processing of Figure 2 has to be followed from bottom to top and from left to right.

Simulation

For the simulation 9 different scenarios are established. Fundamentally, the scenarios are established based on 5 distinctive variables, which define the operation of the simulation, including source of electricity, operating mode, produced gas, source of CO_2 and outlet, each of which are briefly discussed below. Table 1 summarizes all the applied scenarios with the corresponding variables.

Simulation variables

a. Source of electricity

The electrolyzer is operated with two sources of electricity: the PV excess energy and the grid energy. The main goal of the PtG plant is to absorb the PV excess energy. Additional energy is purchased from the wholesale electricity market. The average of the wholesale market price of 44.73 EUR/MWh in 2013, serves as a basis for calculating the additional expenses.

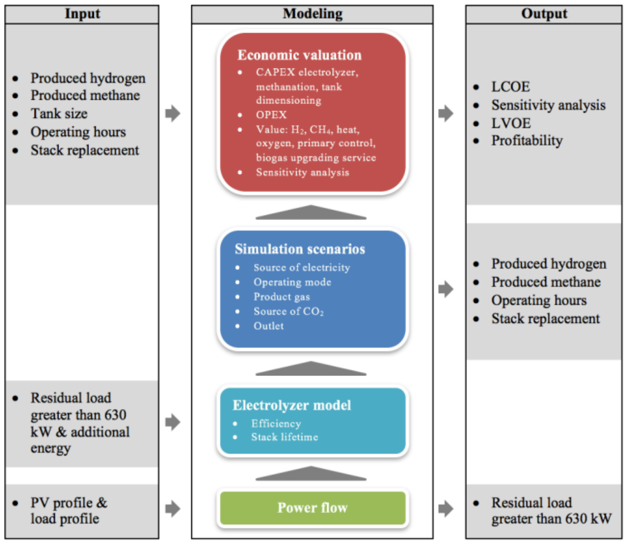

Figure 2: Modeling approach with all the necessary inputs, models and output results.

Table 1. Different operating scenarios with variables.

Scenario Number	Scenario variables				
	Source of electricity	Operating Mode	Produced Gas	CO_2 Source	Outlet
1	Excess	n/a	H_2	n/a	Gas grid
2	Excess &Grid	Baseload	H_2	n/a	Gas grid
3	Excess & Grid	Partload	H_2	n/a	Gas grid
4	Excess & Grid	Baseload	CH_4	Biogas	Gas grid
5	Excess & Grid	Baseload	CH_4	Pure CO_2	Gas grid
6	Excess & Grid	Partload	CH_4	Pure CO_2	Gas grid
7	Excess	n/a	H_2	n/a	Mobility
8	Excess &Grid	Baseload	H_2	n/a	Mobility
9	Excess &Grid	Partload	H_2	n/a	Mobility

b. Operating mode

Two operating modes are established with respect to the total operating hours: baseload and partload at maximum 90% of its capacity. For baseload, additional energy is purchased throughout the year whenever no PV excess energy is present. For partload, the electrolyzer is operated throughout the year from 8 PM until 4 am,

c. Produced gas

As listed in Table 1, scenarios1-3, and 7-9 are producing H_2 with conversion efficiency of 63%. Scenarios 4, 5, and 6 are producing CH_4 out of H_2 and CO_2 with conversion efficiency of 80%. Therefore, the conversion from electricity to methane results in a total efficiency of 50.4%.

d. Source of CO_2

Two sources of CO_2 are considered: pure CO_2 and CO_2

from biogas upgrading service. The PtG system can be combined with a biogas upgrading plant or a wastewater treatment plant. The biogas or the sewage gas contains of 40-50% CO_2 and 50-60% CH_4. For this analysis, CO_2 concentration of 40% is applied.

e. Outlet
Two different outlet markets are considered in the model: feed into gas network and H_2 consumed in mobility. The transportation distance is set not to exceed 100 km. According to [12], the yearly H_2 production rate results in 124.02 tons per year, which leads to a daily production rate of 339.8 kg.

Economic valuation
Listed below are all the considered components for the economic valuation including:

- CAPEX: electrolyzer, methanation, tank
- OPEX
- Value: H_2, CH_4, heat, oxygen, primary control, biogas upgrading service
- Sensitivity analysis.

a. Lifecycle cost analysis
According to [11], the Levelized costs of energy (LCOE) is calculated according to (1):

$$LCOE = \frac{CAPEX + \sum_t^n \frac{OPEX_t}{(1+q)^t}}{\sum_t^n \frac{E_t}{(1+q)^t}} \quad (1)$$

All the variables in the equation are defined as in [11]. All the values required to perform the LCOE calculation are listed in Table 2.

b. Economic value analysis
The concept of the Levelized value of energy (LVOE) is adopted in order to levelize the values. The calculation of the LVOE is similar to the LCOE and is calculated as in [10]. Some given values are already levelized and can be applied directly.

$$LVOE = \frac{\sum_t^n \frac{Revenue_t}{(1+q)^t}}{\sum_t^n \frac{E_t}{(1+q)^t}} \quad (2)$$

All the variables in the equation are defined as in [11].

