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Workpackage 5: Market & Grid

5.1 Modelling of the financial side of the energy market and the electrolysis-combustion chain

5.2 Optimal Integration of an energy storage system into the power grid

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Summary

This report 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 has been established. Data and results from a load flow analysis of a previous study will serve as the basis for the analysis.

After the Fukushima accident in 2011, Swiss Federal government has set forth a new energy policy, so-called Energy Strategy 2050, to implement cessation of the existing nuclear power plants with implementation of a strong expansion of renewable energy sources. PV, for example, shall make up one fifth of Switzerland's total energy production in 2050. Such a drastic expansion rate of PV can lead to so-called reverse power flow in the LV grid. According to a prior study, in which the load flow of a Zürich area was calculated, it was found necessary to install a suitable battery energy storage system (BESS) to resolve the reverse power flow, which may be caused by the excess PV energy production. Alternatively, a PtG plant represents another suitable storage solution for absorbing the excess PV energy production in the LV grid in the future.

This report demonstrates the impact of the PtG technology 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) will be determined to assess the economic feasibility. Moreover, sensitivity analysis is conducted to identify the parameters having the strongest impact on the electricity cost.

1. Introduction

In this chapter the motivation behind the necessity of the integration of storage systems due to the growing penetration of photovoltaics (PV) into the existing grid is discussed. Moreover, the results of a previous study conducted by the author are presented and discussed.

1.1 Energy Strategy 2050

In 2011, the Swiss Federal government decided to withdraw from the use of nuclear energy. 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 this 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 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].

The main measures of the Energy Strategy 2050 can be subdivided in following actions: Enhancement of the energy efficiency, development of renewable energy production, expansion and renovation of the grid, and reduction of CO₂-emissions [1]. In order to fill the gap in electricity production after the phase-out of the nuclear energy, renewable energy sources (RES) represent the only possibility for Switzerland to produce self-reliant and CO₂-emission free energy. With a share of 20% of the entire electric energy consumption, which equals 11 TWh_{el}, PV will make up a fifth of Switzerland energy production. [2]

1.2 Problems expected due to the integration of photovoltaics into the electric networks

PV represents a fluctuating energy source due to its dependence on seasonal and sudden weather changes. These characteristics will lead to challenges in the existing grid. These challenges may cause unacceptable voltage rises as well as overloading of transformers and cables [3].

From the distribution system operator's (DSO) point of view, the photovoltaic systems will be most likely installed on the rooftop of private houses. As a consequence, the generated electricity will be fed into the low voltage (LV) grid. Hence, the problems caused by the integration of PV into the Power Grid (PG) will firstly affect the LV grid. Therefore, special attention of the DSO should be paid to this level in terms of the possible troubles caused by the PV excess energy.

1.3 Necessity of storage system

Storage system will play an important role in ensuring the safe operation of the energy supply system and meeting the future demand of electricity. Storage system in general functions as a controllable production, a flexible consumption as well as adjustments to the existing grid. With the integration of the renewable energy sources-especially PV into the existing grid-, its role is increasingly important in levelling the supply and demand not only for days or weeks but also for months as a long term storage.

Switzerland is in a comfortable situation because of its remarkable amount of storage capacity achieved through the hydro power. Nonetheless, detailed modeling has showed that the pumped-storage plants will be insufficient to deal with the excess energy produced by PV as well as wind [1]. Consequently, it will be necessary to install suitable storage systems apart from the pumped hydro storage plants to assure enough storage capacity not only for the short term but also for the long term needs.

1.3.1 Possible storage solutions

Storage systems such as Battery energy storage systems (BESS) as well as the Power-to-Gas (PtG) plants represent the suitable measure to deal with the PV excess.

Generally, the main task of a storage system is to provide a timely adjustment of supply and demand within the electric energy supply system. Both of the intended solutions are capable of fulfilling this task. However, when it comes to regional adjustments which normally fulfill the electric networks, PtG stands for the only storage solution with the ability to transport the produced gas within pipelines or in tanks and thus creates a regional displacement of the stored PV excess without further stressing the electric networks [4].

Figure 1 [5] shows the possible location of different storage technologies in a simplified grid structure. In this figure only DSM, Electric vehicles and Batteries are indicated as suitable storage solutions at the LV level. However, if the PtG storage shall serve to absorb the PV excess energy its integration in the LV grid can be considered as well.

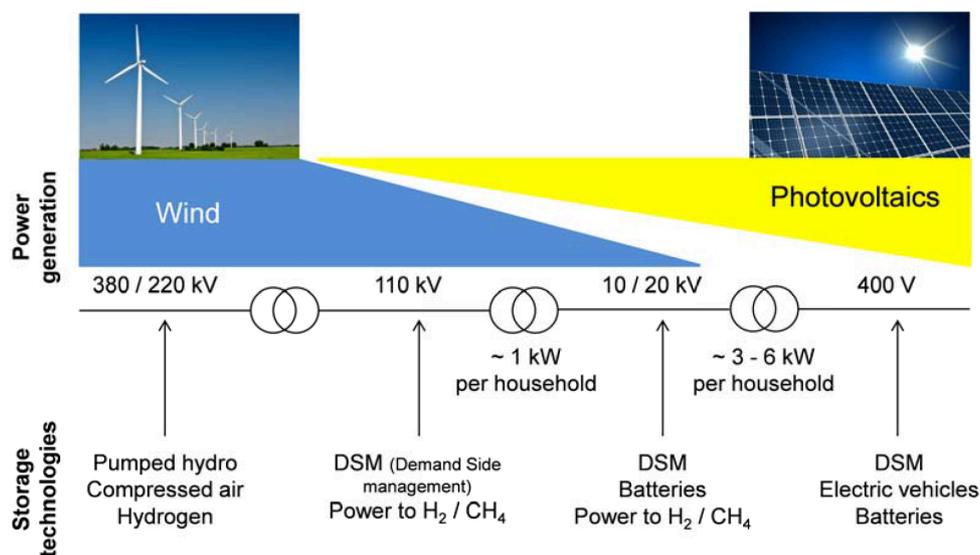


Figure 1: Possible installing locations for different storage technologies in the existing grid structure [5].

1.3.2 Existing Power-to-Gas storage solutions

Although the concept of PtG has been well known for years, there are only a few industrial plants implemented in the real world. Germany is in the leading role, when it comes to implementation of the PtG plants. Several plants are installed, and the first operational experience has been made even though the plants are not economical profitable yet and still dependent upon the subsidy from the government or industry. Nonetheless, Germany is already affected by the excess energy from wind, and its resolution shall be made together with PtG by storing the excess energy in the gas network. However, the situation is different from in Switzerland; there are no industrial PtG plants yet.

This year, *Regio Energie Solothurn* realized a Hybrid power plant, whose purpose is in future to store the PV excess energy in Solothurn. Its PtG plant is responsible for 3.8 GWh in 2035 [6]. The project is supported by the Swiss Federal government and runs under a *Leuchtturmprojekt*. A number of universities and organizations are involved in R&D of the project. Two Polymer Electrolyte Membrane (PEM) Electrolyzers (are installed with a nominal power of 175 kW_{el} each. In the first phase only the hydrogen production will be implemented, and the methane production will be implanted in near future. A hybrid plant is connected with the gas network so that the produced gas will be fed directly into the gas network. In 2016, the plant will run in a normal operation to meet its goal of gathering all the necessary information.

Moreover, Swisspower AG announced a cooperation with the Viessman Group this April [7]. The goal of Swisspower is to promote PtG plants in Switzerland with support from Viessman. PtG shall be coupled with waste water treatment plants, using the CO₂ from the sewage gas. It is reported that the efficiency will be increased as well as the amount of renewable energy production with this coupling. For the methanation, a biological reactor from Viessmann is used.

1.4 Related work

In a previous study [8] by the author a qualitative and quantitative feasibility analysis of the PtG technology in the future Swiss LV grid has been conducted. For this purpose, PtG has been integrated into the grid for absorbing the PV excess energy while producing hydrogen. This hydrogen was assumed to be sold in the mobility sector. This chapter briefly reviews the applied methodology and then sums up the results of this study.

Chapter 1.4.1 shall give an overview of the used methodology and results. Chapter 1.4.2 shall discuss the results and give an overview of further research objectives resulted from this study. These objectives will be the integral part of the study.

1.4.1 Methodology of the previous study

As discussed in chapter 1.2, PV represents a fluctuating energy source due to its dependence on seasonal and sudden weather changes. These characteristics will lead to challenges in the existing grid. A previous study [9] was performed to illustrate the impact of the increased PV production in the LV grid in a Zürich area by simulating the load flow through Powerfactory from DIGSILENT. The characteristics of the urban area are depicted in Table 1.

Table 1: Characteristics of the urban area at “Hüslibachstrasse”

Description	Value
Maximum active power load	0.675 MW
Yearly load energy consumption	2.95 GWh
Maximum PV power	2.096 MW _p
Yearly PV energy production	2.453 GWh

The result of the load flow analysis of the study indicates that 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. The results of the load flow analysis is showed in Figure 2. The black plane indicates the reverse power flow, which occurs when the energy flows from the LV to the mid voltage MV grid. In order to operate the transformer in a safe range, the previous study [9] demonstrated that a BESS with a nominal power of 1.004 MW and a nominal capacity of 6.457 MWh is required. Since the dimension of this battery is nine times larger than that of the largest one existing in Switzerland it seems unrealistic to implement such a system.

Alternatively, PtG represents another suitable storage solution for absorbing the PV excess energy production in the LV grid as discussed in chapter 1.3.1. The PV excess energy calculated in study [9] has been used to operate the electrolyzer in study [8] and will be used to operate the electrolyzer in this study.

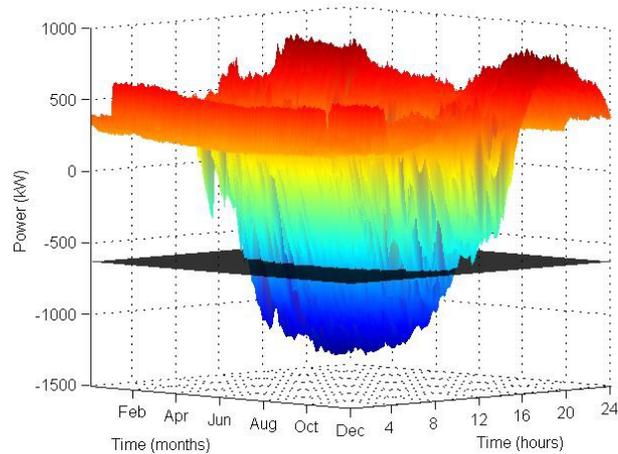


Figure 2: 3-dimensional plot of a transformer power flow of the case under consideration. For the z axis values, the area below the black plane indicates the reverse power flow, which occurs when the energy flows from the LV level to the MV level through the transformer. Graph from [9]

In order to examine the technical and economical feasibility of PtG into the existing LV grid, three different scenarios have been established with respect to the input energy source to the PtG plant. These scenarios including the excess PV energy, curtailed PV excess energy or PV excess energy plus the energy from grid. The different scenarios are summarized in Table 2. For each scenario a tank dimensioning was carried out in order to estimate the resulting tank costs. The tank is emptied 3 times a week and the hydrogen is compressed up to 200 bar in the simulation. Figure 3 shows the simulation layout of the previous study. Table 3 summarizes the applied parameters to run the simulation.

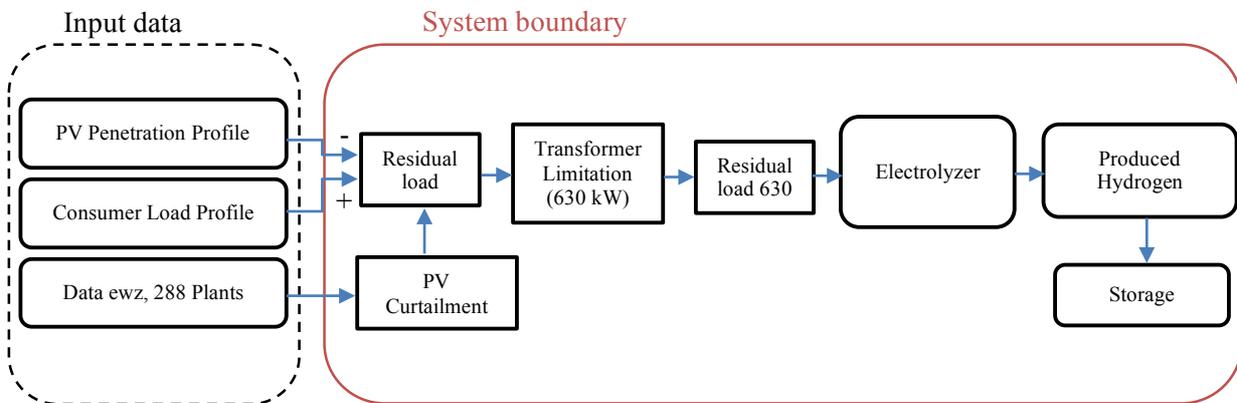


Figure 3: Simulation layout and input data

Table 2: Simulation scenarios of study

Scenario 1	Scenario 2	Scenario 3
<ul style="list-style-type: none"> All PV excess is applied to PtG plant Impact of maximum PV excess is examined 	<ul style="list-style-type: none"> Curtailed PV excess is applied to PtG plant. Optimal curtailment calculated Examine the effect upon investment costs and thus production costs 	<ul style="list-style-type: none"> In addition to PV excess , applied to PtG plant is additional energy purchased from the grid, during the winter months, mainly from November to February, and off-peak hours between 7 PM and 7 AM Boost capacity factor (CF)

Table 3: Simulation parameters

Electrolyzer parameters		Reference
Efficiency including storage	63%	[10]
Investment calculation parameters		Reference
Lifetime of the power plant	25 years	Assumed
Interest rate	5%	Assumed
CAPEX of electrolyzer	2000 CHF/kW	[4]
Yearly operation costs	4% of CAPEX	[4]
Costs for delivery and construction	10% of CAPEX	[4]
Energy curtailment price	0.219 CHF/kWh	[11]
Energy price for additional energy	0.2 CHF/kWh	[12]
Tank costs	990 CHF/kg	[13]

1.4.2 Results and discussion

Summing up the results from study [8], it can be concluded that the PtG plant is not yet economically viable even though significant improvement to the hydrogen production costs can be accomplished by adopting the active PV curtailment and by purchasing additional energy from the grid. Nonetheless, the hydrogen production cost still lies outside the price range, which is considered as competitive with respect to the current market prices. Figure 4 shows the results from the three different simulation scenarios. Graph (a) shows the yearly production rate of the electrolyzer in MWh and kg. (b) shows the resulting hydrogen production costs. The red line indicates a benchmark for competitive hydrogen selling price in the mobility sector which is set to 7.23 CHF/kg with a Diesel price of 1.52 CHF/l. The actual diesel market price has been taken into account to set up this benchmark together with the assumption that a Fuel Cell Electric Vehicle (FCEV) has an improved efficiency of 30% compared to a conventional vehicle [14].

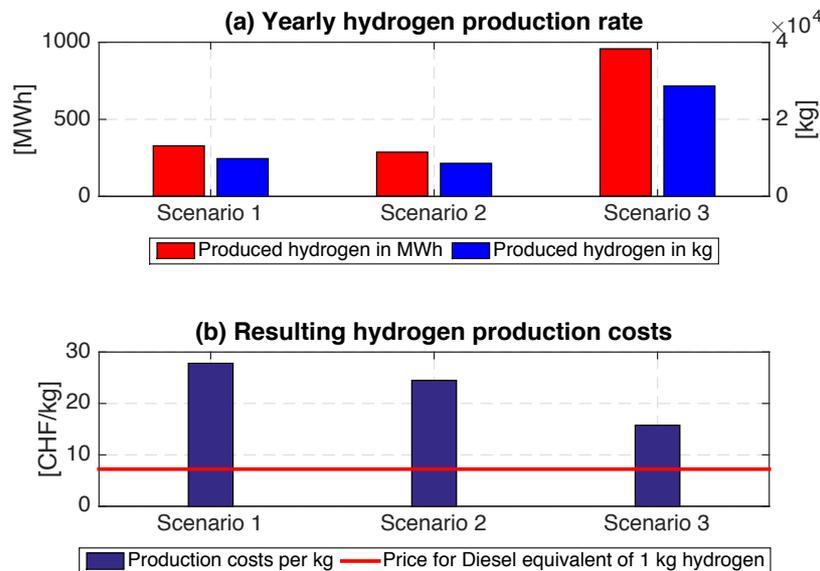


Figure 4: Simulation results of the previous study. (a) yearly production rate of electrolyzer, (b) resulting hydrogen production costs in CHF/kg

Regarding outlook of the PtG plant under study, it appears to be necessary to implement further measures in order to make the PtG system economically viable. As mentioned at the beginning of chapter 1.4, the previous study considered selling the hydrogen into the mobility sector. However, a

PtG plant offers various sources of income and it is therefore not restricted solely to sell the produced hydrogen [15] [16] [17].

One goal of this study was to evaluate different value sources in order to operate the system profitably. For that reason, also methane will be produced besides the hydrogen production and value sources such as primary control service, heat and oxygen recovery will be considered.

2 Scope

In this chapter the scope of this extended study is defined. Subsequently, further listed are the research objectives as well as the structure of this study.

2.1 Problem formulation

Among DSOs, it is increasingly noticed that PtG can be installed not only to handle the excess energy from PV but also to serve as a short term as well as a long term storage. So far, technical as well as economical barriers seem to prevent this technology from spreading in Switzerland. As a result, no real operational experience is available. Nonetheless, a current trend on this technology can be identified as discussed in chapter 1.3.2.

The goal of this extended study is to analyze the impact of a PtG storage system in the case of Hüslibachstrasse. The data of the load flow analysis from the related work described in chapter 1.4 will be used to conduct necessary simulations. The results of the simulations shall give the insights concerning the technical as well as economical feasibility of the integration of PtG into the existing grid of Hüslibachstrasse.

2.2 Research objectives

The primary question of this study is:

“How feasible is the PtG technology from a technical as well as an economical point of view to integrate the full PV potential of Hüslibachstrasse?”

The objectives of this study are summarized as:

- Conduct an analysis to answer following questions:
 - 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?

3 Theoretical basis

This chapter shall give an overview of the most relevant technical aspects of PtG. Furthermore, comparison between PtG and BESS is conducted.

3.1 Concept of 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 areas which it can be used such as: Mobility sector, heat generation and chemistry or it can be used to feed directly into the gas network [18]. Figure 5 shows that the concept of PtG with all the different stages to produce H_2 or CH_4 . Produced H_2 will be stored in tanks. However, they would rather serve as a buffer, and the stored H_2 will be delivered to the consumers in an appropriate time. Or they can be fed and stored into the existing gas network.

