UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master's Thesis

Future Business Cases for Chemical Storage Technologies in Switzerland

Author: Sergey Arzoyan
Supervisor: Prof. Dr. Thomas Justus Schmidt
Co-Supervisor: Dr. Tom Kober

Madrid, July 2017

Official Master's Degree in the Electric Power Industry (MEPI)
Erasmus Mundus Joint Master in Economics and Management of Network Industries (EMIN)

Master's Thesis Presentation Authorization

THE STUDENT:

Sergey Arzoyan

....

THE SUPERVISOR

Prof. Dr. Thomas Justus Schmidt

Signed: .... Date: 30/ 06/ 17

THE CO-SUPERVISOR

Dr. Tom Kober

Signed: .... Date: 30/ 06/ 17

Authorization of the Master's Thesis Coordinator

Dr. Luis Olmos Camacho

Signed.: .... Date: ....../ ....../ ......

UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master's Thesis

Future Business Cases for Chemical Storage Technologies in Switzerland

Author: Sergey Arzoyan
Supervisor: Prof. Dr. Thomas Justus Schmidt
Co-Supervisor: Dr. Tom Kober

Madrid, July 2017

SUMMARY

Ambitious climate targets entitle for smart strategies and innovative technologies in order to decarbonize the electricity generation, transport and heat supply sector during the upcoming decades. Power-to-X (P2G, P2H, P2P) conversion systems can encourage the switch from fossil fuels by providing the possibility to store surplus energy from intermittent sources in the form of hydrogen or synthetic natural gas (SNG).

In this thesis techno-economic optimization tool was developed to asses power-to-X systems which was used in modular, dynamic and scalable models for constituent components. The objective is to carry out the optimization at high temporal resolution for life-cycle systems as well as to optimize plant design and assess the business potential of ESI (100 kW) platform and other future price-taking projects which will ease the modeling and optimization process of P2X.

A P2X facility in Switzerland can function in numerous different configurations depending on technical site-specific and economic circumstances. For the purposes of this study, different operating scenarios have been identified to understand the full range of the technology's value creation potential. As described in detail hereafter, these scenarios represent different combinations of seven main parameters and variables: source of electricity, prices of commodities on the market, investment costs, type of product gas, solar power capacity, and operating mode, annual profit and Equity IRR.

ACKNOWLEDGMENT:

I would first like to thank my thesis supervisors and advisors Prof. Dr. Thomas J. Schmidt, Dr. Tom Kober and Dr. Antriksh Singh. The doors of their offices were always open whenever I ran into a trouble spot or had a question about my research or writing. They consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to acknowledge the experts involved in my daily work in PSI: Mashael Yazdanie, Dr. Evangelos Panos, Kannan Ramachandran, Dr. Martin Densing and Kathrin Volkart. Their highly valuable advices helped me to finish my Master Thesis and I am gratefully indebted for their very valuable comments on this thesis. Also I would like to thank coordinator of EMIN program Luis Olmos for making this lifetime experience possible.

Finally, I must express my very profound and special gratitude to my parents for providing me with immutable support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Without all above mentioned people this page would have been blank

Sergey Arzoyan

Table of Contents

LIST OF FIGURES:

LIST OF TABLES:

1

Introduction

1. INTRODUCTION

1.1 Project Background: Rationale and Goals

In the near future, the increasing share of renewable energy from wind and solar, the phase-out of nuclear energy, and the tendency towards decentralized electricity generation in Switzerland could significantly influence the way electricity is produced, transported, and used in Switzerland. The shift away from an electricity mix dominated by baseload generation to one characterized by the intermittency of wind and solar poses challenges to security of supply and power grid stability. Energy storage is seen as a promising solution to address these issues. Accomplishing the ambition of emission reduction target also requires the decarbonization of other energy sectors than energy supply, specifically heating, transportation, and industry. Methane is emerging as a key energy carrier in these sectors. Apart from natural fossil-based sources, methane can be produced domestically using renewable feedstock.