Table 3 shows all the values sources applied to perform

c. Primary control- Ancillary service
For this analysis, the primary control is assumed to be provided from 8 PM until 4 AM for baseload as well as partload operation in summer. In winter, the primary control will be provided 24 hours a day for the baseload operation and 8 hours in partload from 8 PM until 4 AM.

Based on possible revenue, provided power, winning likelihood, share of revenue, and provided hours per week of this study along with the data of the weekly average price per MWh for the year of 2013 from Swissgrid according to [13], the yearly earnings for baseload and partload are 43,395 CHF and 23,945 CH, respectively.

d. Profitability analysis
The profitability is defined as a difference between the LCOE and LVOE and is calculated with Equation (4). As long as the profitability is above zero the project is profitable.

$$Profitability = LVOE - LCOE \quad (4)$$

e. Sensitivity analysis
A sensitivity analysis is performed for the most influential variables, including CAPEX electrolyzer, electricity price, operating hours, and operating hours with regard of stack lifetime.

Table 2. Summary of the input data for the LCOE calculation (1 CHF = 0.93 EUR)

CAPEX	Electrolysis	Methanation	Unit	Reference
Electrolyzer	2000		[CHF/kW]	[6]
Methanation		482	[CHF/kW]	[9]
Tank	990		[CHF/kg]	[8]
Stack replacement	1200		[CHF/kW]	[13]
Delivery & construction, % of CAPEX electrolyzer & methanation	10	10	[%]	[6]
Oxygen & heat recovery		54’230	[CHF]	[9]
Maintenance, % of CAPEX electrolyzer & methanation	4	4	[%]	[6]
Electricity, wholesale price 2013 mean 44.73 EUR/MWh			[EUR/MWH per 15 min]	[data from utility company]
Delivery costs hydrogen for mobility scenarios	1		[CHF/kg]	[12]
Efficiency	63	80	[%]	[7]
Lifetime	20	20	[year]	assumed
Stack lifetime	63000		[h]	[7]

Table 3: Value sources applied for different scenarios.

Value source	Scenarios									Unit
	1	2	3	4	5	6	7	8	9	
	Value									
Hydrogen	35 1.379	35 1.379	35 1.379	n/a	n/a	n/a	232.8 9.17	232.8 9.17	232.8 9.17	[CHF/MWh] [CHF/kg]
Methane	n/a	n/a	n/a	35	35	35	n/a	n/a	n/a	[CHF/MWh]
Oxygen	n/a	n/a	n/a	0.1	0.1	0.1	n/a	n/a	n/a	[CHF/kg]
Heat	n/a	n/a	n/a	63	63	63	n/a	n/a	n/a	[CHF/MWh]
Biogas upgrading	n/a	n/a	n/a	40	n/a	n/a	n/a	n/a	n/a	[CHF/MWh]
Primary control	n/a	43,395	23,945	43,395	43,395	23,945	n/a	43,395	23,945	[CHF/a]

RESULTS

LCOE

LCOE of scenario 4, in Figure 3, with baseload mode, and methane & biogas, the exact amount of additional energy purchased from the grid results in 7,460 hours of operation at nominal capacity. In addition, the scenario includes a methanation reactor and recovery systems for recovering oxygen and heat, respectively. The total LCOE is about 35% higher than when hydrogen is produced because less energy has been produced and the total expenses are higher.

Sensitivity analysis

Also shown in Figure 3, the sensitivity analysis shows that the operating hours have the highest influence upon the LCOE, followed by the electricity price and the CAPEX of the electrolyzer. This result seems consistent with the cost contribution since the cost for purchasing electricity and the CAPEX of the electrolyzer follow the same order.