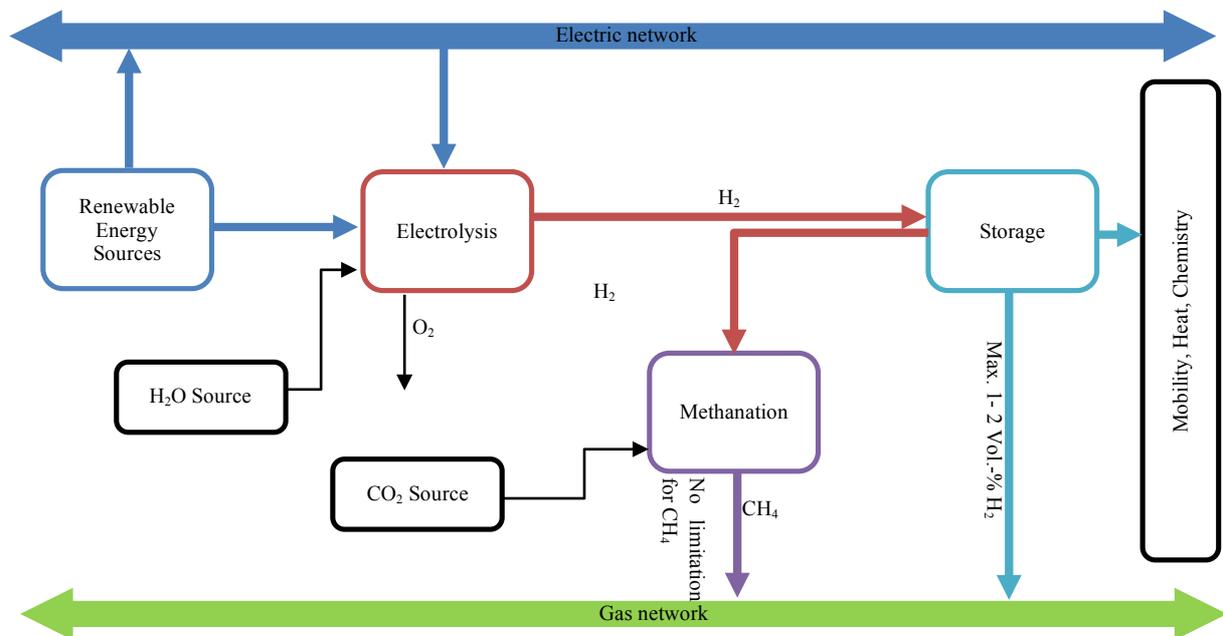


Figure 5: Concept of PtG

3.1.1 Comparison between hydrogen and methane production

The maximum amount of H_2 allowed to be fed into the gas network is limited to 1-2 Vol.-%. On the other hand, CH_4 can be fed in without any restrictions. This limitation along with non-existing gas infrastructure for H_2 as well as lacking consumers (especially in the mobility sector) implies the restriction of the maximum production rate of this gas [18].

In terms of their energy density at 0 °C and 1.013 bar, CH_4 with 10 kWh/m³ outreaches hydrogen with its 3 kWh/m³ by more than a third but the efficiency of the H_2 process is with 54-84% higher than the methane process with 49-79%. For this purpose, as long as the produced H_2 can be used or the maximum allowable amount in the gas network is not reached, the H_2 production should be preferred [4].

3.2 Water electrolysis technologies

Nowadays, 3 different procedures are available for the water electrolysis. These are Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane Electrolysis (PEM) as well as High Temperature Electrolysis of Steam or Solid Oxide Electrolysis (HTES or SOEL). Due to the ability of a dynamic operation [4], the PEM electrolysis is considered as the most suitable to absorb the fluctuating production of PV. Therefore, only PEM electrolysis is for this BA.

3.2.1 Principles of the Polymer Electrolyte Membrane Electrolysis

In this subchapter the principles of PEM are shortly discussed. Figure 6 shows the principles of a PEM cell. The Anode, cathode and the membrane together are forming the Membrane Electrode Assembly (MEA) which is the core of the cell. On the both sides bipolar plates are situated. These plates are directing the water towards the anode and allowing the produced gas to escape. In order to produce H_2 , water is fed into the anode compartment, where the water is split up in an atomic oxygen and two protons. The oxygen will get combined to O_2 -molecules and directed outside the anode compartment. The protons are transported through the proton exchange membrane to the cathode compartment where they react with two electrons to H_2 -molecules. In order to increase the production rate of H_2 , multiple cells are combined, then forming so called stacks [4], [18].

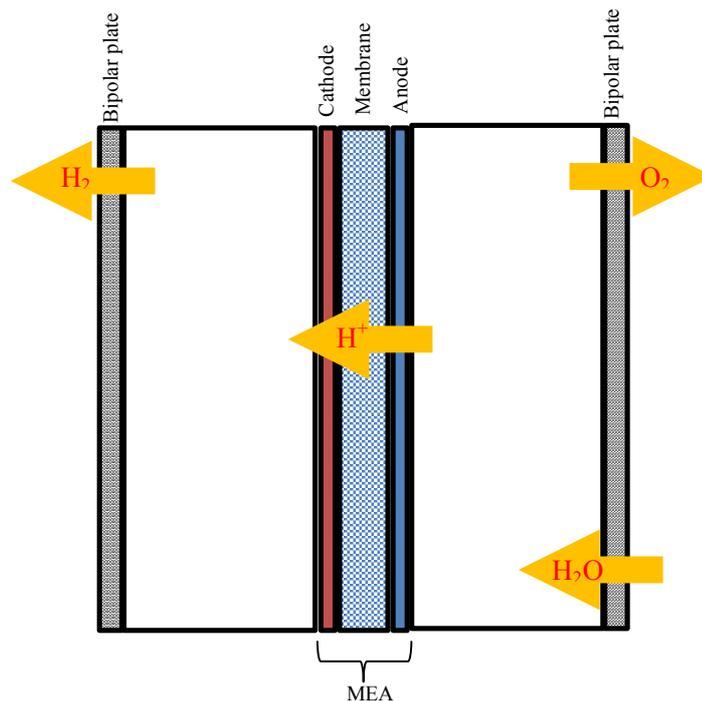


Figure 6: Basic principle of a PEM cell.

3.3 Methanation

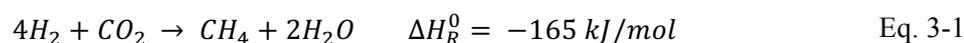
For the production of methane another process step is needed as briefly described in chapter 3.1. There are two main principles to produce CH₄ out of H₂ and CO₂: thermochemical catalysis and biological catalysis. The following chapters shall give a brief overview of these two types.

3.3.1 Thermochemical catalysis

Thermochemical catalysis also called the Sabatier process was discovered over 100 years ago by the French chemist Paul Sabatier. Although the principle has been discovered for such a long time it was not until recently that the principle was discussed in context of energy storage. In 2007, Jürgen Schmid and Michael Sterner from the institute for solar energy supply techniques in Kassel, today Fraunhofer Institut IWES, introduced the principle of PtG. This development provided a breakthrough in the CO₂ methanation between the years of 2009 and 2011 [4].

The Sabatier reaction is highly exothermic and operates in temperature ranges of 200 – 600 °C and pressures from 20 to 60 bar [4]. The reaction needs a catalyst in order to avoid the need of high reaction temperatures [4]. Nowadays, Nickel can be seen as state of art for the catalyst material because of its availability, selectivity and activity within the chemical reaction. Moreover the price is relatively modest [4].

The total chemical reaction can be written as follows:



The maximum achievable conversions from H₂ to CH₄ is 83% since 17% of the chemical energy from the hydrogen is converted into heat. Typically a mean efficiency of 80% is reported in the literature according to [19].

3.3.2 Biological catalysis

Biological catalysis needs also catalysts but in this case these are provided by the nature. The chemical catalysts can be substituted by enzymes which carry the bio-catalyst. The enzymes are produced by a methanogenic bacteria, which belongs to the domain of Archea [18]. Below are listed some of the advantages and disadvantages of biological catalysis. This list is by no means complete, for more detailed information see [4].

Advantage

- High purity methane (more than 98%) is achievable within one process step and low reactor load
- Low process temperatures, 40 to 60 °C vs. 200 to 600 °C
- Low process pressures, 1 to 3 bar vs. 20 to 60 bar
- Low requirements in purity for CO₂ or H₂

Disadvantages

- Constant feeding of bacteria
- Wastewater recycling needed
- Upscaling is more difficult to realize. Systems with higher than 1 MW are not feasible

3.4 Sources of CO₂

Basically there are four possible ways to gain CO₂ for the methanation process. These sources can be listed as follows:

- CO₂ from fossil power plants
- CO₂ from industrial processes
- CO₂ from biomass
- CO₂ from air

Following chapter will briefly discuss the different concepts and the involved costs. It shall be noted, that from an economical point of view it seems most convenient to use synergies whenever possible. In other words, it is favorable for example to place the PtG facility close to a fossil power plant where CO₂ is generated. The hybrid power plant described in chapter 1.3.2, uses the generated CO₂ from a local waste incineration plant and shows a good example of how synergies can be used [6].

3.4.1 CO₂ from fossil power plants

In order to gain the CO₂ from fossil power plants the so called carbon capture and storage (CCS) method is applied. This method is widely investigated and technical options are available. The related costs are estimated in a range of 20 – 70 CHF/t_{CO2} [20].

3.4.2 CO₂ from industrial process

In this case the CO₂ is gained from the resulting flu gas of the industrial process. Also the same the technology from CCS is applied [20].

3.4.3 CO₂ from biomass

It seems a promising option to integrated the PtG facility into a biogas site where the needed CO₂ for methanation is present in the biomass. Especially the combination with a waste water treatment plant is favorable because 460 candidates plants are existing in Switzerland [15].

The biogas or the sewage gas contains of about 40 – 50% of CO₂ and 50-60% of methane and can be feed into the methanation step, doubling the output of methane [4]. Another advantage is that the input energy to upgrade the biogas to methane can be avoided [4].

The gasification and combustion step in the biogas plant offers a CO₂ source which can be harvested with traditional technologies. The fermentation step however offers a free of charge CO₂ source where no additional costs or energy is needed [20].

3.4.4 CO₂ from air

There are four different principles to extract CO₂ from air. These are: adsorption, absorption condensation and membrane separation [4].

Due to the high energy and economic efforts CO₂ from air is not yet a valuable option. Energy efforts as high 500-800 kJ/mol_{CO2} which corresponds to 3000-5000kWh/t_{CO2} are reported [20].

3.5 Efficiency chain of the PtG process

The relatively low efficiencies of the PtG process represents the major reason, besides the high investment costs, why such systems are not yet economical profitable. Table 4 shows the different efficiencies reached in the PtG process according to [10]. The mean efficiency of 63% for the conversion from electricity to hydrogen has been applied to the simulations performed in this BA.

Table 4: Efficiency chain of different PtG processes [10]

Path	Efficiency	Conditions
Electricity to gas		
Electricity to hydrogen	54 – 72%	Compression to 200 bar
Electricity to methane	49 – 64%	
Electricity to hydrogen	49 – 64%	Compression to 80 bar
Electricity to methane	49 – 64%	
Electricity to hydrogen	49 – 64%	Without compression
Electricity to methane	51 – 65%	
Electricity to gas to electricity		
Electricity to hydrogen to electricity	34 – 44%	Compression to 80 bar and conversion to electricity with efficiency of 60%.
Electricity to methane to electricity	30 – 38%	
Electricity to gas to combined heat and power (CHP)		
Electricity to hydrogen to CHP	48 – 62%	40% power and 45% heat with compression to 80 bar
Electricity to methane to CHP	43 – 54%	

3.6 Comparison between PtG and BESS

In this chapter, a comparison between these two storage systems is presented. It must be noted that this comparison is by no means complete. Nevertheless, it shall give an overview of the characteristics regarding these two storage systems. Aspects such as investment costs, efficiency, energy density as well as ecological considerations have been taken into account. The BESS is represented by lithium ion (Li-Ion) battery cells.

3.6.1 Investment costs

It can be noted that both systems involve high investment costs. Table 6 includes the costs for the nominal power as well as the storage capacity of the both systems. More detailed information about the PtG costs can be found in chapter 4.2

Table 5: Investment costs of PtG and BESS in comparison

PtG		BESS	
Power capacity	Energy storage capacity	Power capacity	Energy storage capacity
CHF/kW	CHF/kWh	CHF/kW	CHF/kWh
2000-6000 EUR/kW [4]	900 EUR/kg [13] 1 kg = 33.4 kWh [4] 26.95 CHF/kWh	170-600 EUR/kW [4]	170-600 EUR/kW [4]

3.6.2 Efficiency

When it comes to efficiency, BESS surpasses the PtG by far. The BESS can reach the efficiency ranging from 90% to 97%, when the lithium ion technology is used for a full cycle (charge and discharge). On the other hand, PtG reaches only the efficiency ranging from 34% to 44% for the conversion from electricity to hydrogen to electricity. This fact shows the importance of using the hydrogen directly, if possible, because in this case the efficiency varies between 54% and 72% as stated in chapter 3.5.

3.6.3 Energy density

Regarding the energy density, the hydrogen is better positioned because it can be stored under pressure, achieving high energy density. When hydrogen is stored at 200 bar, energy densities of 391 kWh/m³ can be achieved [21]. Hydrogen is compressed up to 700 bar in FCEV. At this pressure, energy densities of 13000 kWh/m³, are reachable [22]. Lithium ion batteries on the other hand reach energy densities between 190 and 375 kWh/m³ [4].

3.6.4 Ecological considerations

From an ecological point of view, it can be noted that the lithium ion battery cells applied in the BESS can lead to problems regarding the social acceptance because of the questionable mining in the affected countries [5]. Moreover, the lithium resources are limited only to a few countries in the world, and the recycling of the batteries can cause pollution if not conducted properly. The PtG system on the other hand can be considered as a “clean technology.” The single input besides the electricity is water and the outcome hydrogen and oxygen. Regarding the application in the mobility sector it is crucial that the electricity is produced from renewable energy sources only in order to reduce the CO₂ emission. This issue is of course related to the both storage systems.

3.7 Grid stability

As briefly discussed in Chapter 1.3, the production and consumption in the grid must be balanced at all times. The grid itself offers a minor storage capacity for the electric energy. Moreover it can be stored only for a short amount of time [23]. As consequence, the production follows traditionally the consumption.

3.7.1 Swing equation and frequency stability

The generators in the existing grid, which are connected to the grid, save energy in a form of kinetic energy stored in the rotating mass of the rotor. Since the generators are never operated at full load, they will serve as an energy buffer whenever a change of the load occurs in both directions. When there is an imbalance in production and consumption of active power the moving rotor of the involved generator is either accelerating or decelerating. This will lead to a frequency change in the system and can be described with the following so called swing equation [24]:

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H} (P_m - P_e) \quad \text{Eq. 3-2}$$

$$\text{with } \omega = 2 * \pi * f$$

$$\frac{df}{dt} = \frac{f_s}{2H} (P_m - P_e) \quad \text{Eq. 3-3}$$

where H is the inertia constant of the generator:

$$H = \frac{\text{stored kinetic energy at synchronous speed}}{\text{generator MVA rating}} = \frac{\frac{1}{2} J \omega_s^2}{S_{rated}}, p. u.$$

f_s = actual system frequency [Hz]

ω_s = actual system frequency $[\frac{rad}{s}]$

P_m = mechanical power supplied by the prime mover, p. u.

P_e = electrical power output of the generator, p. u.

J = total moment of inertia of the rotating masses [kgm^2]

Eq. 3-2 or Eq. 3-3 indicates that the system frequency will stay stable as long as P_m and P_e are equal. In case of a load increase, the frequency will decrease as long as it is not compensated by the operating generators while a decrease of the load will increase the frequency. These equations stand for a single generator, however, they can be applied for the entire system. Thus, H represents then the total system inertia of all generators producing energy in the grid.

As discussed thoroughly in the introduction, the integration of RES will lead to problems in the existing grid. One problem in the future, not indicated in this section, can be anticipated regarding the frequency stability. Since the production of RES is intermitted, the production will not longer follow the consumption and can therefore cause frequency deviations. Moreover, traditional energy production with involving generators will be replaced due to the integration of RES, reducing the total system inertia H. As a result, the grid will become more and more vulnerable to load changes since the energy buffer of the rotating mass is getting smaller.

In order to keep the system frequency stable, control reserves are necessary. These control reserves are classified as primary, secondary and tertiary control reserves. The primary and secondary control reserves are applied automatically in the system while the tertiary control reserves are switched on manually. How this reserves are applied is discussed in chapter 3.8.1.

As disused in chapter 1.3, alternative energy storage solutions will become more and more important in the future since detailed modeling has shown that the pumped-storage plants will be insufficient to deal with the excess energy produced by PV as well as wind [1]. Here the PtG system seems to be an option to provide control reserves in the future grid.

3.8 Ancillary Services

The Transmission System Operator (TSO) is responsible for a safe and reliable operation of the transmission system (TS) within the controlled area as well as the connection with neighboring TS. In case of the Swiss TS, Swissgrid is in charge of this task. In order to operate the TS safe and reliable, Swissgrid needs ancillary service (AS). These services are essential for the functioning of the system and can be divided into Frequency control (primary control, secondary control, tertiary control), Voltage support, compensation of active power losses, black start and island operation capability, system coordination and operational measurement [23].

Since 2009, Swissgrid has been purchasing AS in a transparent, non-discriminatory and market-based procedure in accordance with the technical specifications of the European Network of Transmission System Operators for Electricity ENTSO-E [23].

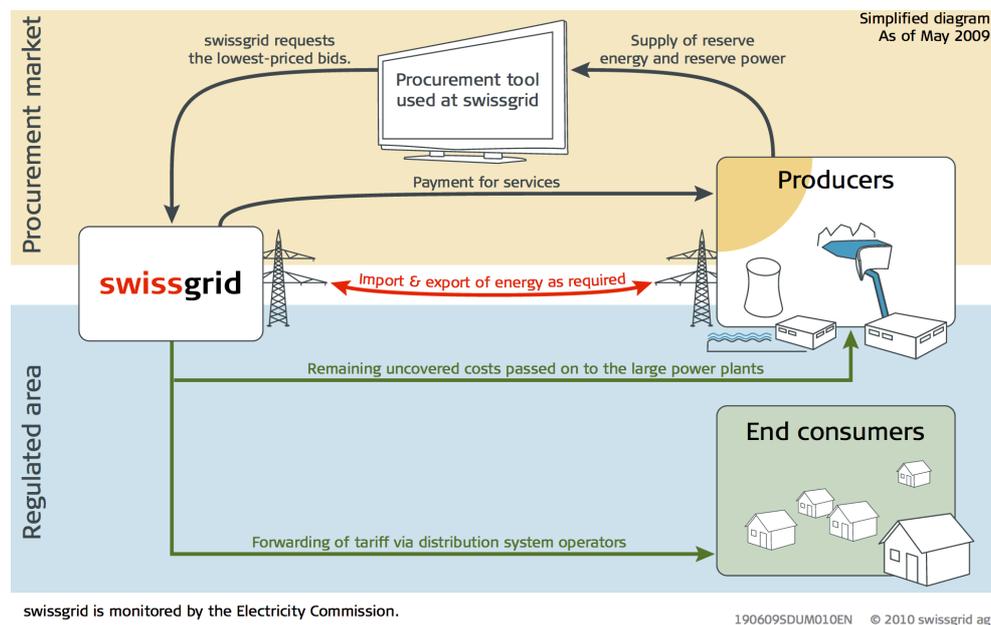


Figure 7: Simplified diagram over the ancillary service market [23]. .