The goal of this project is to conduct literature and techno-economical review as well as apply tool which will evaluate different business cases and compare them. In this project, future business opportunities of P2X (power-to-x) technologies in Switzerland's energy transition are analyzed (P2X is a chemical conversion of electricity in to other forms of energy). In P2G (power-to-gas) technology, electricity is converted to hydrogen (power-to-hydrogen, P2H) or methane (power-to-methane, P2M) for direct injection and storage in the existing natural gas grid. Moreover, in order to convert and store energy, the P2G process generates heat and oxygen as by-products and is sufficiently flexible to provide ancillary services (frequency regulation) to the power grid with the help of P2P (power-to-power) when electricity is fed back into the network. Some P2G technologies are able to provide biogas upgrading as a service, thus replacing conventional upgrading techniques. From an energy storage standpoint, the technology's key distinguishing factor from storage is the conversion of electrical energy to chemical energy and vice-versa. This allows P2G to use the existing natural gas grid as storage infrastructure, which enables several benefits not shared by conventional energy storage technologies, including an immense storage capacity and the capability to transmit energy geographically using the existing gas pipelines. Furthermore, P2G can create one or/and bi-directional link between the power and gas sectors as well as transport sector, increasing the flexibility with which these energy systems can be managed and promoting the merging of different energy sectors.

The goal of this project is to conduct literature and techno-economical review as well as apply tool which will evaluate and compare different business cases of P2X and different

1.2 Highlights

- Comparing analysis of different P2X technologies under different use cases
- Economics of ‘power to gas’ integration into the local energy system.
- Analysis of the utilization of surplus electricity from renewable sources.
- Storage used for optimizing the operational costs of the electricity system.
- Capturing of sector coupling options

1.3 Literature review

In recent years energy storage topic have been widely analyzed and studied. There were published numerous papers, journal articles, reports and books regarding this subject. The main focus of those papers is technological, economical and environment analysis of P2G. Also, it is worth to mention that I worked in close collaboration with Technology Assessment Group (TAG) in PSI, who kindly provided me with all necessary literature

Zakeri and Syri (2015) critically examine the existing literature in the analysis of life cycle costs of utility-scale electricity storage systems, providing an updated database for the cost elements [1]. The results reveal that the cost estimations/projections of the Energy Enhancement Systems (EES) are rather dispersed and inconsistent among different references. CAES has the highest costs for PCS (845 €/kW) while NiCd batteries offer the minimum power interface costs (240 €/kW). However, electrochemical batteries show higher costs for storage compartment (up to 800 €/kWh for Li-ion. The Total Capital Cost (TCC) of hydrogen-based systems indicate a large difference between gas turbine (1570 €/kW) and fuel cell systems (3240 €/kW). To conclude, P2X technologies have lowest costs of storage, 4 €/kWh (Zakeri *et al.*, 1997).

Guandalini et al. (2015) analyze the potential of a grid balancing system based on different combinations of traditional gas turbine based power plants with innovative power-to-gas plants [2]. Different economic scenarios are assessed in this work, leading to identification of optimal sizes of the proposed system. Finally, an aspect which favors the power-to-gas technology is the environmental impact: electrolysis based systems lead to a neutral balance of CO2 emissions, whereas the gas turbines add significant emissions (about 500–1000 ktonCO2/year for 16 GW wind power generation capacity). In conclusion, this study shows that reasonable conditions exist in which a P2G balancing system can be economically feasible (Guandalini, Campanari and Romano, 2015).

Götz et al. (2016) compare the available electrolysis and methanation technologies with respect to the stringent requirements of the P2G chain such as low CAPEX, high efficiency, and high flexibility [3]. Finally, the whole process chain is discussed. It has been found that for economic feasibility, different business cases such as mobility, balancing services, and CO2 certificates have to be combined (Götz *et al.*, 2016).

Ulleberg et al. (2010) analyze an autonomous wind/hydrogen energy demonstration system located at the island of Utsira in Norway [4]. The main components in the system installed are a wind turbine (600 kW), water electrolyzer (10 Nm3/h), hydrogen gas storage (2400 Nm3, 200 bar), hydrogen engine (55 kW), and a Proton exchange membrane (PEM) fuel cell (10 kW). The system demonstrated that it is possible to supply remote-area communities with wind power using hydrogen as the energy storage medium (Ulleberg, Nakken and Eté, 2010).