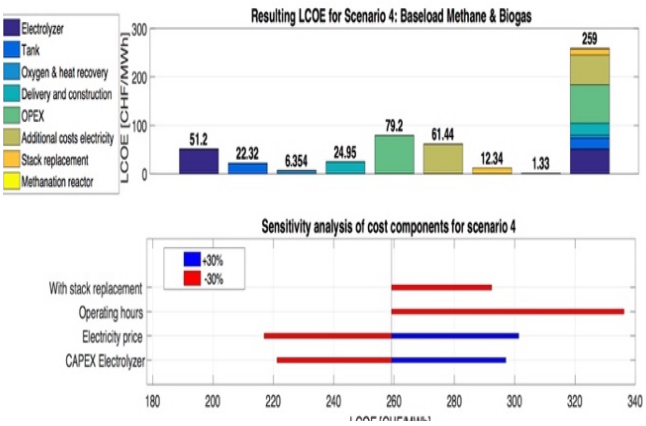

Figure 3. LCOE and sensitivity analysis for scenario 4.

Moreover, the analysis shows that the influence of the operating hours with regard to the stack lifetime declines since the stack should be replaced only once if the operating hours are reduced by 30%. However, it is still more beneficial to operate the electrolyzer for as long duration as possible to achieve the lowest LCOE.

LVOE

Scenario 4, as shown in Figure 4, results in the highest aggregated LVOE of all the scenarios. The biogas upgrading service adds the most value of 60.42 CHF/MWh, followed by the methane and the oxygen.

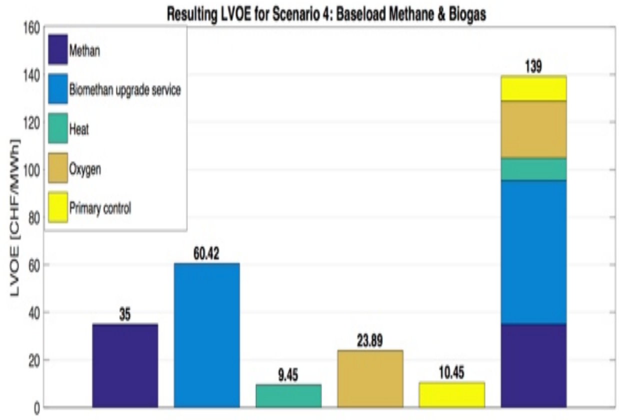

Figure 4. LVOE for scenario 4.

DISCUSSION AND CONCLUSIONS

Summary of the LCOE by scenario

When the PtG system is operated solely with the PV excess energy, the LCOE seems drastically higher than when operated in baseload or partload with the grid energy. It can be stated that with the resulting operating hours of 499 hours at nominal capacity the PtG system can never be proven profitable, see Figure 5.

The baseload operating modes (scenarios 2,4,5, and 8) perform better than the partload operating modes (scenarios 3, 6, and 9) because the CAPEX can be amortized with higher quantity of produced gas over the lifetime, either hydrogen or methane.

With the decreased CAPEX of the electrolyzer in future, the difference between the baseload and partload operating modes may be narrow since the CAPEX has less influence on the LCOE. With this future outlook, it may be more beneficial to run the electrolyzer in the partload mode and to find strategies to operate it when the electricity price is low.

The hydrogen production leads to the lowest LCOE over the lifetime of the plant since the methanation step is skipped and the lower CAPEX due to no methanation reactor.

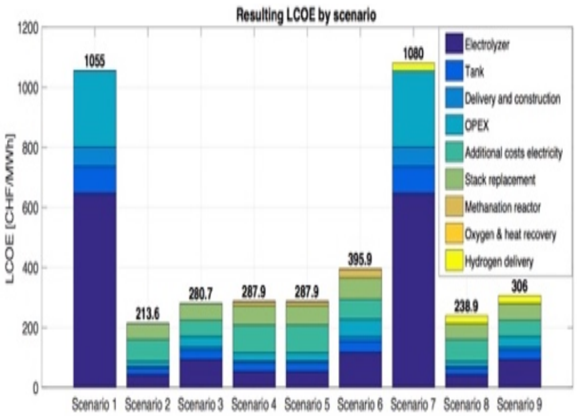

Figure 5. Resulting LCOE by scenario.

Summary of the LVOE by scenario

When the produced gas is fed into the gas pipeline (scenarios 1 to 6), scenario 4 generates the highest value. because the biogas upgrading service adds a significant value to the LCOE. Also the revenue from the production of oxygen and heat adds more value to scenarios 4 to 6 since they can be used in the process of the biogas plant. The primary control contributes only marginally to the LVOE, see Figure 6.

For the hydrogen sold in the mobility sector (scenarios 7 to 9), the LVOE seems to be increased significantly in comparison to scenarios 1 to 3.