Every producer qualified for ancillary service supplies its reserve energy and reserve power on the market. Swissgrid then accepts the lowest priced bids. In the end, the resulting costs are forwarded to the end consumer. Figure 7 shows a simplified diagram over the AS market.

3.8.1 Frequency control

Primary control

Primary control is the first measure to restore the balance between power generation and consumption in case of frequency deviation. As described in chapter 3.5.1, the spinning reserve of all operating power plants represents the primary control, and it is activated automatically by means of turbine regulators within seconds of the disturbance. The goal is to stabilize the frequency within the permissible limits.

All TSO in the ENTSO-E must fulfill certain requirements. Main requirement for all the participating plants is that the primary control power must be kept in reserve at any time. In Switzerland for example, the total primary reserve amounts to 70 MW with a frequency deviation of ± 200 mHz [23]

Secondary control

Secondary control is activated usually seconds after the primary control. The goal is to preserve the desired energy exchange within the affected control area as well as the connected grid while

maintaining the frequency at 50 Hz. It is activated automatically but by the central grid controller. Typically, secondary control holds on for 15 minutes and when the disturbance is not eliminated the tertiary control will be activated [23].

Tertiary control

Tertiary control, as described above will be activated after 15 minutes from the frequency deviation. The goal is to relieve the secondary control and maintain the frequency in case of production outages or unexpected long-lasting load changes. In contrast to primary and secondary control, this measure will not be activated automatically. The activation is effected by the Swissgrid dispatcher which will send an special electronically transmitted message to the provider [23].

Figure 8 illustrates a power plant outage in France and the resulting frequency deviation. Firstly, the primary control is activated within seconds after the failure in the entire ENTSO-E grid in order to stabilize the frequency and not allowing it to decrease further. Secondly, the secondary control takes over and brings the frequency back to 50 Hz. This is accomplished by power plants in France. After 15 minutes, the tertiary control is provided by two power plants in France and one in Spain.

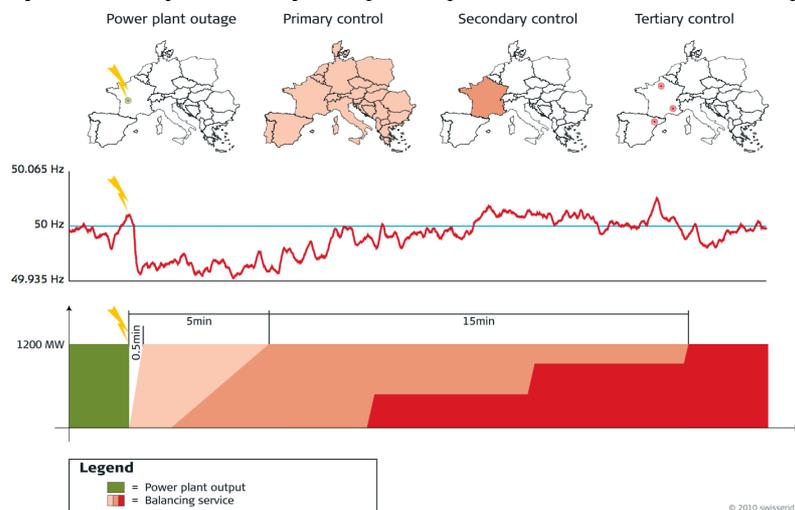


Figure 8: Illustration of power plant outage in France and corresponding frequency deviation [23].

4 Methods

In this chapter an overview of the area of Hüslibachstrasse is presented. Moreover, the current cost situation regarding the electrolyzer investment costs and hydrogen prices are discussed. Lastly the simulation layout as well as the simulation parameters are explained.

4.1 Overview of the area of Hüslibachstrasse

The area where the PtG storage system shall be integrated into the LV is in the area of Hüslibachstrasse located at the address of 8041 Zürich Leimbach. The transformer station expected to be overloaded due to reverse power flow is located in this area according to [9].

Table 6 shows the relevant facts for this BA, extracted from the study [9].

Table 6: Relevant facts regarding the Hüslibachstrasse

Description	Value
Number of houses	312
Maximum active power load	0.675 MW
Yearly load energy consumption	2.95 GWh
Maximum PV power	2.096 MWp
Yearly PV energy production	2.453 GWh

It seems logical to install the PtG facility somewhere close to the transformer station. Therefore, the area must have enough space to do so. In order to get an idea of the space requirements of such a facility, Figure 9 shows the building which houses the two electrolyzers of Regio Energy Solothurn as described in chapter 1.3.2. The red circle indicates the building (in construction) where the two electrolyzer and other installations are situated.

Figure 10 on the other hand shows the area of Hüslibachstrasse. Both satellite pictures are created to the same scale by the Google maps. Although the installed electrolyzers in Solothurn have a power rating which is about 3 times smaller than the one required at Hüslibachstrasse it can be noted that the building from Region Energy Solothurn is about the size that would be required for the electrolyzer in Hüslibachstrasse since the building in Solothurn houses a lot of other equipment such as two heat pumps, oil tank as well as a combined heat and power unit.

Therefore, it would be possible to integrate such a system into this area regarding solely the space requirements. Additionally, there will be more space needed for the tank system which is not indicated in Figure 10.

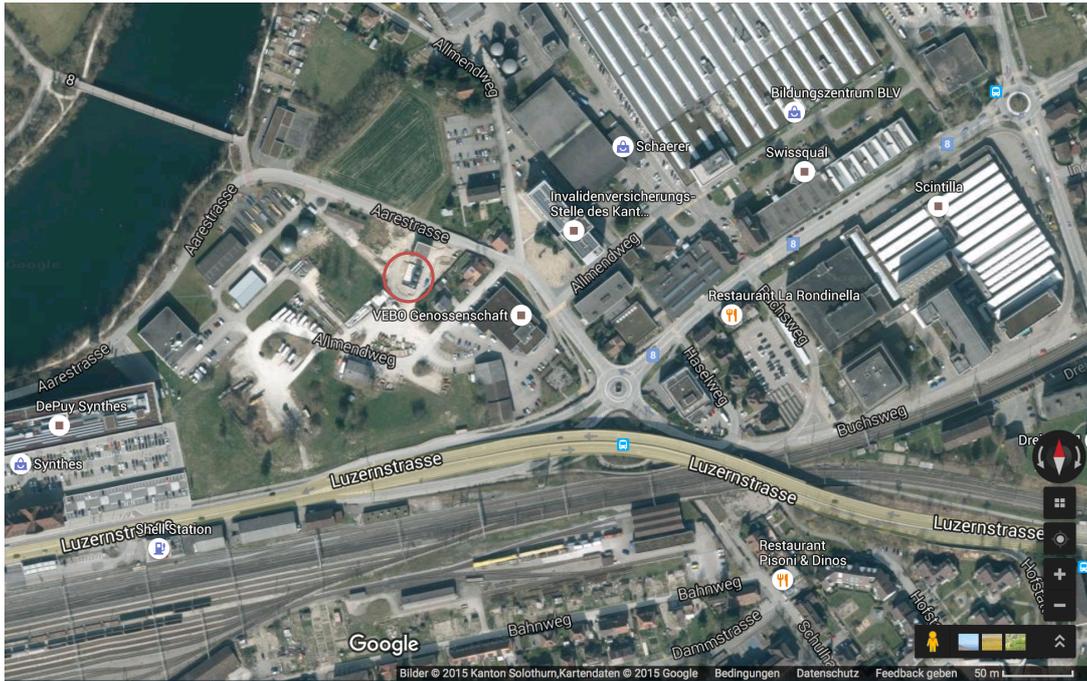


Figure 9: Satellite picture of the area in Solothurn where the facility of “Regio Energie Solothurn” is located. The red circle indicates the building which houses the two electrolyzes.

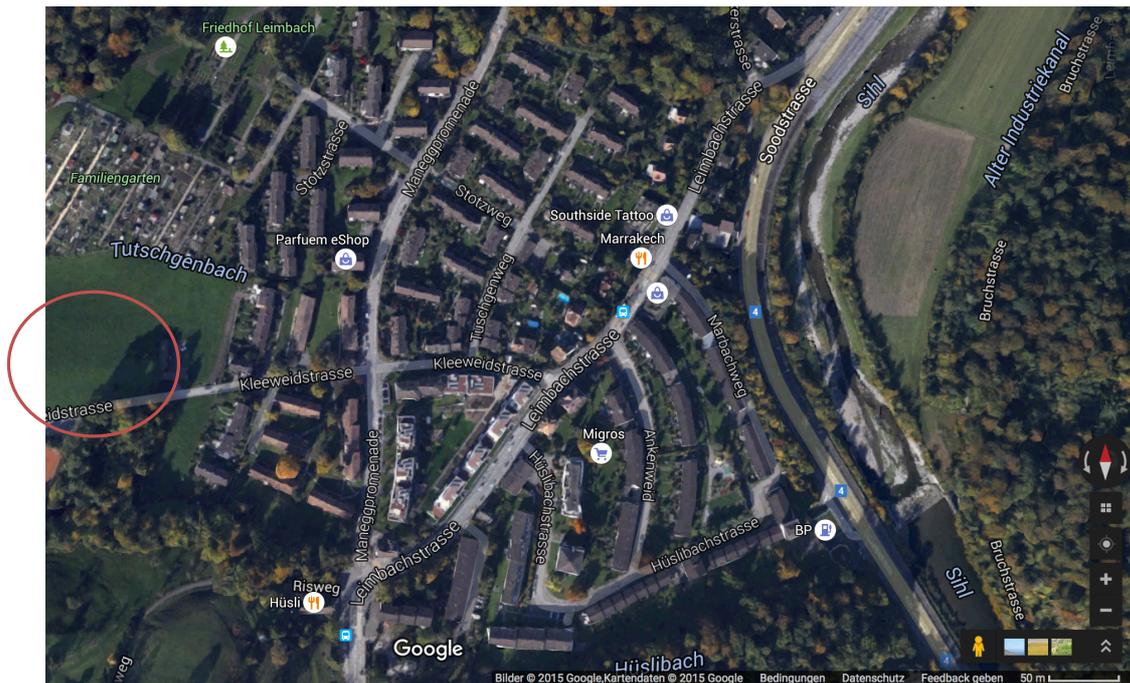


Figure 10: Satellite picture of the area of “Hüslibachstrasse”. The red circle indicates a possible construction site for the PtG storage system.

4.2 Cost considerations of PtG systems

The chapter shall give an overview of the current cost allocation of PEM electrolyzer and the actual stack lifetime. Also discussed are the current investment cost and future estimated cost development.

4.2.1 Cost allocation of PEM electrolyzers

The key component of the electrolyzer is the stack, which consists of multiple cells. A certain number of these cells are connected together to form the stack as described in chapter 3.2.1. Nowadays the stack component contributes more than the half of the total investment [26]. Besides the stack, the cost can be grouped in expenditures for power electronics, gas conditioning and balance of the plant. Figure 11 shall give an overview of the cost allocation.

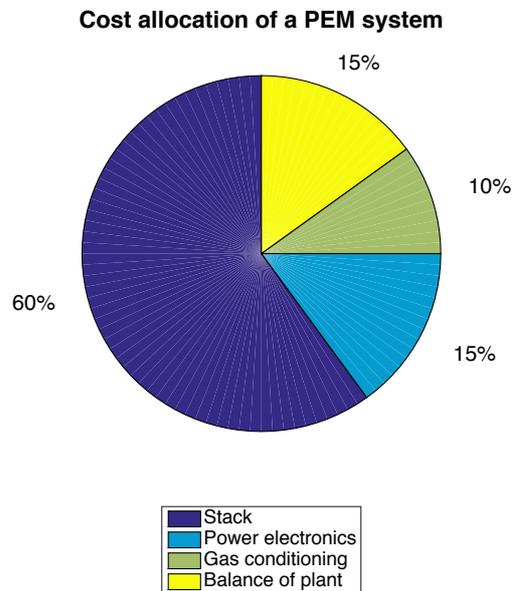


Figure 11: Cost allocation for a PEM electrolyzer system. Figure modified from [24].

4.2.2 Stack lifetime

Due to the cell degradation, the efficiency of the electrolyzer decreases over time, and the cell can reach its operational limit and has to be exchanged. The stack lifetime of a PEM electrolyzer varies from 20'000 hours up to 90'000 hours according to [13] [24] [27]. Since the stack allocates for over 50% of the total investment cost the European stationary fuel cell players emphasize the need to further improve the system durability [27]. Siemens, for example, ensures a lifetime of over 80'000 hours today with the SILYZER 200 PEM electrolyzer [28].

4.2.3 Investment costs

Data concerning the total capital expenditure (CAPEX) range from 1200 up to 2000 EUR/kW [26] in 2015. According to [29], the CAPEX for a PEM system is at least two times higher in comparison with a AEL system which is currently about 1000 Euros/kW. However, Siemens is reporting costs below 1000 EUR/kW by 2018 [30]. Figure 12 shows the actual CAPEX for PEM systems and estimated trends for the future. The average costs in 2020 are estimated in a range of 700 to 1300 EUR/kW, in 2025 between 480 and 1270 EUR/kW and by 2030 the cost are estimated to be in a range of 250 to 1270 EUR/kW [26].

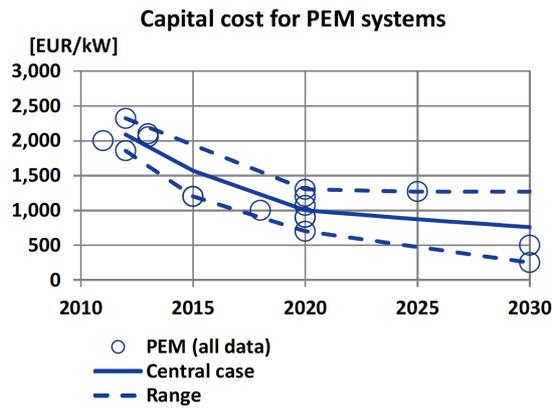


Figure 12: Actual CAPEX of PEM systems and estimated development [24].

The current operational cost as well as costs for delivery and construction are summarized in table 4 according to [4].

Table 7: Cost summary of PtG system. [4]

Delivery and construction	Maintenance, Operation and insurance
10% of investment costs	4% of investment costs

Additional cost for the storage system are considered with 900 EUR/kg stored hydrogen according to reference [13].

4.3 Cost of methanation

Not much literature is available about methanation investment. According to the studies listed in [29], costs of 400 EUR/kW for a 5 MW plant and 130 EUR/kW for a 110 MW plant are reported.

According to [15], the cost for a methanation reactor amounts to 482 CHF/kW. This upper value will be used in this analysis.

4.4 Modeling approach

In this chapter the modeling approach, the methodology, assumptions, and simplifications of the analysis are discussed.

Overall the analysis will be 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 13 has to be followed from bottom to top and from left to right.

Firstly, the residual load which represents the consumer load profile minus the PV excess energy has been calculated. Secondly, a simple electrolyzer model is defined. Thirdly, the different operating scenarios are established, and of the PtG system together with the electrolyzer model is operated. Lastly, the economic valuation model is defined to perform the economic values including the Levelized cost of energy (LCOE), Levelized value of energy (LVOE) and profitability. Moreover, a sensitivity analysis is conducted.

Figure 13 shows the analysis layout applied to conduct the simulation.

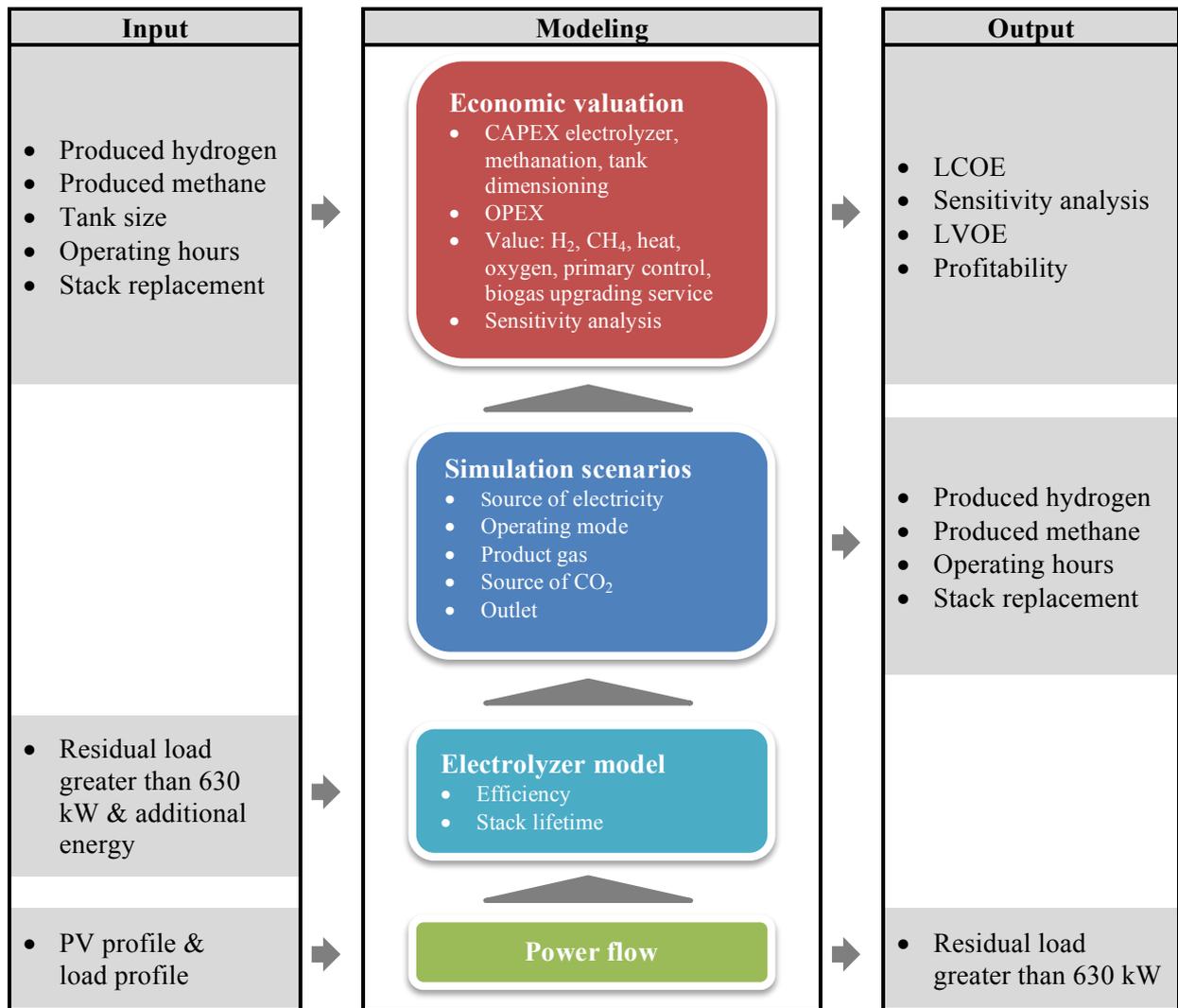


Figure 13: Modeling approach with all the necessary inputs, models and output results.