Jentsch et al. (2014) use a unit commitment model of Germany in order to investigate the optimal capacity and spatial distribution of P2G plants in a German network with 85 % renewable energy [5]. A simplified representation of the transmission system and a DC approximation approach is used to model the load flow in the system. Results show that P2G in the scenarios analyzed can contribute to the integration of renewable power sources, and thereby the reduction of CO2 emissions. The optimal economic capacity is given to be between 6 and 12 GW and should be located closer to the renewable production in order to reduce power flows and achieve the highest profit (Jentsch, Trost and Sterner, 2014).

In paper by Qadrdan et al. (2015) the potential impact of integrating Great Britain(GB) gas and electricity network operation using power-to-gas systems were investigated. Modelling of the GB gas and electricity networks shows that employing electrolyzers to produce hydrogen and injecting it into the GB gas network (power-to-gas) can significantly reduce wind curtailment during high wind periods [6].It was shown that such a pairing of systems can lead to a significant reduction in operational costs of the GB gas and electricity networks (Qadrdan *et al.*, 2015).

Reiter and Lindorfer (2015) evaluate different CO2 sources concerning their potential utilization within the power-to-gas energy storage technology with regard to capture costs, specific energy requirement and CO2 penalties [7]. The results of a case study of Austria indicate that there is enough CO2 available from point sources to store all of the electricity produced from fluctuating renewable power sources (wind power plants and photovoltaics) via P2G. The qualitative evaluation of CO2 sources in Austria indicates that CO2 from biogas upgrading facilities and the bioethanol plant is best suited for utilization in possible future power-to-gas plants. Due to low capture costs, low CO2 penalties, biogenic origins, and short distances to wind power plants, biogas upgrading facilities and a bioethanol plant were determined to be the CO_2 sources best suited for utilization in novel power-to-gas plants in Austria (Reiter and Lindorfer, 2015).

In conclusion, we can clearly notice a growing body of work on the topic of P2G in recent years. The performance and economic potential of a P2X system is highly influenced by a large number of local exogenous factors. Based on literature review will be characterized P2X technology and identified business cases which use computer-based tool to evaluate business cases for P2X in Switzerland.

2

Energy Storage

2. ENERGY STORAGE

Nowadays, when the renewable energy supply highly depends on solar and wind energy it is extremely crucial to be able to store the energy in surplus production periods. Simultaneously, the ability to match intermittent energy supply with demand, turn out to be enormously problematic. Methods of storing energy can be divided into three categories, within which only two of them are of interest: electricity storage and chemical storage. Mostly used and renowned examples of will be presented in the next sections. The focus will be given to chemical storage.

2.1 Electric energy storage

Capacitors and batteries can be used in order to directly store electric power. When speaking about capacitors, generally it is referred to supercapacitors and ultracapacitors. Capacitors store the energy in electrical charge form at the surface of the electrodes. Charging and discharging time of the capacitors is very high as well as their lifetime is very long while the maintenance is free. Additionally, they have a very high discharge rate, which make them incompatible for long-term energy storage purposes.

Energy is stored in batteries through reversible electochemical reaction. Numerous kinds of batteries exist and currently used, such as: nickel, sodium, lead and lithium based. All of the types of batteries have moderately different features. The common downside of batteries is a limited charge-discharge cycles and lifetime. Batteries and capacitors share common downside in the face of limited overall capacity, as both of these systems are composed of numerous cells. Today, storage of electricity used in small scale in the frequency regulation of the grids and local energy systems. Electricity storage has a potential to be used in peak shaving applications, but the technologies offered today are unable to store energy for long periods (Andresen *et al.*, 2014) (Jentsch, Trost and Sterner, 2014) (Hansen and Nybroe, 2012).

2.2 Chemical storage-power to gas

In an electrochemical process or in combination of electrochemical and chemical processes electric power is used in order to produce synthetic fuel. Feedstock materials that are used have very low energy content, when the end products of it have very high energy content. The reason for it is the energy input in the form of electricity, with certain losses. This method of energy storage is highly attention-grabbing because of its explicit features such as: moderately high energy content (if compared with compressed air and pumped hydro), the possibility of producing carbon-neutral fuel and ability of long-term storage, because of the stability in chemical medium. The stored energy can be definitely to be used for many purposes, for example in transportation sector, where fossil fuels substitutes are always welcomed ('National Report Denmark 2014').