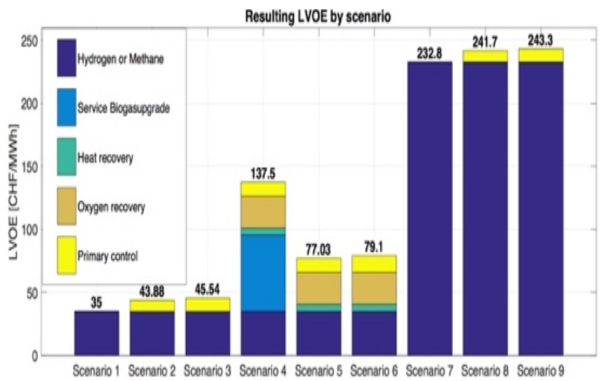

Figure 6. Resulting LVOE by scenario.

Summary of the profitability by scenario

In summary, the PtG system is yet far from being economically viable regardless of the operating scenarios. Especially when operated with PV excess only (scenarios 1 and 7) PtG system seems far from any chance of profitability. If the produced gas is intended to be fed into the gas grid it is most favorable to produce methane since more value sources are available, see Figure 7.

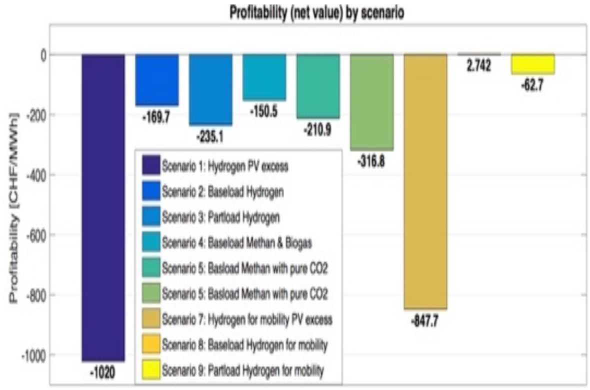

Figure 7. Resulting profitability by scenario.

The most suitable operating scenario is scenario 4, in which the produced gas is fed directly into the gas grid, leading to the least loss. In this scenario the PtG system is coupled with a biogas plant or a wastewater treatment plant. Consequently, the CO_2 source is taken through the biogas upgrading station, the biogas is upgraded to bio methane. This adds a significant amount of value since the necessity of a biogas upgrading station is avoided. Moreover, heat and oxygen can be recycled and used in the process, adding more value.

On the other hand, with hydrogen produced for mobility sector, scenario 8 shows a positive profitability. In this scenario, the plant is operated in baseload as well.

The most influential cost drivers are identified as the CAPEX of the electrolyzer and the additional purchased energy from the grid. When operated in baseload, the additional energy is the main cost driver whereas the CAPEX of the electrolyzer takes the lead when operated in partload or solely with the use of the PV excess energy.

When it comes to maximizing profitability of the PtG, the operator has to strive for the maximum possible operating hours regardless of the scenario. This allows the CAPEX to amortize over a large amount of produced gas, eventually leading to the lowest possible LCOE. Moreover, it can be noted that adding other sources of value seems favorable. Therefore, careful evaluation regarding the place of construction should be considered in order to utilize synergies to run the plant profitably.

ACKNOWLEDGEMENT

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

REFERENCES

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

[2] L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden, and E. Standen, “Development of Water Electrolysis in the European Union,” 2014

[3] B. Schlatter, “Bachelor Thesis in Energy and Environmental Engineering Simulation, analysis and optimization of load flows in low voltage grid,” ZHAW, 2015.

[4] M. Lehner, R. Tichler, H. Steinmüller, M. Koppe, Power-to-Gas: Technology and Business Models, Springer, 2014

[5] F. Bigler, “Projektarbeit in Energy and Enviromental Engineering, Feasebility study of Power-to-Gas technology, ZHAW,” 2015.

[6] M. Sterner and I. Stalder, *Energiespeicher*. Heidelberg, Dordrecht, London, New York: Springer, 2014.

[7] M. Sterner, M. Jentsch, and U. Holzhammer, “Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes,” 2011.

[8] L. Grond, S. Paula, and J. Holstein, “Final Report: Systems Analyses Power to Gas,” Groningen, 2013.

[9] D. Hofstetter, B. Battke, B. Cox, and J. Jughes, “Power-to-Gas in Switzerland,” pp. 1 – 100, 2014.

[10] D. Parra and M. K. Patel, “Techno-economic implications of the electrolyser technology and size for power-to-gas systems,” *Int. J. Hydrogen Energy*, vol. 1, 2016.

[11] L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden, and E. Standen, “Development of Water Electrolysis in the European Union,” 2014.

[12] C. Yang and J. Ogden, “Determining the lowest-cost hydrogen delivery mode,” *Int. J. Hydrogen Energy*, vol. 32, no. 2, pp. 268–286, 2007.

[13] Swissgrid, “Basic principles of ancillary service products.” [Online] https://www.swissgrid.ch/