In the following chapters every model will be discussed in more details.

4.4.1 Assumptions and simplifications

First of all, the assumptions and simplifications undertaken for the modeling approach are as follows:

- The PV excess energy is considered as free of charge;
- Gas network feed-in is available nearby;
- Biogas upgrading site or wastewater treatment plant is near the PtG plant;
- The applied PEM type electrolyzer fulfills the prequalification for primary control;
- All the produced O₂ in the electrolysis can be used;

4.4.2 Powerflow

The applied input data for the power flow analysis can be divided into three parts. The PV Generation Profile, the Load Profile, and the measurement data, all of which are provided by the *Elektrizitätswerk Stadt Zürich* (ewz). The data provided by ewz consists of the yearly production rate of 288 PV plants located near Zürich.

The Load Profile are data extracted from [9]. The PV Generation Profile is build for the year of 2013 instead for 2012 as in [9] but with the same approach. The PV profile is generated from and based on

the mean production rate of 288 PV plants located near Zürich. This data has been provided by ewz. The mean production rate has been taken together with the PV Potential of the Hüslibachstrasse area to generate a single PV Profile on a quarter-hourly basis for the year of 2013. To estimate the PV potential of the Hüslibachstrasse area, the application *Solarkataster* has been used as in [9]. The PV Potential according to Solarkataster is about 2.453 GWh. The Load Profile consists of a quarter-hourly active power value flow for the area of Hüslibachstrasse for the whole year [9].

Figure 14 shall give an overview over the power flow situation at Hüslibachstrasse. Graph (a) shows the yearly PV penetration at the Hüslibachstrasse. A maximum PV power of 2.096 MW can be detected on 18th May at 1 PM. Graph (b) shows the yearly consumer load flows occurring in the area of Hüslibachstrasse. Graph (c) shows the yearly consumer load flows vs. the yearly PV penetration. For that reason, the yearly PV penetration was subtracted from the yearly consumer load flows. As a result, whenever a PV excess occurs, the power flow has a value below zero. The 630 kW active power threshold which represents the limit of the transformer, is indicated with a red line. Finally, graph (d) shows the Residual load which represents the load flows higher than the 630 kW threshold. The residual load represents the energy amount that has been used to run the electrolyzer. A maximum power of 1.04 MW can be detected on 18th May at 1 PM. The maximum power will determine the size of the electrolyzer.

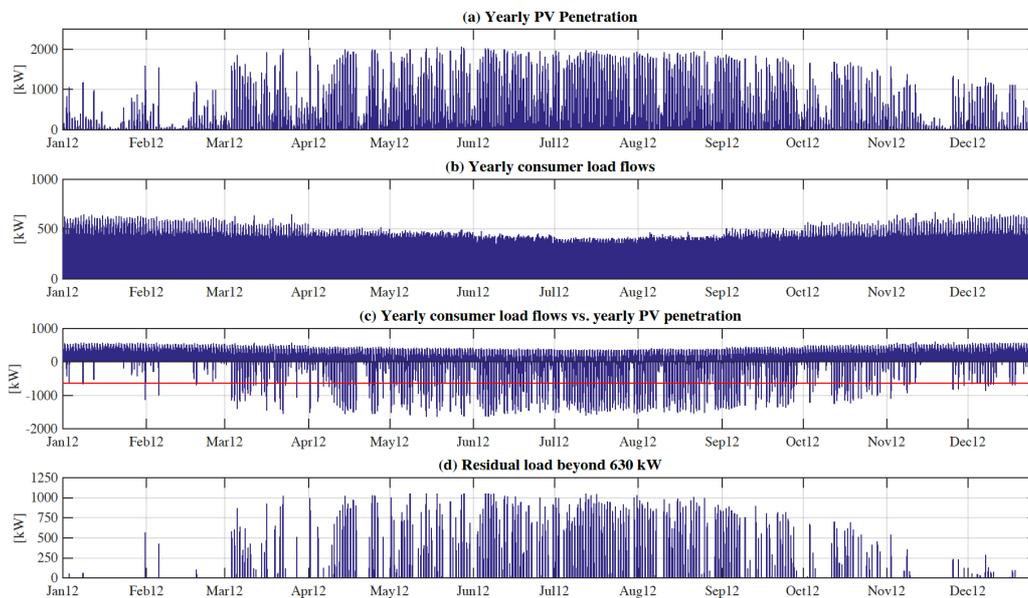


Figure 14: (a) Yearly PV penetration, (b) yearly consumer load flows, (c) yearly PV penetration subtracted from the yearly consumer flows, (d) residual load beyond 630 kW threshold

Following equations shall show of how the residual load has been calculated. Whenever the energy production is greater than the consumption, the excess power is present, which is defined as the Residual_load. The Residual_load is calculated as follows:

$$\text{Residual_load (i)} = \text{Consumer_Load_Profile (i)} - \text{PV_Penetration_Profile (i)} \quad \text{Eq. 4-1}$$

Before the excess energy is provided to the electrolyzer, it is cut by the limitation of the transformer station at the Hüslibachstrasse. The reverse flow limitation of the transformer is 630 kW active power and therefore only the amount of energy which is higher than this threshold will be directed to the electrolyzer. This load is defined as Residual_load_630 and calculated as follows:

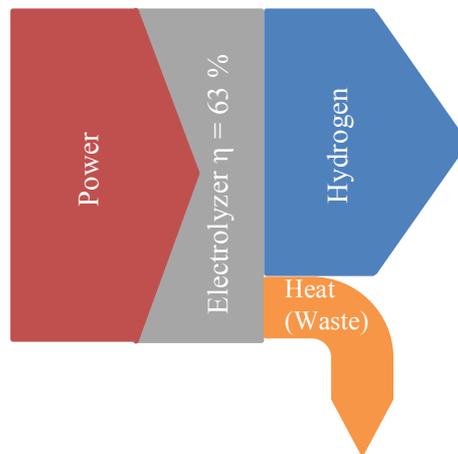
$$\text{when (Residual_load (i) > 630 kW)} \\ \text{Residual_load_630 (i)} = \text{Residual_load (i)} + 630 \text{ kW} \quad \text{Eq. 4-2}$$

$$\text{when (Residual_load (i) <= 630 kW)} \\ \text{Residual_load_630 (i)} = 0 \quad \text{Eq. 4-3}$$

4.4.3 Electrolyzer model

A simple electrolyzer model, which is built as shown below, will determine the output rate of the H₂. As discussed in chapter 3.5 the efficiency of PEM electrolyzers varies between 54 and 72%. For this analysis, the mean value of 63% has been taken into account. The efficiency has to be interpreted with regard to the combustion value of the H₂, which is set to 39.4 kWh/kg or 3.54 kWh/Nm³. The stack lifetime has been set to 67'000 hours, which corresponds to the mean value as discussed in chapter 4.2.2. **Error! Reference source not found.** Figure 15 illustrates the applied electrolyzer model. With an operating time of 1 hour and an electricity input of 1 MW, an output of 720 kWh hydrogen is produced. The rest can be considered as heat waste since the heat is not used in the model.

Table 8 summarizes the input electrolyzer model as well as all of which define the model.



and resulting output of the all the remaining parameters,

Figure 15. Electrolyzer model

Table 8: Parameters of the electrolyzer model including the resulting output rate

Parameters of electrolyzer model				
Efficiency [%]	Stack lifetime [h]	Plant lifetime [years]	Combustion Value [kWh/Nm ³]	Combustion Value [kWh/kg]
63 [10]	67'000 [26]	20	3.54	39.4
Production rate				
Input		Output		
Operating time [h]	Electricity [MW]	Hydrogen [kWh]	Hydrogen [Nm ³]	Hydrogen [kg]
1	1	720	203.4	18.27

4.4.4 Simulation scenarios

This chapter shall give an overview of the different simulation scenarios. In total, 9 different scenarios have been established. Fundamentally, the scenarios are established based on 5 distinctive variables, which define the operation of the simulation. Figure 16 shows the 5 variables that form the scenarios, and they will be discussed in the following chapters. Table 9 summarizes all the applied scenarios with the corresponding variables.

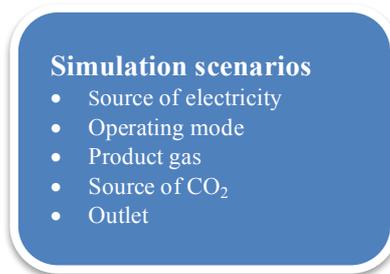


Figure 16: Variables of operating scenarios

Table 9: Different operating scenarios with variables

Scenario Number	Scenario variables				
	Source of electricity	Operating Mode	Product Gas	CO ₂ Source	Outlet
1	Excess	n/a	Hydrogen	n/a	Gas grid
2	Excess & Grid	Baseload	Hydrogen	n/a	Gas grid
3	Excess & Grid	Partload	Hydrogen	n/a	Gas grid
4	Excess & Grid	Baseload	Methane	Biogas	Gas grid
5	Excess & Grid	Baseload	Methane	Pure CO ₂	Gas grid
6	Excess & Grid	Partload	Methane	Pure CO ₂	Gas grid
7	Excess	n/a	Hydrogen	n/a	Mobility
8	Excess & Grid	Baseload	Hydrogen	n/a	Mobility
9	Excess & Grid	Partload	Hydrogen	n/a	Mobility

4.4.4.1 Source of electricity

The electrolyzer will be 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. Therefore, the PV excess energy can be considered as the primary input energy. In order to boost the capacity factor of the electrolyzer, additional energy will be purchased from the wholesale electricity market. This will take place in certain operating modes only as will be discussed in the following chapter. The wholesale market price of 2013 will serve as a basis for calculating the additional expenses since this data is available on a 15 min interval resolution. The highest price has been recorded on 2nd April at 07:45 with a value of 147.71 EUR/MWh. The mean value throughout the year is 44.73 EUR/MWh. Figure 16 shows the recorded SwissIX wholesale electricity market price of 2013.

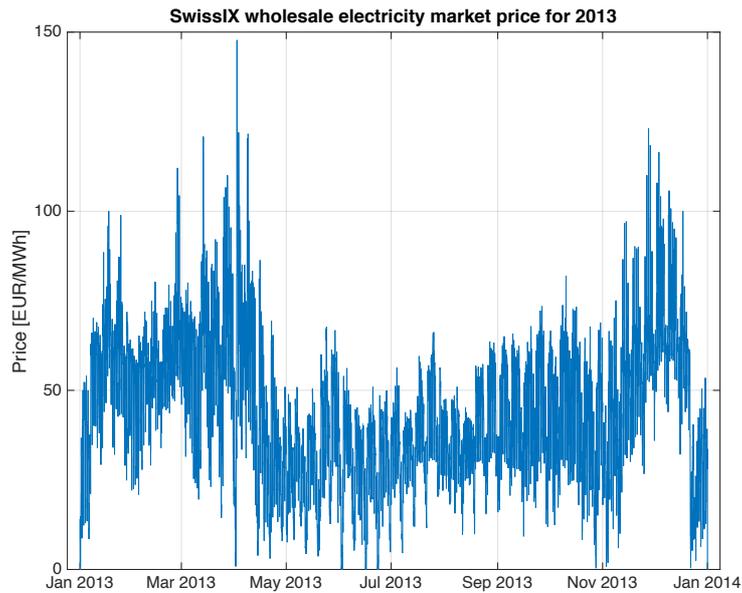


Figure 16: SwissIX wholesale electricity market price for 2013

4.4.4.2 Operating mode

In order to demonstrate the effect of the operating hours up on the LCOE, two operating modes have been established with respect to the total operating hours. These operating modes are called *baseload* and *partload*. When operated in baseload, additional energy is purchased throughout the year whenever no PV excess energy is present. When operated in partload on the other hand, the electrolyzer is operated throughout the year from 8 PM until 4 am. Moreover, the electrolyzer shall be used at maximum 90% of its capacity in both cases.

Figure 17 illustrates the operating modes with the load situation. The yellow area is the PV excess energy and the red area indicates the consumer load profile. It should be noted that the load profiles shall rather serve as an illustration since they are not complying with the real situation. The dashed arrows and lines indicate the time when the additional energy is purchased from the grid. The violet dashed line indicates the 630 kW threshold of the transformer. The PV energy above the violet dashed line can be considered as the excess energy. The resulting operating hours and operating hours at nominal capacity are also listed in Figure 17.

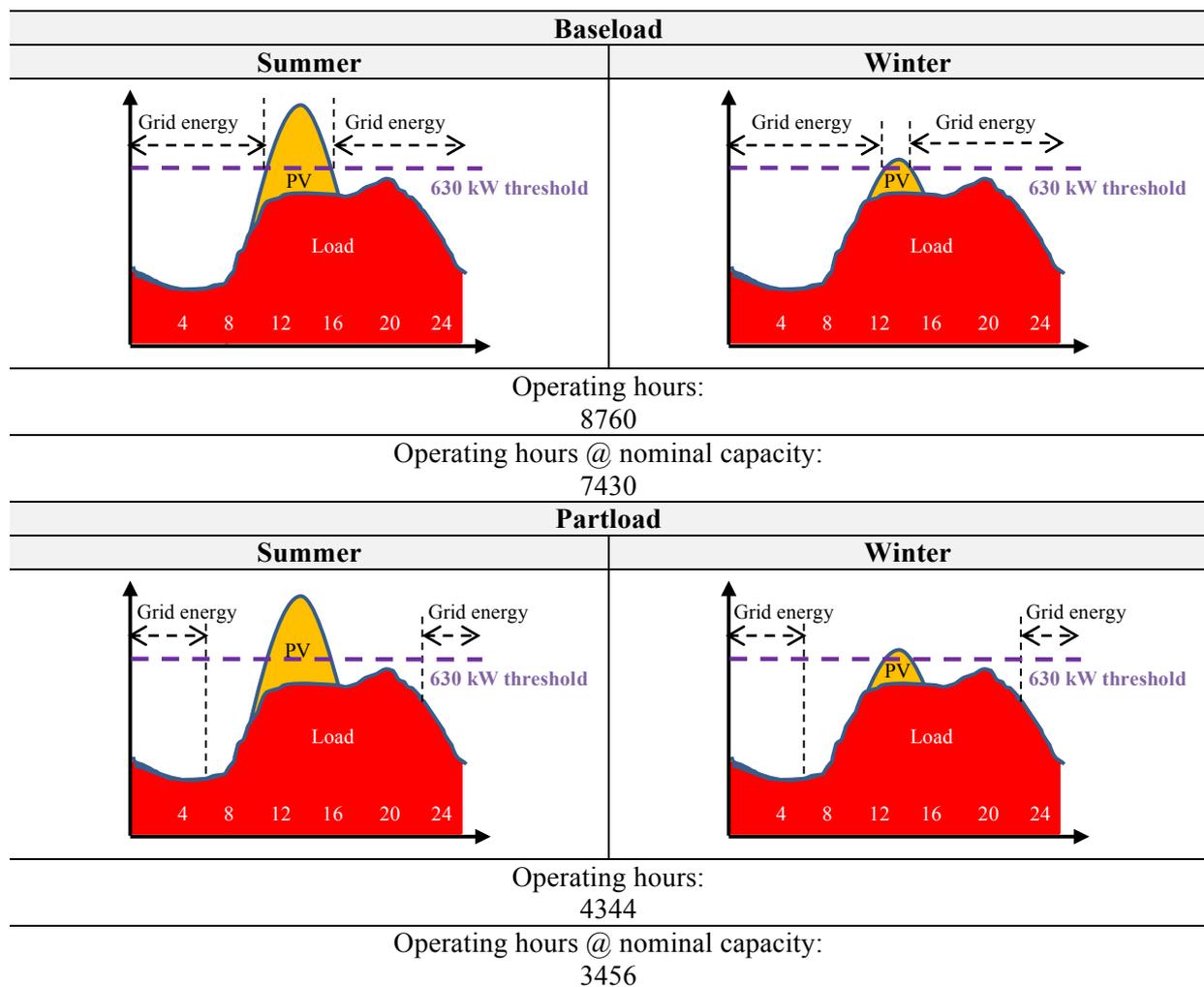


Figure 17: Established operating modes, baseload and partload with resulting operating hours and operating hours at nominal capacity

4.4.4.3 Product gas

The first measure to deal with the PV excess energy is to produce H_2 through the electrolyzer. However, as described in chapter 3.1 and 3.3, CH_4 can be also produced by adding a methanation reactor into the process. As listed in Table 9, scenarios 4, 5, and 6 are producing CH_4 out of H_2 and CO_2 . A conversion efficiency of 80% will be applied to the methanation process as discussed in chapter 3.3. Figure 18 shows the simplified electrolyzer model as defined in chapter 4.4.3 with the additional methanation step. The conversion from electricity to methane results in a total efficiency of 50.4%. In this case, the produced heat will be recovered and used in the process.

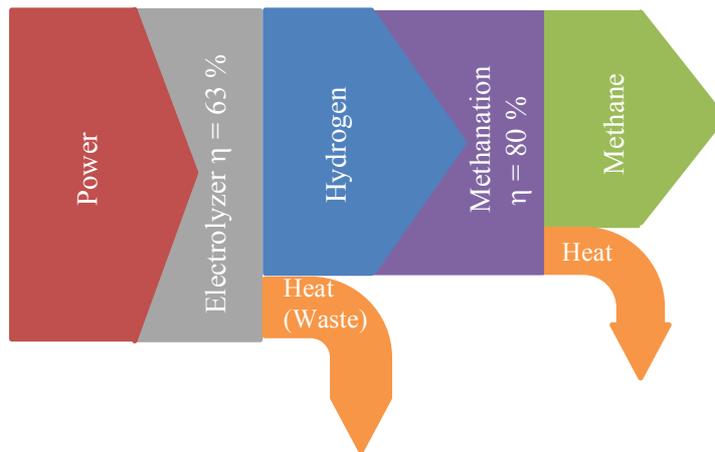


Figure 18: Electrolyzer model with methanation step

4.4.4.4 Source of CO₂

Two sources of CO₂ will be considered in the analysis, including pure CO₂ and CO₂ from biogas upgrading service. As discussed in chapter 3.4.3, 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% CO₂ and 50-60% CH₄ as discussed in chapter 3.4.3. For this analysis, CO₂ concentration of 40% is applied. Taking the the electrolyzer model with the integrated methanation step together with this concentration, the resulting consumption and production rate are listed in Table 11. The chemical equation from the Sabatier process (Eq. 3-1) has been applied to calculate the required pure CO₂ amount per produced CH₄. In Table 10 the required parameters for the conversion are listed. With an input energy of 1 MWh electricity, 52.2 Nm³ CH₄ will be produced. This requires 131.5 Nm³ Biogas or 52.6 Nm³ pure CO₂.