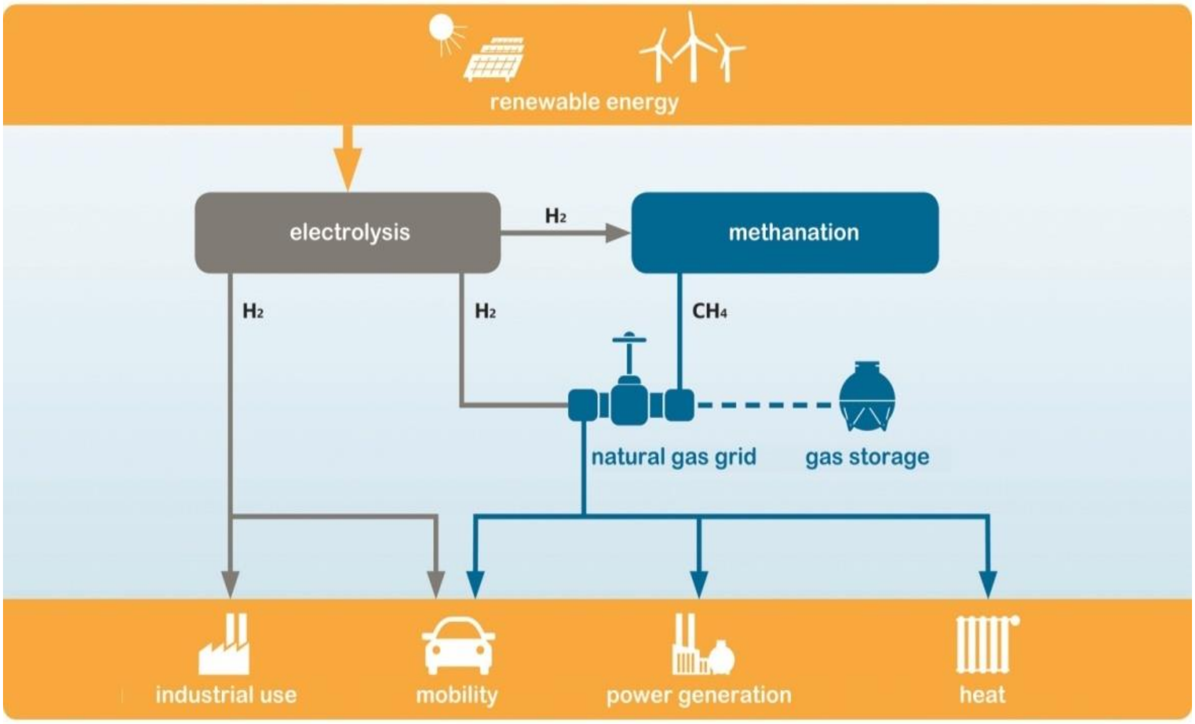

Figure 1 Power-to-X system (Introduction to Power to Gas, 2017)

Power to gas is a technology which converts electric power into chemical energy in gaseous form. Hydrogen and methane are the end products of the process of energy conversion. The produced methane has equal assets with natural gas and is also called *substitute natural gas*. Power to gas technology allows integrate the gas and electric networks. In the case if surplus power from generation is accessible, it might be converted into methane gas and hydrogen and later on be available to store and distribute in the gas network. Oppositely, when occurs electricity deficit, the produced or stored gas can be utilized with purpose of generating electricity in fuel cells or in combustion plants.

2.3 Gas storage

During periods of low demand natural gas can be stored in gas storages and be withdrawn from them in periods of high demand. There are several of ways of storing gas such as: Depleted Natural Gas or Oil Fields, Aquifer reservoir, Salt Caverns, LNG and Gasholders. Moreover, it is possible to store gas in the short term in gas pipeline system. In this study only Gasholders and pipeline capacity method is in of our interest, which are the most commonly used with power-to-gas technology.

3

Power-to-X products

3. POWER TO X PRODUCTS

3.1 Hydrogen fuel

3.1.1 Hydrogen fuel

In the periodic table hydrogen is the first element. Gaseous H2 in small concentrations can be found in the atmosphere. Nevertheless, in order to use H2 in industrial purposes, it should be produced from raw materials such as water or natural gas. Hydrogen is considering being an energy carrier like electricity, but not a definite energy source like natural gas. The energy density of H2 is not principally high, but its lower heating value (120 MJ/kg) is higher than that of natural gas(50.1 MJ/kg), due to hydrogen molecule's very light weight (Hendriksen and Energikonvertering)

3.1.2 Hydrogen applications

Today hydrogen is largely used in the chemical industry. As many other products, hydrogen is used to produce methanol and ammonia (Clerens et al)

Power and heat in a fuel cell or in a gas combustion engine can be produced from the chemical potential energy of hydrogen. When burned with oxygen, the process of combustion produces water vapor, which is not an emission. Thus, hydrogen is considered to be low emission and a zero-carbon fuel when it is burned in a gas engine. Usually, hydrogen is burned in combustion engine in a gas mixture with natural gas.