Table 10: Parameters for conversion from hydrogen to methane

Parameters for conversion from hydrogen to methane				
Efficiency [%]	Reactor lifetime [years]	Combustion Value CH ₄ [kWh/Nm ³]	Combustion Value CH ₄ [kWh/kg]	Specific weight CO ₂ [kg/Nm ³]
80 [19]	20	11.03	15.4	1.951

Table 11: Input of 1 MWh electricity with resulting biogas or pure CO₂ consumption as well as methane output rate

Production rate							
Input		Consumption			Output		
Operating time [h]	Electricity [MW]	Biogas [Nm ³]	Pure CO ₂ [Nm ³]	Pure CO ₂ [kg]	CH ₄ [kWh]	CH ₄ [Nm ³]	CH ₄ [kg]
1	1	131.5	52.6	102.6	576	52.2	37.4

4.4.4.5 Outlet

Two different outlet markets will be considered in the model. Firstly, the produced hydrogen or methane will be fed into the gas grid. As mentioned earlier, it is assumed that the gas grid feed-in facility is in place. Secondly, the assumption is made that the produced hydrogen will find its end consumers in the mobility sector. For this reason, the hydrogen will be transported 3 times a week by trucks to the refueling stations. According to [31], the resulting transportation costs can be estimated according to the rate shown in Figure 19.

The transportation distance has been set to not more than 100 km. The yearly production rate results in 124.02 tonnes per year, which leads to a daily production rate of 339.8 kg. With this two parameters, hydrogen delivery costs of approximately 1 CHF/kg occur according to Figure 19.

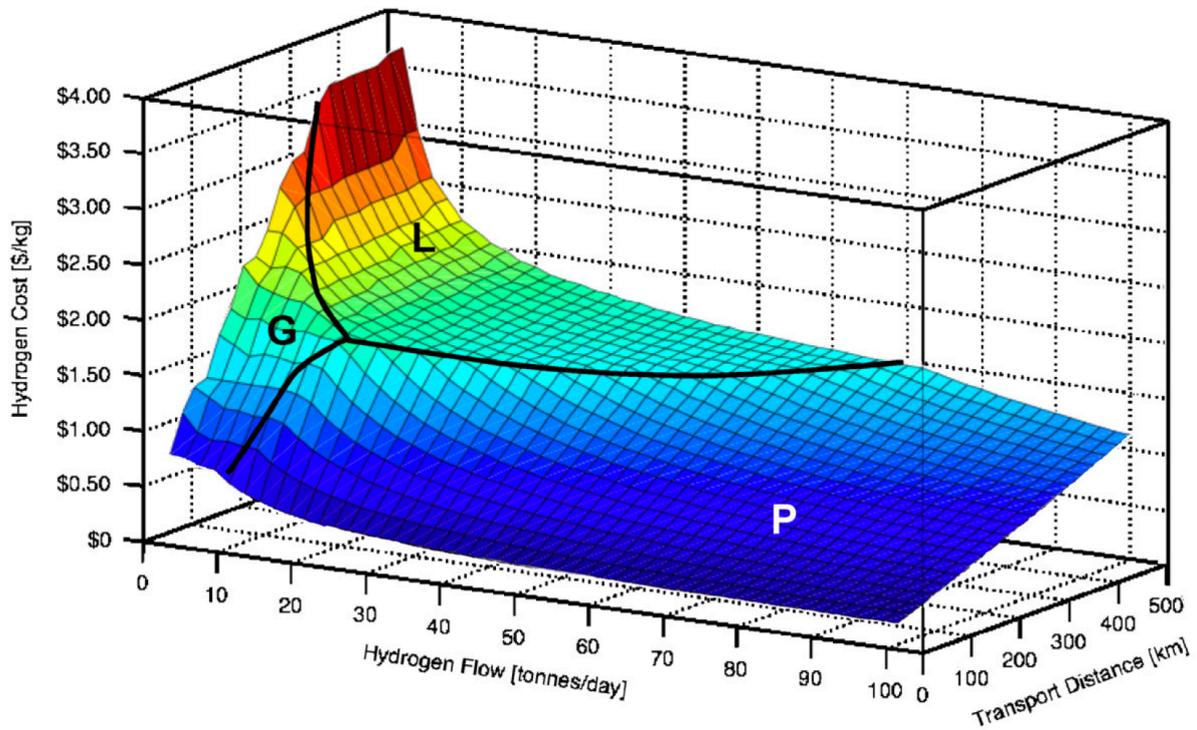


Figure 19: Minimum hydrogen transmission costs as a function of H₂ flow and transport distance [31].

4.4.5 Economic valuation

In this chapter, the economic valuation procedure is explained. Generally, the valuation is based on the cost, value and resulting profitability of the different scenarios. Since the valuation is strongly depended on the taken assumptions, a sensitivity analysis is also performed for the most influential variables. Figure 20 shows the economic valuation model with all the considered components.



Figure 20: Economic valuation model with

4.4.5.1 Lifecycle cost analysis

The concept of the Levelized costs of energy (LCOE) has been adopted for the analysis of the production costs. It allows a fair comparison of the production costs of the hydrogen or methane among the different scenarios as well as other technologies. According to [32], the LCOE is calculated with the following equation.

$$LCOE = \frac{CAPEX + \sum_t^n \frac{OPEX_t}{(1+q)^t}}{\sum_t^n \frac{E_t}{(1+q)^t}} \quad \text{Eq. 4-4}$$

LCOE	Levelized cost of energy in CHF/MWh	t	Year of lifetime (1,2,3...n)
CAPEX	Capital expenditure in CHF	n	Lifetime of the power plant
OPEX	Annual operational expenditure in CHF	q	Interest rate in %
E _t	Produced quantity of energy in the respective year in MWh		

In Table 12, all the required values required to perform the LCOE calculation are listed. The corresponding references are also listed along with the chapter where the costs or parameters are discussed.

Table 12: Summary of the input data for the LCOE calculation

CAPEX	Electrolysis	Methanation	Unit	Reference	Chapter
Electrolyzer	2000		[CHF/kW]	[4]	4.2.3
Methanisation		482	[CHF/kW]	[15]	4.3
Tank	990		[CHF/kg]	[13]	4.2.3
Stack replacement	1200		[CHF/kW]	[26]	4.2
Delivery & construction, % of CAPEX electrolyzer & methanation	10	10	[%]	[4]	4.2.3
Oxygen & heat recovery		54'230	[CHF]	[15]	4.3
OPEX (Operation and maintenance)					
Maintenance, % of CAPEX electrolyzer & methanation	4	4	[%]	[4]	4.2.3
Electricity, wholesale price 2013 mean 44.73 EUR/MWh			[EUR/MWh per 15 min]	[data from ewz]	4.4.4.1
Delivery costs hydrogen for mobility scenarios	1		[CHF/kg]	[31]	4.4.4.5
Efficiency and lifetime					
Efficiency	63	80	[%]	[10]	3.5, 4.4.3
Lifetime	20	20	[year]	assumed	4.4.3
Stack lifetime	63000		[h]	[26]	4.2.2, 4.4.3

4.4.5.2 Tank dimensioning

In order to determine the expenditures for the tank system the tank size has to be known. For that reason, a simple emptying algorithm was written. The tank will be emptied 3 times a week always on Monday, Wednesday and Friday at 7 am.

The assumption is made that the hydrogen will be stored in tanks compressed up to 200 bar before being fed into the gas pipeline, delivered by truck or directed to the methanation step. In order to calculate the needed tank size, Eq. 4-5 for the real gas was applied to calculate the specific volume of 0.063816 m³/kg.

$$p * v = Z * R_i * T \quad \text{Eq. 4-5}$$

The produced hydrogen has been calculated in kg and the specific volume in m³/kg of the volume of the gas. Table 13 lists the parameters of the Eq. 4-5 and indicates the used values as well as the references.

Table 13: Parameters used for the real gas equation

Parameter	Unit	Value	Reference
p = Pressure	[Pascal]	200 * 10 ⁵	-
v = specific volume	[m ³ /kg]	0.063816 (calculated value)	-
Z = compressibility factor	[-]	1.133 @ 200 bar, 273.15 K	[33]
R _i = particular gas constant	[J/kg * K]	4124.11	[34]
T = temperature	[K]	273.15	-

4.4.5.3 Economic value analysis

The PtG system has different value sources described in chapter 4.4.5.4. Depending upon the scenarios, the economic value is equal to the aggregate of all the applicable value sources. The concept of the Levelized value of energy (LVOE) has been adopted in order to levelize the values. The calculation of the LVOE is similar to the LCOE and is calculated as follows according to [16]. Some given values are already levelized and can be applied directly.

$$LVOE = \frac{\sum_t^n \frac{Revenue_t}{(1+q)^t}}{\sum_t^n \frac{E_t}{(1+q)^t}} \quad \text{Eq. 4-6}$$

LVOE	Levelized value of energy in CHF/MWh	t	Year of lifetime (1,2,3...n)
Revenue	Total revenue in the perspective year in CHF	n	Lifetime of the power plant
E _t	Produced quantity of energy in the respective year in MWh	q	Interest rate in %

In Table 14, all the required values are listed to perform the LVOE calculation. The different value sources will be discussed in the following chapter.

Table 14: 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]
Service 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]

4.4.5.4 Value sources

In total, 6 different value sources have been considered. These sources are:

- Methane
- Hydrogen
- Oxygen
- Heat
- Biogas upgrading service
- Primary control

In the coming sections these sources will be discussed and their values will be defined.

Methane

According to [15], a price ranging from 27 to 35 CHF/MWh for the direct feed-in seems realistic. This price range is in accordance with the wholesale spot market price for the fossil natural gas in Europe for the year 2012. The upper end of 35 CHF/MWh has been applied to this analysis.

Hydrogen

In the scenarios 1 to 3, the produced hydrogen will be sold in the gas sector instead of being fed into the gas grid directly. However, in scenarios 7 to 9, the assumption is made that the hydrogen will find its end consumers in the mobility sector. This distinction has the following ground: the potential selling price of the hydrogen in the mobility sector is significantly higher than the feed-in price since the mobility is related to conventional fuel selling prices. Moreover, it has been also concluded in other studies according to [20] that the most economic use of hydrogen lies in the mobility sector .

The assumption is made that for direct feed-in of the hydrogen demands the same price as the methane. However, according to [15], it can be assumed that the gas grid operator will handle the value of hydrogen differently since it is more expensive to transport hydrogen due to required adjustments in the gas infrastructure. Moreover, hydrogen has a lower energy density than that of methane, and as a result, it requires more space for the same energy value.

In order to define a competitive selling price in the mobility sector, the following approach was taken. First of all, the average price of diesel fuel over the last 22 years has been evaluated (see Figure 21). The mean value of 1.5287 CHF/l has been calculated, which will serve as a diesel market price. Secondly, the assumption is made that a conventional vehicle has a consumption rate of 6 liters per 100 km. The consumption rate of the Toyota Mirai is listed with 0.76 kg per 100 km according to [35]. A moderate approach is used and the consumption rate is set to 1 kg per 100 km in this analysis. With this assumptions a competitive hydrogen selling price has been calculated to be 9.1722 CHF/kg (see Figure 22).

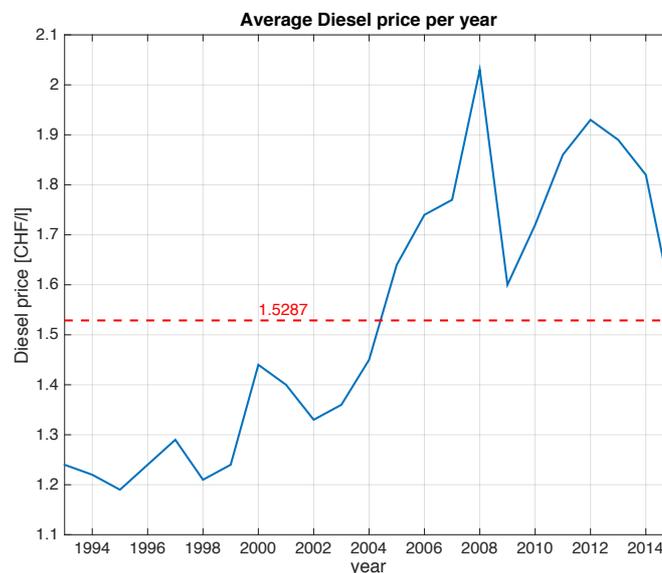


Figure 21: Average diesel market price per year in Switzerland from 1993 to 2015. Data according to [36]

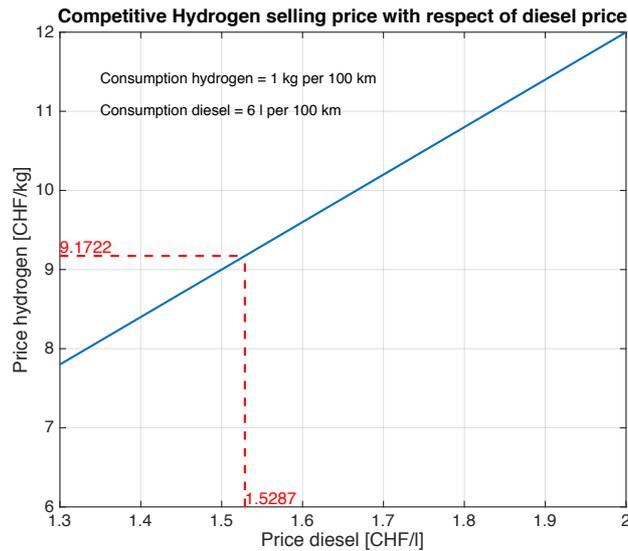


Figure 22: Competitive hydrogen selling price with respect to diesel market price and consumption rates

Oxygen

Oxygen will be considered as a value source for the scenarios containing the methanation step. The reason for this distinction is that this system can be combined with a wastewater treatment plant or a biomass gasification plant allowing to recycle the oxygen on site [37]. Figure 23 and Figure 24 show both concepts, respectively.

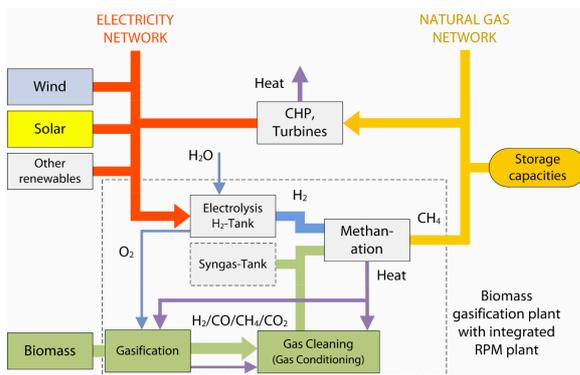


Figure 23: Concept with biomass gasification plant [37]

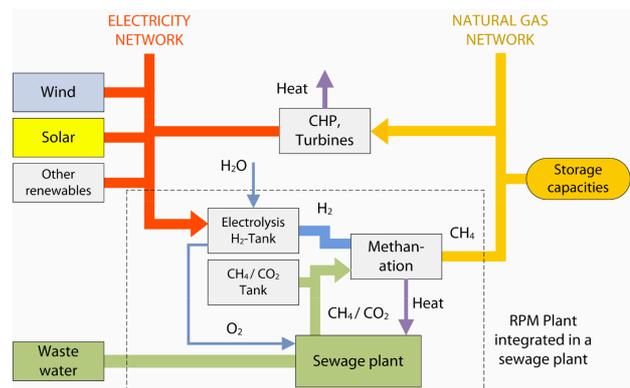


Figure 24: Concept with wastewater treatment plant [37]

According to [15], the price for oxygen ranges between 0.02 CHF/kg and 1.8 CHF/kg. The mean value of 0.1 CHF/kg has been taken for this analysis. The electrolysis produces 8 kg of O₂ per kg H₂ according to [29]. This output rate will be applied to this analysis to calculate the value of the produced O₂.

Heat

Like the case of Oxygen, the produced heat can be used when combined with a wastewater treatment plant or a biogas gasification plant (see Figure 23 and Figure 24). Moreover, the heat could be used in district heating regions but this is not the case of Hüslibachstrasse area.

According to [15], the price for heat ranges between 25 and 37 CHF/kWh. It is an estimated value for the wholesale market. The heating district price in Winterthur amounts to 47.52 CHF/kWh, for example.

The costs for heat and hydrogen recovery are also taken from [15] and amounts to 54'230 CHF.

Biogas upgrading service

Biogas upgrading service can be applied again to the above mentioned concepts. The added value is the saved cost for the biogas upgrading unit, which must be otherwise installed to extract the CO₂ from the biogas before it is fed into the gas grid.

The cost for such upgrading ranges between 30 and 60 CHF/MWh of the upgraded bio methane according to [15]. The mean value of 40 CHF/MWh has been applied to this analysis.

Primary control

First of all, the assumption has been made that the installed PEM electrolyzer fulfills the requirements to participate in the primary control market.

As discussed in chapter 3.8, ancillary service can serve as a value source when the frequency control is provided to the grid. For this analysis, primary control is assumed to be applied to all baseload and partload scenarios whenever no PV excess energy is present. The reason for this assumption is that the electrolyzer can mainly provide negative power reserves, which can be applied when operated with constant and planned power. According to sources from *Elektrizitätswerke des Kantons Zürich (EKZ)*, primary control can be provided on a 4 hour basis. As a result, primary control will be provided from 8 PM until 4 AM for baseload as well as partload operation in Summer. In Winter, primary control will be provided 24 hours a day for the baseload operation and 8 hours in partload from 8 PM until 4 AM. The applied operating modes are listed in Table 15.

Table 15: Time when primary control is provided

Primary control			
Baseload		Partload	
Summer	Winter	Summer	Winter
Provided 8 hours a day from	Provided 24 hours a day	Provided 8 hours a day from	Provided 8 hours a day from

In order to estimate the obtained value through primary control, the following procedure was applied. According to [38], a minimum of +/- 1 MW power has to be provided to be qualified to participate as a single actor in the primary control bid market. When the available power is lower than +/- 1 MW the opportunity exists to join a pooling group. The pooler ensures that the other half of the power is covered by another power plant or similar.

For this analysis, it is assumed that the PtG system offers a power of – 800 kW and the other half is provided by another generating unit. According to the information obtained from different poolers including EKZ and Swisscom Energy Solutions AG, the estimated revenue for the plant operator ranges between 50 and 90%, and the other part goes to the pooler. For this analysis, the lower end is adopted. Moreover, it is assumed that a bid winning chance of the bidding process is 80%.

In order to calculate the revenue from primary control, the data of the weekly average price per MWh from Swissgrid will be used. Figure 25 shows the price for the year of 2013.

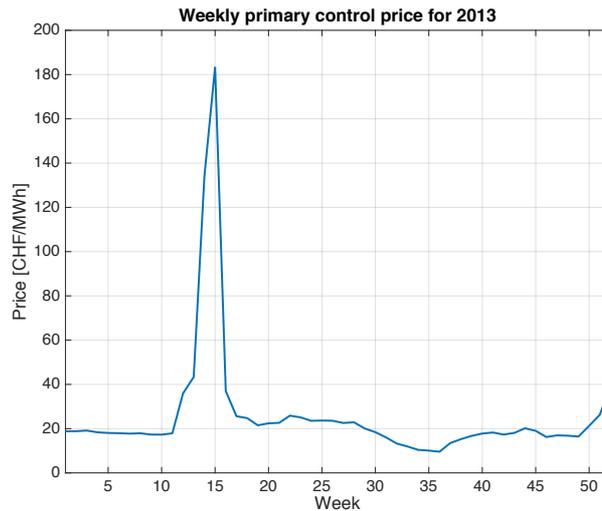


Figure 25: Weekly primary control price for 2013. Data from Swissgrid

With the above outlined assumptions and parameters, the revenue from primary control is calculated as follows with equation Eq. 4-7:

$$Revenue = R_W * P * h_w * x * R_S \quad \text{Eq. 4-7}$$

R_W Possible revenue per week in MWh/CHF
 P Provided power
 h_w Provided hours per week
 x Winning change
 R_S Share of revenue

Table 16: Yearly earning of primary control service

Yearly earning of primary control service	
Baseload	Partload
43'395 CHF	23'945 CHF

The yearly earning for baseload and partload are listed in Table 16.

4.4.5.5 Profitability analysis

The profitability is defined as a difference between the LCOE and LVOE and is calculated with Eq. 4-8. As long as the profitability is above zero the project is profitable.

$$Profitability = LVOE - LCOE \quad \text{Eq. 4-8}$$

4.4.5.6 Sensitivity analysis

As mentioned earlier, the valuation is strongly depended on the taken assumptions. Therefore, a sensitivity analysis is performed for the most influential variables. The variables will be decreased or increased by 30% of its value. Following variables will be analyzed:

CAPEX electrolyzer

The CAPEX of the electrolyzer is by far the highest cost driver over the aggregated investment cost. Moreover, it can be assumed that the price has the potential of decreasing in the coming years as predicted by the industry experts and stated in chapter 4.2.3.

Electricity price

The electricity price is the highest cost driver when it comes to the annual operational expenses. Furthermore, it is difficult to predict how the price will develop in the future, making it necessary to evaluate the PtG system with different electricity prices. It can be assumed that the price will become more and more volatile with the integration of renewable energy due to its intermittent nature.

Operating hours

The amount of hours during which the plant is operated over the year directly influences the output rate of the plant as well as the LCOE. More operating hours seem to imply a reduction of the LCOE since the expenses can be divided by a higher yearly energy amount. However, with higher operating hours can also imply increase of the expenses for the additional energy. This context shows that an economic optimum with regard of the operating hours is dependent on the electricity price as well. With high volatility in electricity price, it may require strategies to avoid purchasing the electricity during high price times.

Operating hours with regard of stack lifetime

The sensitivity analysis concerning the operating hours described above does not consider that a reduction or increase of the operating hours may effect the required number off stack replacements over the whole lifecycle of the power plant. For that reason, the resulting operating hours will be compared with the stack lifetime and if necessary the number of stacks over a lifetime will be adjusted accordingly. For example, if a decrease of the operating hours of 30% leads to a reduction of the number of stack replacements, the costs for one stack will be subtracted in the result. However, if the goal is to assess the influence of the operating hours exclusively, the above mentioned approach is essential.

5 Results of the analysis

In this chapter, the results of all the scenarios are presented and discussed.

5.1 Scenario 1

5.1.1 LCOE

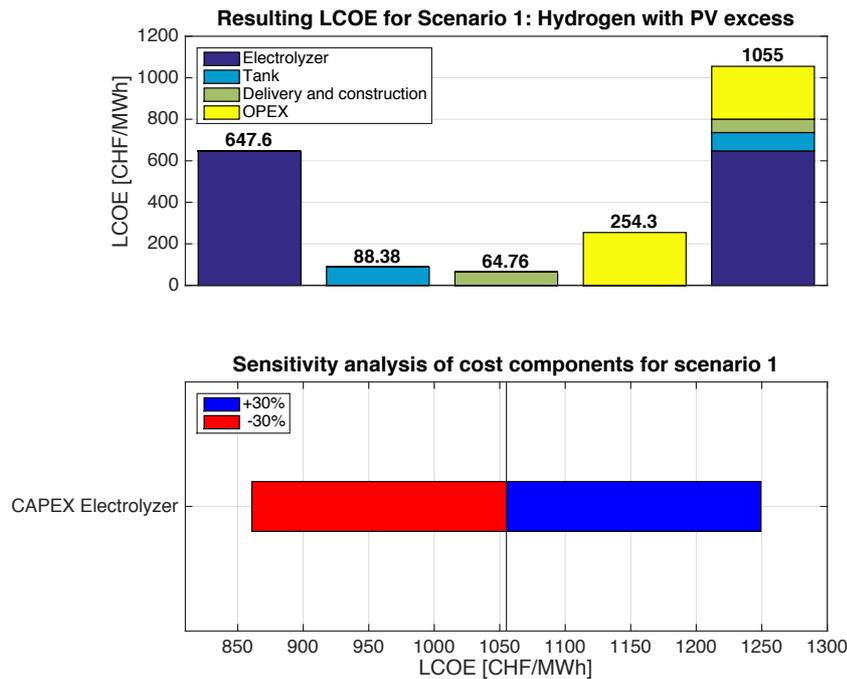


Figure 26: Resulting LCOE and sensitivity analysis of scenario 1

From Figure 26 the following conclusions are drawn regarding the resulting LCOE of scenario 1:

LCOE

The CAPEX of the electrolyzer is the main cost driver of the resulting LCOE. It makes up more than the half of total cost. The main reason for this is the relatively high price of the electrolyzer. Moreover, the low capacity of the electrolyzer, running with 499 operating hours at nominal capacity, results in high LCOE.

The second largest contributor of the total cost is the OPEX with a share of about 20%. The cost for delivery and construction as well as the tank cost contribute only marginally to the LCOE in comparison.

Sensitivity analysis

The sensitivity analysis indicates that even with a 30% reduction of CAPEX, the overall LCOE is still far from any profitability.

5.1.2 LVOE

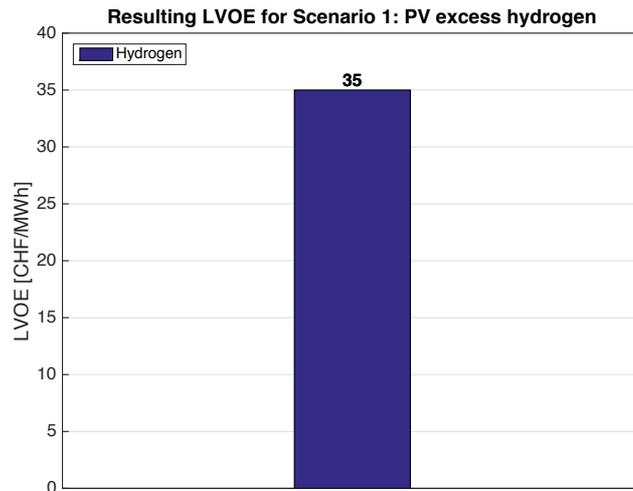


Figure 27: LVOE of scenario 1

Figure 27 shows the resulting LVOE of scenario 1. Hydrogen is the single value source of this scenario, and the LVOE of 35 CHF/MWh displays a hug contrast to the LCOE of 1055 CHF/MWh.

5.2 Scenario 2

5.2.1 LCOE

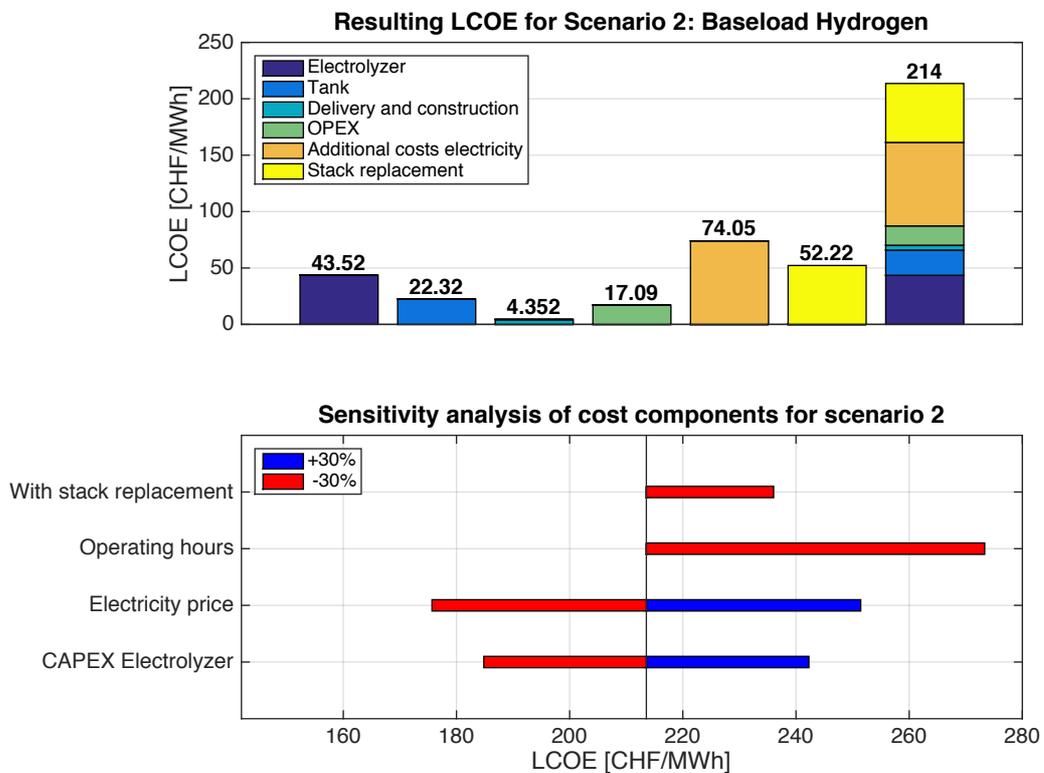


Figure 28: Resulting LCOE and sensitivity analysis for scenario 2

From Figure 28 the following conclusions can be drawn regarding the resulting LCOE of scenario 2:

LCOE

In scenario 2, additional energy has been purchased from the grid. As a result, the overall results have changed significantly in comparison to scenario 1. Due to the increase of the operating hours up to 7340 hours at nominal capacity, the LCOE lost approximately 80% of its value in comparison to scenario 1.

However, the cost for purchasing the electricity results in becoming a leading cost driver. The second highest cost driver is the cost for replacing the stacks. With a total of 175'200 operating hours two stack replacements are necessary as the lifetime of the stack is set to 67'000 hours for the analysis. As a result, the CAPEX of the electrolyzer becomes the third highest cost driver.

Sensitivity analysis

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.

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%. (Compared in Figure 28 the top bar) However, it is still more beneficial to operate the electrolyzer for as long duration as possible to achieve the lowest LCOE.

5.2.2 LVOE

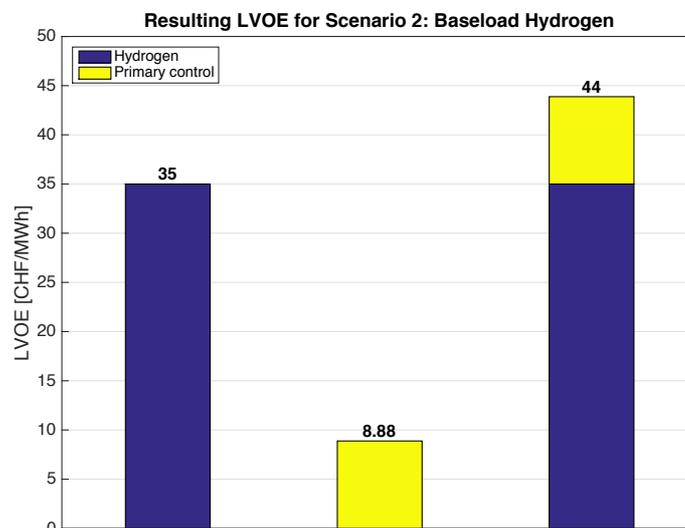
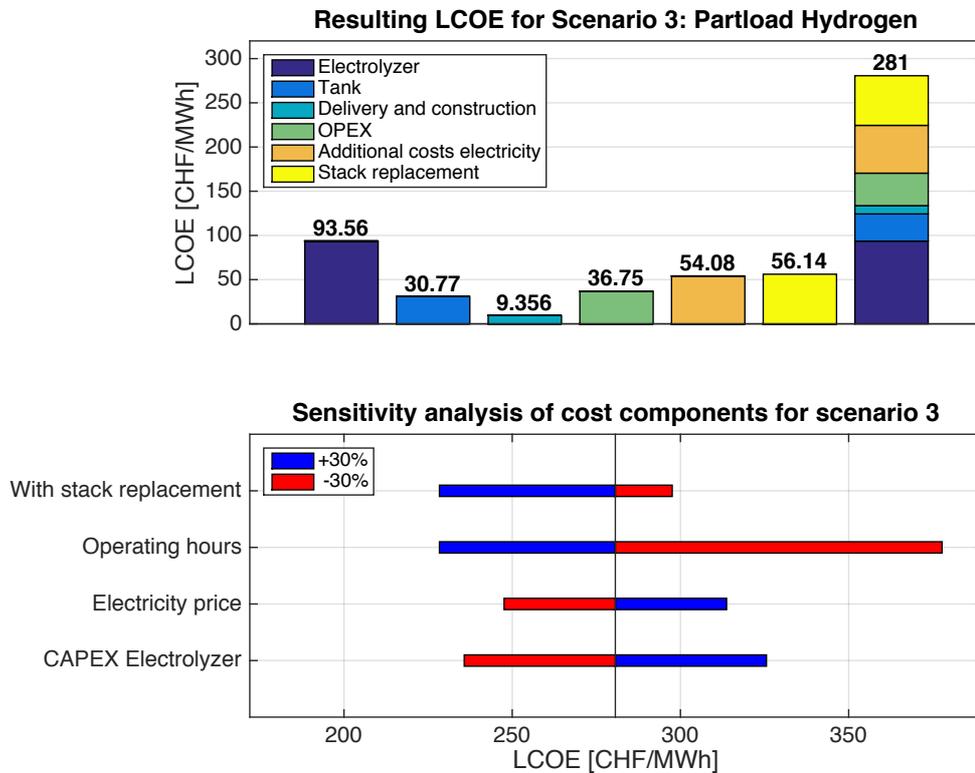


Figure 29: LVOE of scenario 2

Figure 29 shows the resulting LVOE of scenario 2. Besides the value from hydrogen, the primary control provides an additional value source. The value from the primary control amounts to 8.88 MWh/CHF.

5.3 Scenario 3

5.3.1 LCOE



β 30: Resulting LCOE and sensitivity analysis for scenario 3

From β 30 allows the following conclusions are drawn regarding the resulting LCOE of scenario 3:

LCOE

In scenario 3 in partload mode, additional energy has been purchased from the grid with a less extent in comparison to scenario 2. 3456 hours of operation at nominal capacity has been achieved, which is about the half of scenario 2. As a result, the resulting LCOE is increased by 30% in comparison to scenario 2 since less hydrogen has been produced.

In terms of cost leaders, the situation has changed in comparison to the baseload operation. The CAPEX of the electrolyzer is the major cost driver again, followed by the stack replacement cost and the right behind is the cost of the electricity.

Sensitivity analysis

The sensitivity analysis shows that also in partload mode the operating hours have the highest influence upon the LCOE. The second highest influence is the CAPEX of the electrolyzer, followed by the cost of the electricity. This result seems consistent since the cost contribution of the CAPEX and the electricity electricity follow the same order.

Moreover, the analysis shows that the influences of the operating hours with regard of the stack lifetime declines since the stack doesn't have to be replaced if the operating hours are reduced by 30%. (Compared in β 30 the top bar) However, it is still more beneficial to operate the electrolyzer with 3456 hours a year than reducing it by 30%.

5.3.2 LVOE

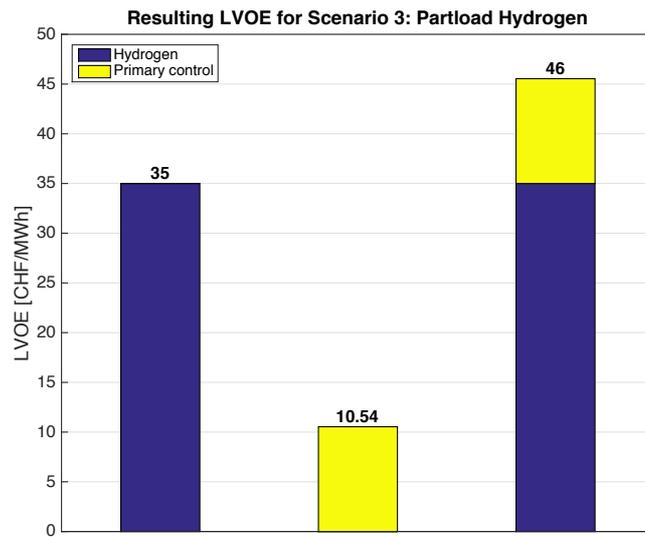


Figure 31: LVOE of scenario 3

As in scenario 2, a second value is added due to the primary control. In this case, it amounts to 10.54 CHF/MWh, which is slightly higher than in scenario 2. This circumstance can be explained with the LVOE Eq. 4-6. The value of the primary control decreases less than the operating hours in comparison with scenario 2. Therefore, the ratio of the value to the produced energy is higher leading to a higher LVOE in scenario 3.

5.4 Scenario 4

5.4.1 LCOE

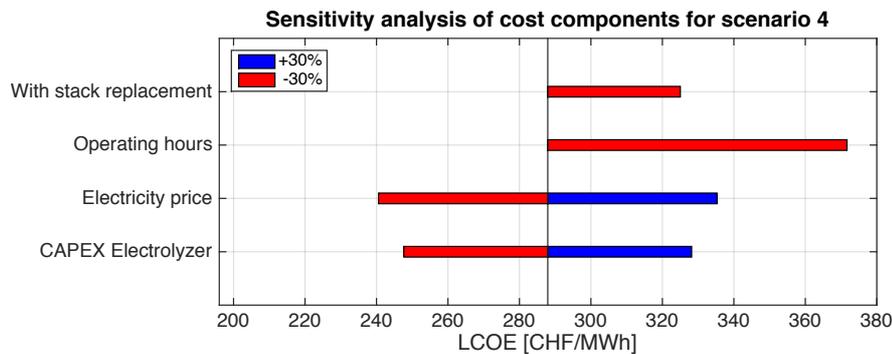
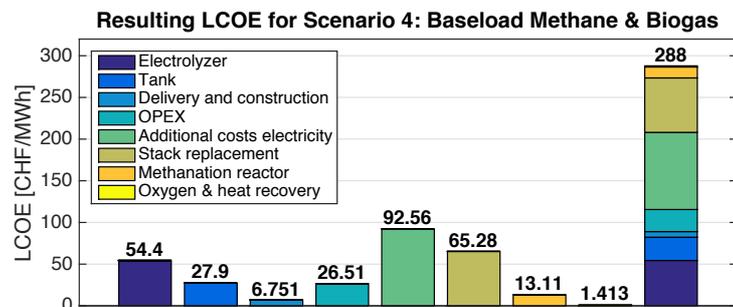


Figure 32: Resulting LCOE and sensitivity analysis for scenario 4

From Figure 32 the following conclusions are drawn regarding the resulting LCOE of scenario 4:

LCOE

In scenario 4, with baseload mode, and methane & biogas, the exact amount of additional energy as in scenario 2 has been purchased from the grid, resulting in 7460 hours of operation at nominal capacity. In addition, a methanation reactor and an oxygen as well as heat recovery system have been installed. The resulting LCOE for the recovery system can be neglected while the cost of the methanation reactor adds only marginally to the overall result. The total LCOE is about 35% higher than when hydrogen is produced because less energy has been produced and the total expenses are higher.