In equation 1.1 is described the combustion reaction of hydrogen

1.1 $$H_2 + ½\, O_2 \rightarrow H_2O + energy$$

In equations 1.2-1.4 is shown reduction and oxidation reactions in a fuel cell. Because of the exchange of electrons e- electric current is created. Additionally, heat is also released.

1.2-1.4
$$Anode:\ H_2 \rightarrow 2H^+ + 2\,e^-$$
$$Cathode:\ O_2 + 4\,e^- \rightarrow 2\,O^{-2}$$
$$Chemical:\ 2H^+ + O^{-2} \rightarrow H_2O$$

Already for many years hydrogen was seen as a way to make a breakthrough in mobility, specifically as a fuel for fuel cell vehicles. In recent years numerous of experimental projects were carried out and a vast infrastructure was developed (Sterner, Institut für Solare Energieversorgungstechnik. and Institut für Elektrische Energietechnik Rationelle Energiewandlung., 2009).

The second highly important process chain in power-to-gas is the possibility to use hydrogen in the process of methanation. Hydrogen is combined with carbon source in the methanation process to form methane. This process is presented in detail in section 4.5. Hereby, synthetic natural gas produced in this was can be used in standard natural gas applications without any modifications, when in the case of hydrogen there may arise many associated problems in this process.

3.1.3 Hydrogen storage

Normally, hydrogen is stored in high pressure cylinders, which high pressures provide better energy content by volume, but cause losses in efficiency, since compression energy is needed. Currently, underground long-term storage caverns are under research, but no projects have been realized by this time. The primary method of distribution is the gaseous form through the natural gas grid, as regards to power-to-gas concept. In local natural grids the maximum concentration of hydrogen that has been tested so far is 20% (Ameland and GRHYD) (Sterner, Institut für Solare Energieversorgungstechnik. and Institut für Elektrische Energietechnik Rationelle Energiewandlung., 2009) (De Joode *et al.*, 2014).

Hydrogen links with metals to form a solid hydride and the hydrogen is discharged by adding heat to the storage system. The most used medium in solid state charge are a magnesium hydride (MgH2). When hydrogen is stored in a solid state it eliminates the problems and safety issues of pressed gas, nevertheless various issues still exist. For example, challenges connected to maintaining required temperatures occurred and additionally storage systems are also pretty massive. In order to store 3 kg hydrogen a system of 215 kg is required, when the same amount of hydrogen can be stored in a pressure tank of 350 bars, and will require only a system of 45 kg. (Mohseni, Gorling and Alvfors, 2013)

3.2 Synthetic Natural Gas & heat

3.2.1 Synthetic Gas

In order to create Synthetic natural gas, thermo-chemical conversion is required. The first step in conversion is the gasification of solid carbon source (it can be coal or biomass) with steam or oxygen: equation 1.5 Secondly, the coal is burned with limited deliver oxygen and here the important input is carbon dioxide.

1.5 $$2C + O_2 \rightarrow 2CO$$

With the purposes of reducing amount of nitrogen in the gas, pure oxygen is used in combustion. When adding pure oxygen

With SNG, which can be served as fuel, also the heat from electrolyzer can be used for district heating and industrial process steam. The opportunity to sell surplus heat can further benefit to power-to-gas applications

3.2.2 SNG applications

SNG can be used in backup, base-load and peak-shaving systems. Nowadays, developing of complex controlling systems provided more safety through the process as well as enhanced gas quality as an outcome. Exists three main strategies of NG applications. First: backing up natural gas interruptions of supply due to accidents or any other kind of difficulties. Additionally, it can help to deal with natural gas supply restrictions in peak hours, for example, because of high pressure drops in old gas pipelines. Moreover, it can overcome the difficulties connected to a shortage of natural gas supply in base-load for a few years, because of natural gas constrains.

Furthermore, P2G process generates heat as by-product and is sufficiently flexible to be regarded as a resource to be used in local household heating systems(Costa *et al.*, 2015).

3.2.3 Gas & heat storage

We already spoke about Gas Storages in section 3.3

Thermal energy storage (TES) includes numerous different technologies. Using chemical reactions, thermal energy is stored from -40 °C to 400 °C as sensible heat, latent heat and chemical energy. Sensible heat is usually kept in storage tanks with high thermal insulation. Nowadays, the most widely spread commercial heat storage is water, which has many industrial and residential applications. Additionally, underground storage of sensible heat (both liquid and solid media) is also used in large scale applications. Moreover, Phase change materials (PCMs) storage and Thermo-chemical storage (TCS) can provide high storage capacity. Today, TES systems, which are based on sensible heat, are widely available on the market, when TSC and PCM storages are mostly under development (Renewable Energy Agency)

3.3 Power-to-power (P2P)

3.3.1 Power -to-power

In order to get power from power-to-gas system the fuel cell is required. The fuel cell is a tool that generates electrical power, by converting hydrogen into electricity through a chemical reaction. This process can also be called power-to-power (P2P). Additionally, continuous source of hydrogen and oxygen is required in order to run a fuel cell, this can be compared with internal combustion engine, which require continuous flow of diesel or gasoline to operate.

Fuel cell requires three main components to create chemical reactions: anode, cathode and electrolyte. Polymer electrolyte membrane allows ions to pass between cathode and anode. Thus, if electrolyte allows ions to pass freely, it will disrupt the chemical reaction. At the end, hydrogen atoms that are positively charged will react with the oxygen in order to form heat and water while electrical charge is created. In this case if particular amount power is needed, a stack of individual fuel cells can be formed to meet required power demand.

3.3.2 Power-to-power applications

The PHP system can be used in numerous ways. For example, power produced from PHP can be injected in cars, trucks, buses and other power supplied vehicles. Secondly, it can work as a major power supplier of commercial, industrial and residential buildings. The last but not least it can be utilized as a backup power source to vital computer and communications networks (*What is a Hydrogen Fuel Cell and How Does it Work?*)

3.4. Electrolysis

The dominant and lowest cost method to industrially produce hydrogen is the steam reformation uses natural gas as a raw material. The use of renewable power generation as a electricity source and the water as the source of hydrogen designate this process to be a carbon neutral and abolish the need of suing fossil raw material

During the process of electrolysis of water electric power splits water into oxygen and hydrogen, as in following equation 1.6

1.6 $$2\,H_2O(l) + \; energy = 2\,H_2(g) + O_2(g)$$

Nowadays exists three main methods of electrolysis. All of them are working due to the same equation reaction 1.1. In following sections detailed description of each electrolysis method is explained.

3.4.1 Alkaline electrolysis

The most developed and in use technology of electrolysis is alkaline electrolysis (AEL). In AEL, direct is passing between water-based solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and electrodes. In order to separate the hydrogen and oxygen product gases, a membrane is placed between cathode and anode. Hydroxide ion (OH) is passing throughout membrane for transportation the electric charge and closing the circuit. The schema of the alkaline electrolysis is presented in figure 1:

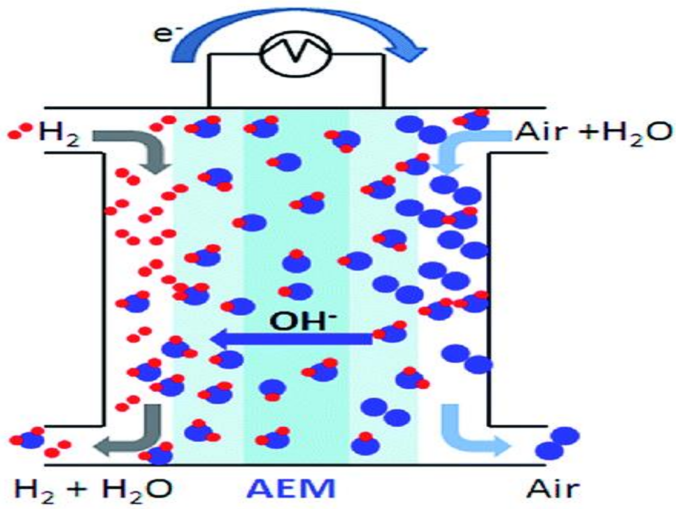

Figure 2 . Working principle of alkaline electrolysis **(Varcoe *et al.*, 2014)**

In equations 1.7 and 1.8 are presented the electrochemical reactions taking place in anode and cathode.