In terms of cost leaders, the cost of the electricity is at top position, followed by the cost for the stack replacement and the CAPEX of the electrolyzer as in scenario 2.

Sensitivity analysis

The sensitivity analysis shows the same results as in scenario 2. The highest influence is the operating hours, followed by the electricity price and the CAPEX of the electrolyzer.

5.4.2 LVOE

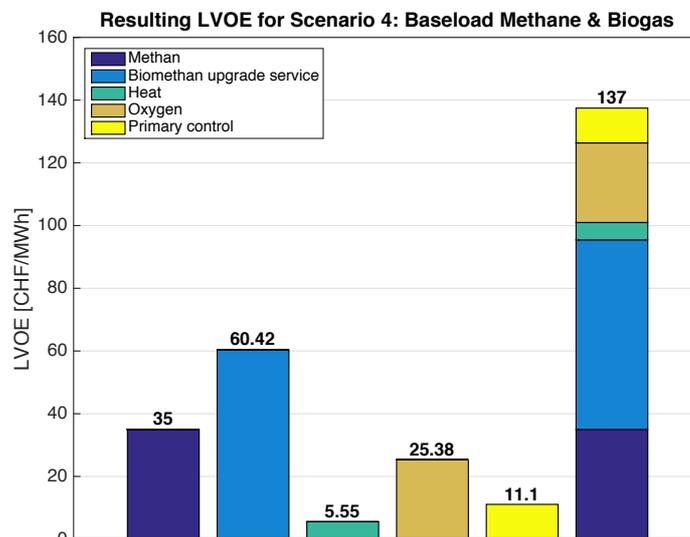


Figure 33: LVOE for scenario 4

From Figure 33 the following conclusions are drawn regarding the resulting LVOE of scenario 4:

In scenario 4, three additional value sources have been added. These values are the biogas upgrading service, heat recovery as well as oxygen recovery. As a result, the highest aggregated LVOE has been achieved so far in this scenario.

The biogas upgrading service adds the most value of 60.42 CHF/MWh, followed by the methane and the oxygen. The added value from the heat plays only a marginal role with 5.55 CHF/MWh while the primary control amounts to 11.1 CHF/MWh.

5.5 Scenario 5

5.5.1 LCOE

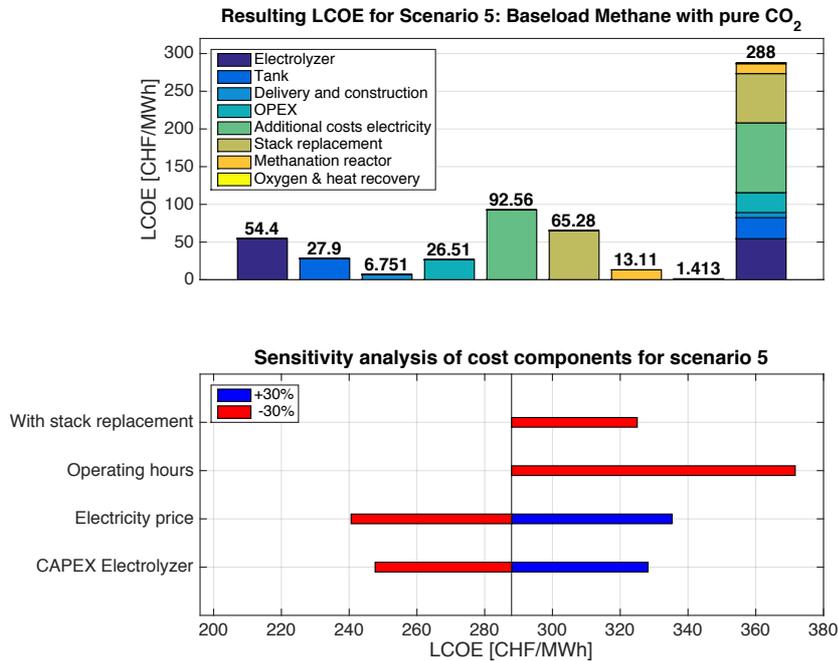


Figure 34: Resulting LCOE and sensitivity analysis for scenario 5

Figure 34 the following conclusions are drawn regarding the resulting LCOE of scenario 5:

LCOE

For scenario 5, in baseload mode, methane with pure CO₂, the exact same results as in scenario 4 are produced because the total expenditures as well as the operating hours stay the same.

Sensitivity analysis

The same applies to the sensitivity analysis. The highest influence is the operating hours, followed by the electricity price and the CAPEX of the electrolyzer.

5.5.2 LVOE

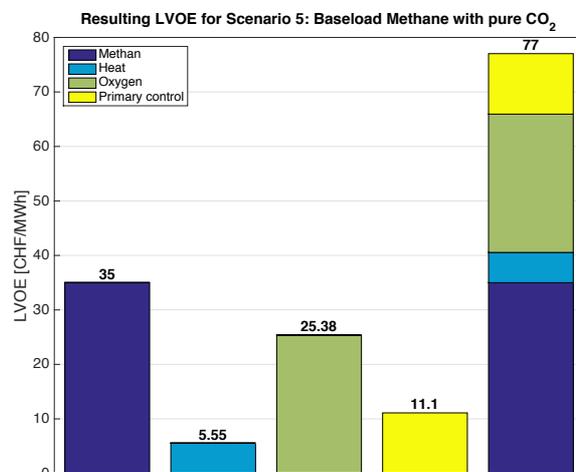


Figure 35: Resulting LVOE for scenario 5

From Figure 35 the following conclusions are drawn regarding the resulting LVOE of scenario 5:

In comparison to scenario 4, the main value driver of the biogas upgrade service is missing as pure CO₂ has been considered in this scenario. Otherwise, the LVOE stays the same.

5.6 Scenario 6

5.6.1 LCOE

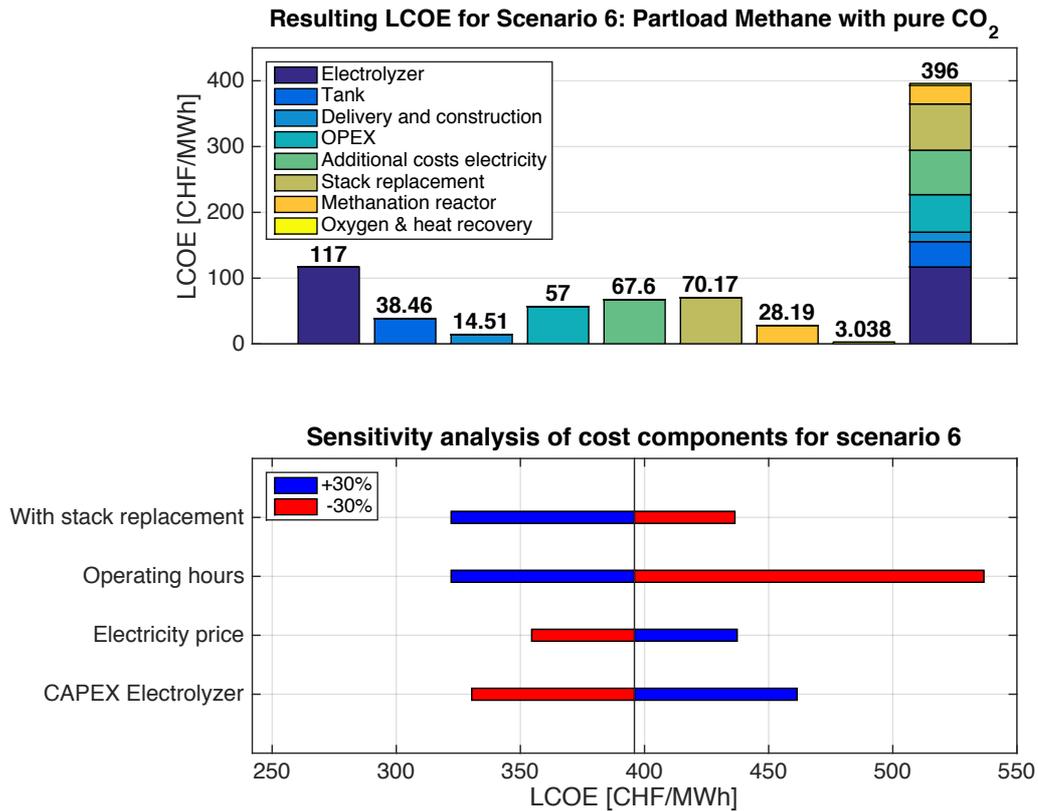


Figure 36: Resulting LCOE and sensitivity analysis for scenario 6

From Figure 36 the following conclusions are drawn regarding the resulting LVOE of scenario 6:

LCOE

In scenario 6, in partload mode, methane with pure CO₂, the exact amount of additional energy as in scenario 3 has been purchased from the grid, resulting in 3456 hours of operation at nominal capacity. Compared with scenario 5 with baseload methane operation, the CAPEX of the electrolyzer is the major cost driver again, followed by the stack replacement cost and the electricity cost. The total LCOE is about 37% higher than when methane is produced in partload. This indicates the importance of running the electrolyzer for as long duration as possible.

Sensitivity analysis

The sensitivity analysis shows the same results as in scenario 3. The highest influence is the operating hours, followed by the CAPEX of the electrolyzer and the electricity price.

5.6.2 LVOE

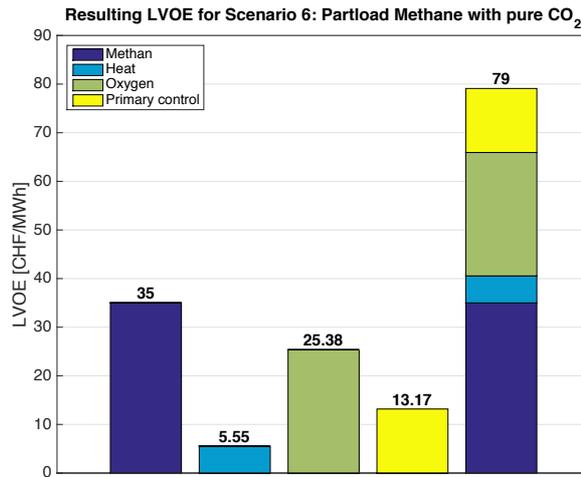


Figure 37: Resulting LVOE for scenario 6

From Figure 37 the following conclusions are drawn regarding the resulting LVOE of scenario 6:

The overall LVOE shows the same results as scenario 5. Only the value from the primary control is 13.17 CHF/MWh, slightly higher than the resulting value in scenario 5 of 11.1 CHF/MWh.

This circumstance can be explained with the LVOE Eq. 4-6. The value of the primary control decreases less than the operating hours in comparison with scenario 5. Therefore, the ratio of the value to the produced energy is higher leading to a higher LVOE in scenario 6.

5.7 Scenario 7

5.7.1 LCOE

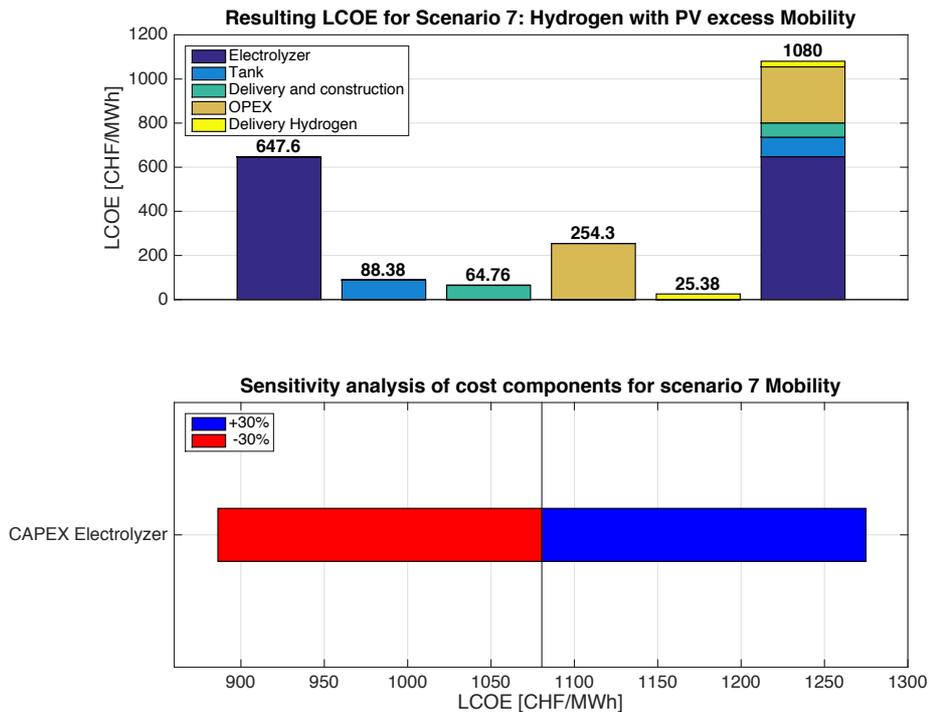


Figure 38: Resulting LCOE and sensitivity analysis for scenario 7

From Figure 38 the following conclusions are drawn regarding the resulting LCOE of scenario 7:

LCOE

In scenario 7, for hydrogen production with PV excess energy, for mobility, additional cost of the hydrogen delivery has been considered because the end consumer of the hydrogen is assumed to be the mobility sector. This cost amounts to 25.38 CHF/MWh. In comparison to the other cost drivers, the delivery cost contributes only marginally to the total LCOE.

Sensitivity analysis

The sensitivity analysis indicates the influence of the CAPEX of the electrolyzer. Even with CAPEX reduction of 30%, the overall LCOE is still far from any profitability.

5.7.2 LVOE

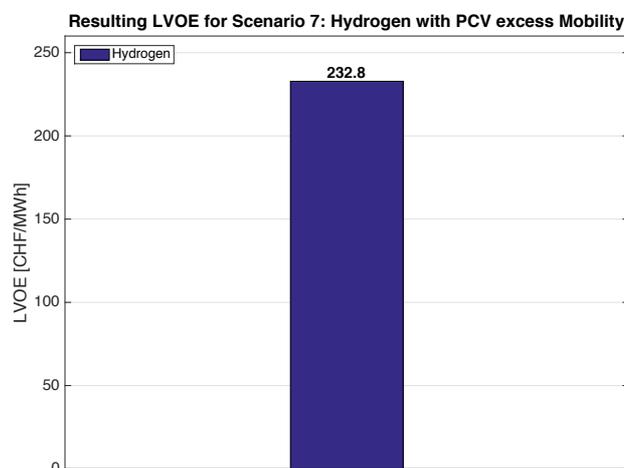


Figure 39: Resulting LVOE for scenario 7

From Figure 39 for the following conclusions are drawn regarding the resulting LVOE of scenario 7:

Unlike the scenarios 1 to 3, the hydrogen is assumed to find its end consumers in the mobility sector. As a result, the LVOE of the hydrogen is increased significantly as the hydrogen selling price is in relation to the diesel market price. However, scenario 7 lies still far from profitability as the LCOE of 1080 CHF/MWh is far greater than the LVOE of 232.8 CHF/MWh.

5.8 Scenario 8

5.8.1 LCOE

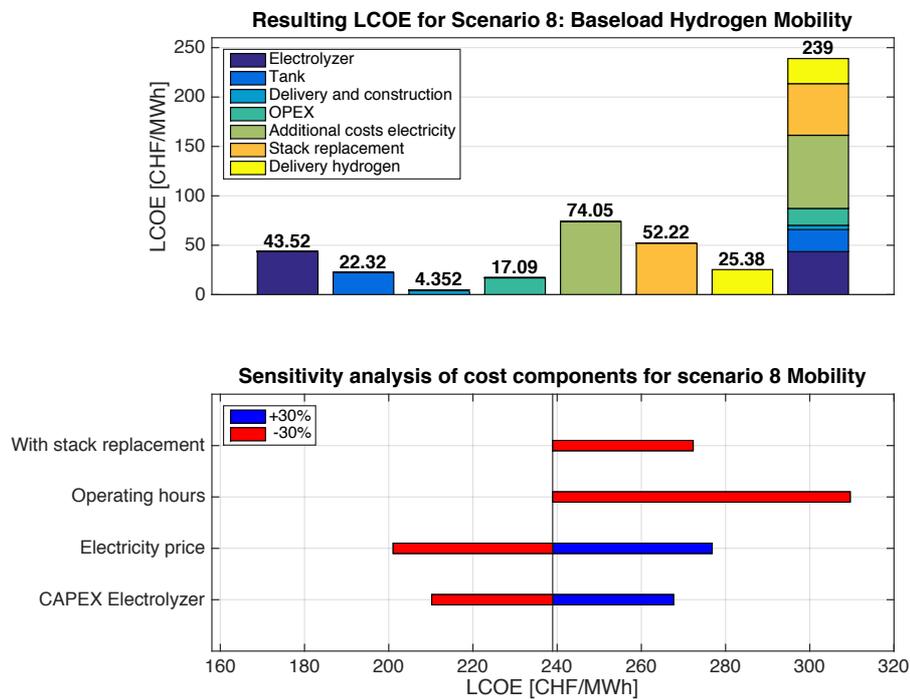


Figure 40: Resulting LCOE and sensitivity analysis of scenario 8

From Figure 40 the following conclusions are drawn regarding the resulting LCOE of scenario 8:

LCOE

In scenario 8, the hydrogen will find its end consumer in the mobility sector like in scenario 7 as well, adding the cost of the hydrogen delivery. This time the electrolyzer was operated in baseload as in scenarios 2, 4, and 5, resulting in 7460 hours of operation at nominal capacity. As a result, the resulting LCOE is basically the same as in scenario 2, and the only difference is the delivery cost. The cost of the electricity is the main cost driver, followed by the stack replacement cost and the CAPEX of the electrolyzer.

Sensitivity analysis

The conclusion of the sensitivity analysis stays the same as in the other baseload scenarios. The operating hours is still the highest influence, followed by the electricity price and the CAPEX of the electrolyzer.

5.8.2 LVOE

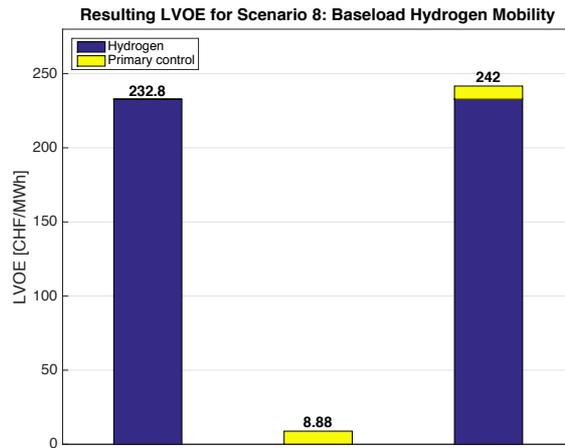


Figure 41: Resulting LVOE of scenario 8

From Figure 41 the following conclusions are drawn regarding the resulting LVOE of scenario 8:

In comparison to scenario 7, the primary control has been provided, adding the value of 8.88 CHF/MWh to the total LVOE. With the assumptions made for the hydrogen selling price based on the diesel market, the LVOE is higher than the LCOE, generating a profitability 2.742 CHF/MWh. This has been achieved by running the electrolyzer in baseload and providing primary control to the grid.

5.9 Scenario 9

5.9.1 LCOE

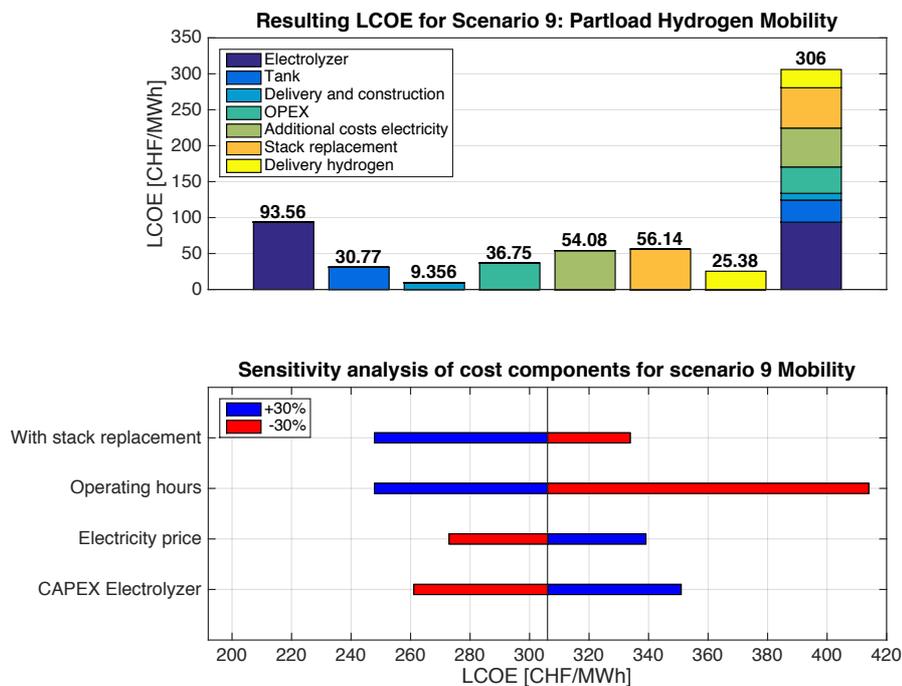


Figure 42: Resulting LCOE and sensitivity analysis of scenario 9

From Figure 42 the following conclusions are drawn regarding the resulting LCOE of scenario 9:

LCOE

In scenario 9, the hydrogen will also find its end consumer in the mobility sector, adding the cost of the hydrogen delivery. This time the electrolyzer was operated in partload mode as in scenarios 3 and 6, resulting in 3456 hours of operation at nominal capacity. As a result, the resulting LCOE is basically the same as in scenario 3, and the only difference is the delivery cost. The CAPEX of the electrolyzer, as in other partload scenarios, is the main cost driver, followed by the stack replacement cost and the cost of the additional energy.

Sensitivity analysis

The conclusion of the sensitivity analysis stays the same as in the other partload scenarios. The operating hours is still the highest influence, followed by the CAPEX of the electrolyzer and the electricity price.

5.9.2 LVOE

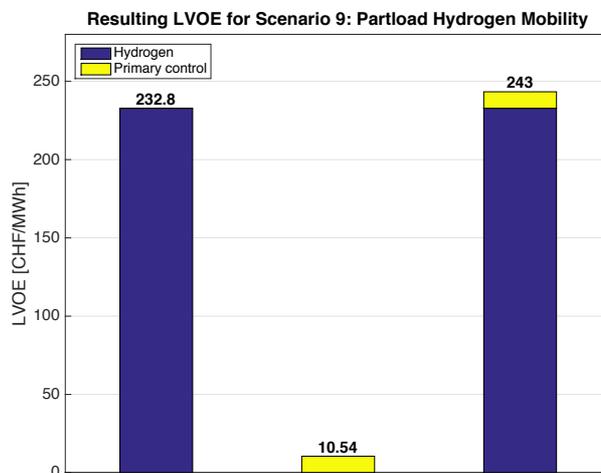


Figure 43: Resulting LVOE of scenario 9

From Figure 43 the following conclusions are drawn regarding the resulting LVOE of scenario 9:

The overall LVOE shows basically the same results as in scenario 8. Only the value of the primary control is 10.54 CHF/MWh, slightly higher than the that in scenario 8 of 8.88 CHF/MWh.

This circumstance can be explained with the LVOE Eq. 4-6. The value of the primary control decreases less than the operating hours in comparison with scenario 8. Therefore, the ratio of the value to the produced energy is higher leading to a higher LVOE in scenario 9.

In contrast to scenario 8, profitability has not been reached since less hydrogen has been produced over the lifetime as a result of the partload operation.

6 Discussion

In this chapter, the results from this BA are summarized and discussed. Lastly an outlook for the future is given.

6.1 Summarized results and discussion

In this chapter, the results of the LCOE, LVOE, and the profitability are summarized and compared with each other.

6.1.1 Summarization of the LCOE by scenario

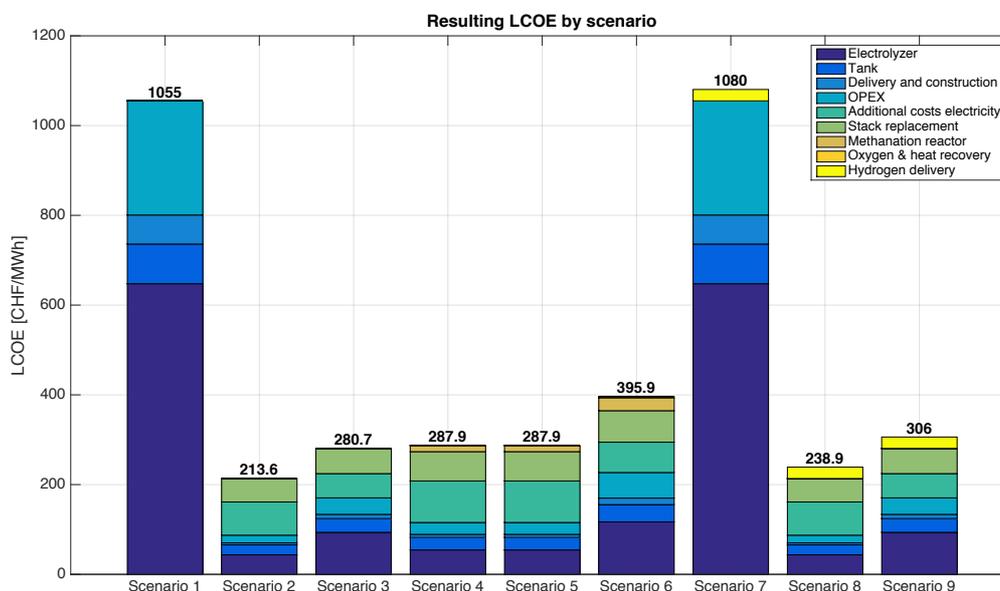


Figure 44: Resulting LCOE by scenario

From Figure 44 the following conclusions can be drawn regarding the resulting LCOE of each scenario:

Operating solely with PV excess energy

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.

Baseload vs. Partload

The baseload operating modes (scenarios 2,4,5, and 8) perform better than the partload operating modes (scenarios 3, 6, and 9). This is due to the fact that the CAPEX can be amortized with higher quantity of product gas over the lifetime, either hydrogen or methane. This shows the relevance of striving for high operating hours of the PtG system.

It has to be noted that this conclusion is only a snapshot based on the current price situation and the assumptions made for the analysis. As discussed in chapter 4.2.3, it can be assumed that the CAPEX can potentially decrease in the coming years when improvement of the electrolyzer manufacturing process will occur. If this is the case, the difference between baseload and partload operating modes will be narrow since the CAPEX has less influence over the LCOE. Moreover, it can be noted that in future the electricity price can potentially increase and also become more volatile due to the integration of renewables. 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.

Hydrogen vs. Methane

The hydrogen production leads to the lowest LCOE over the lifetime of the plant. This is due to the higher production rate of the gas because the methanation step is skipped and the lower CAPEX because no methanation reactor has to be used.

CO₂ form biogas vs. pure CO₂

In this analysis, no cost difference has been applied whether the hydrogen is produced with CO₂ from biogas or CO₂ from a pure source. The result was displayed that the LCOEs for scenarios 4 and 5 are the same. However, this issue warrants further investigation for a more realistic result.

Main cost drivers

In the baseload operation, the main cost driver is the expenses for the additional electricity, followed by the stack replacement cost and the CAPEX of the electrolyzer. In the partload operation, the CAPEX of the electrolyzer takes the leading position of cost driver, followed by the stack replacement costs and the expenses for the additional electricity.

Moreover, it can be concluded that the methanation reactor only marginally contributes to the resulting LCOE. The electrolysis step is by far the most cost intensive part of the PtG system. For all the scenarios, the OPEX seems to play only a marginal role.

6.1.2 Summarization of the LVOE by scenario

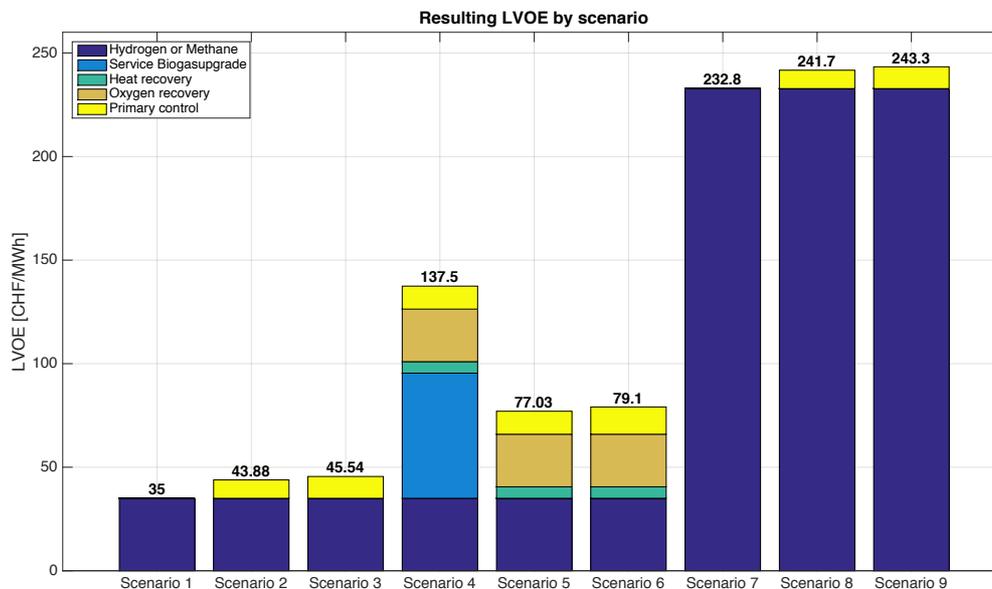


Figure 45: Resulting LCVE by scenario

From Figure 45 the following conclusions can be drawn regarding the resulting LVOE of by scenario:

Direct fed-in to gas pipeline

When the product gas is fed into the gas pipeline (scenarios 1 to 6), scenario 4 generates the the highest value. This is due to the fact that the biogas upgrading service adds a significant value to the LCOE. Moreover, 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 value from the primary control contributes only marginally to the LVOE, and it has to be noted that no expenses for the process or equipment for the primary control qualification have been taken into account.

In conclusion it can be noted that in light of the results from LVOE it is more favorable to produce methane since more possible value sources are available.

CO₂ form biogas vs. pure CO₂

As mentioned above it is more favorable to use CO₂ from a biogas or wastewater treatment plant since more value is added with the biogas upgrading service.

Hydrogen in mobility

When the hydrogen is sold in the mobility sector (scenarios 7 to 9), the LVOE can be increased significantly in comparison to scenarios 1 to 3. This is because the hydrogen selling price is based on the diesel market price. However, this conclusion relies on the assumption that the infrastructure of the hydrogen based mobility sector already exists.

H₂ vs. CH₄

It is difficult to compare these two cases. However, it can be said that for hydrogen production it seems more favorable to look for a business case in the mobility sector since the value of the hydrogen can be set much higher as discussed above. Otherwise, the production of methane seems more favorable because this concept can use synergies with already existing biogas plants generating more value.

6.1.3 Summarization of the profitability by scenario

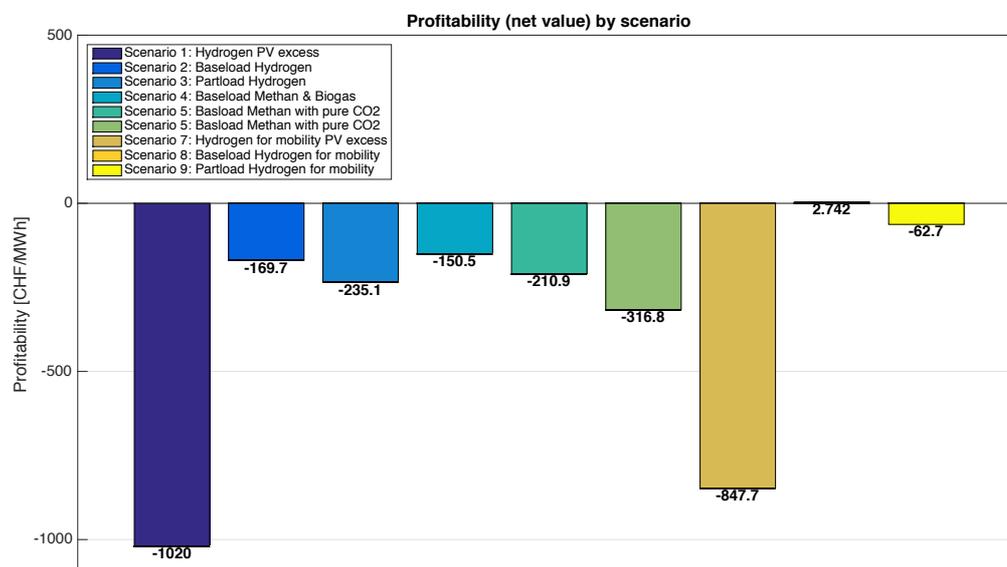


Figure 46: Resulting profitability by scenario

From Figure 46 the following conclusions can be drawn regarding the resulting profitability of by scenario:

Operating solely with PV excess energy

It can be concluded that when operated with PV excess only (scenarios 1 and 7) the PtG system seems far from any chance of profitability. This indicates the importance to strive for high operating hours.

Direct fed-in to gas pipeline

As already mentioned in the previous chapter, if the product gas is intended to be fed into the gas grid it is most favorable to produce methane since more value sources are available. Even though all the scenarios produced the negative profitability, scenario 4 displays the least negativity because the biogas upgrading service adds a significant contribution to the value. However, positive profitability has not been reached in all the scenarios, where the product gas is fed into the gas grid.

Direct fed-in vs. mobility

It can be concluded that more promising option is to find a business case in the mobility sector because the hydrogen can be sold for a much higher value. However, it has to be noted that no hydrogen infrastructure for the mobility sector has been established until now in Switzerland.

6.2 Review of research objectives

In this chapter the research objectives defined in chapter 2.2 are reviewed in order to verify whether the goals have been reached. Some questions are asked to define the objectives. The results and insights of the study are listed directly below the questions.

How economically profitable will be the PtG system under different operating scenarios?

As already outlined in chapter 5, the PtG system is yet far from being economically viable regardless of the operating scenarios.

Which is the most suitable operating scenario?

If the product gas is fed directly into the gas grid, scenario 4 achieves the least negative profitability. In this scenario the PtG system is coupled with a biogas plant or a waste water treatment plant. Consequently, the CO₂ 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. Thus, the avoided costs result in an additional value for the PtG system. 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. It should be noted that this results are based on the assumption regarding the hydrogen selling price. This assumption may vary and put the results on an uncertain ground depending on the hydrogen selling price.

What are the most influential cost drivers?

The most influential cost drivers are 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.

What value sources are available and what measures have to be taken to make the PtG most profitable?

It can be noted that a Power-to-Gas 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 product 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 profitable. As mentioned above, such synergies can be a waste water treatment plant. Other synergies such as heat district grid or waste incineration plants could also contribute to a more profitable operation of the plant.

In conclusion, the author would like to state that the research objectives of this study have been reached. The produced results are based on relatively high amount of parameters, which were obtained through exhaustive research effort. However, the results must be reviewed with a consideration that a certain degree of uncertainty over the parameters still remain, which can influence the results more or less.

6.3 Outlook

The results of this study show that PtG technology is yet far from being economically viable. It was discovered that the profitability will be highly affected by the future development in the CAPEX of the electrolyzer, the electricity price as well as the cost situation in the conventional gas or fuel prices.

Especially, the low prices of conventional gas and fuel would make it difficult to find a business case for the PtG system. In addition, in Switzerland, the hydrogen refueling infrastructure has to be established beforehand if the hydrogen shall be used in the mobility sector. All these factors put the profitability of the PtG system on an uncertain ground in the coming years.

However, if a cost reduction of over 50% takes place by 2035, as predicted by the industry experts, the system could reach a state of profitability. In the meantime, the author believes that PtG should be promoted by the policy makers since it has the great potential of contributing to achieving the targets of climate policy.

7 Publications

- Park, Chan; Bigler, Felix; Korba, Petr, *Power-to-Gas concept for integration of increased photovoltaic generation into the distribution grid*, 10th International Renewable Energy Storage Conference (IRES) Peer reviewed.
- Park, Chan; Segundo Sevilla, Felix Rafael; Knazkins, Valerijs; Korba, Petr, *Feasibility Analysis of the Power-to-Gas Concept in the Future Swiss Power System*, CIRED WORKSHOP 2016, June 14-15, Helsinki, Finland 14-15 June. Peer reviewed.
- Segundo Sevilla, Felix Rafael; Park, Chan; Knazkins, Valerijs; Korba, Petr, *Model Predictive Control of Energy Systems with Hybrid Storage*, IEEE PES General Meeting 2016, July 17-21, Boston, MA, USA Peer reviewed.
- Park, Chan; Bigler, Felix; Korba, Petr, *The Utility of Power-to-Gas Concept for Integration of Increased Photovoltaic Generation into the Distribution Grid*, 32nd European Photovoltaic Solar Energy Conference and Exhibition 20-24 June. Peer reviewed.

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