1.7; 1.8 $$2\,H_2O + 2e^- \rightarrow H_2 + 2\,OH^-$$

$$2\,OH^- \rightarrow \frac{1}{2}\,O_2 + H_2O + 2\,e^-$$

Lehner et al illustrates the prototypical efficiency of alkaline electrolysis to be 60-80 %. When integrating alkaline electrolysis into power to gas system, long start-up time and incapability to respond to quick variations in electricity supply causes numerous of issues. [18, p 26)

The produced hydrogen normally should be compressed for transportation and grid injection in the case when the electrolyzer is operated in an atmospheric pressure, which causes energy loss corresponding to the compressing work. In order to avoid this, the electrolyzer's settings can be configured to work on a particular level of pressure. Nevertheless, in this case it will result in decreasing the gas quality and electro-chemical efficiency, when the overall efficiency will be augmented because of the lack of the stage of hydrogen compression. (Varcoe *et al.*, 2014)

3.4.2 Proton exchange membrane electrolysis

This type of electrolyzer is also known as polymer electrolyte membrane electrolysis (PEM), which uses solid polymer electrolytes. Proton is the ion that is transported from anode to cathode, which passes through the polymer membrane (electrolyte). The schema of PEM electrolysis is presented in figure 2:

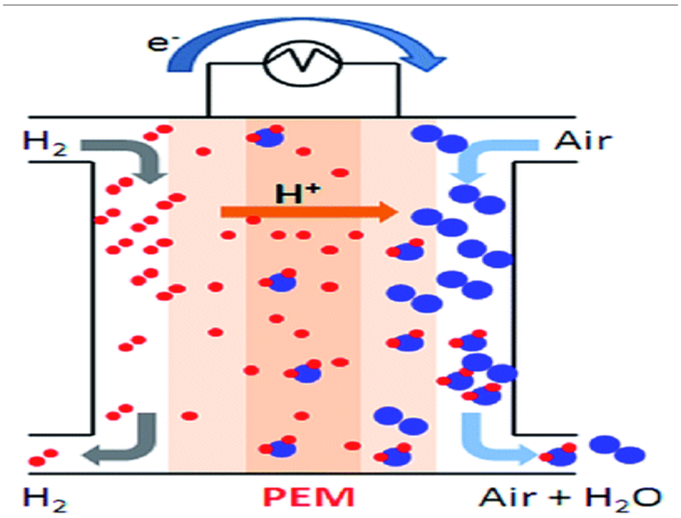

Figure 3 : Working principle of proton exchange membrane electrolysis **(Varcoe *et al.*, 2014)**

In equations 1.9 and 1.10 are presented the electrochemical reactions taking place in anode and cathode.

1.9; 1.10 $$2\,H^{+} + 2\,e^{-} \rightarrow H_2$$

$$H_2O \rightarrow \tfrac{1}{2}O_2 + 2\,H^{+} + 2\,e^{-}$$

The main feature of PEM is its capability to respond to load changes very fast, in the range of hundreds of milliseconds. PEM cells normally operate at pressures from 30-60, but sometimes up to 200 bar, which significally reduces the losses of energy in the process of hydrogen compression. Additionally, the electro-chemical efficiency is 60-70% and the cleanliness of the produced gas is very high (Varcoe *et al.*, 2014)**.**

Obviously PEM technology seems to be a very promising to use with power-to-gas applications, despite there exist some major issues. The cost of materials of PEM cells is significally high and PEM cells are complicated to upscale into large plant sizes. Because of comparatively immature stage of the development of PEM cells and ongoing research, the further improvements of the technology are expected. The improvements will include lower costs, larger sizes and better efficiencies.

3.4.3 Solid oxide electrolysis

Solid oxide electrolysis (SOEC) is the least mature technology existing. Different from other two technologies, in this case the water is in steam form. Oxygen ions take the charge through a solid oxide membrane which is acting as the electrolyte. The schema of SOEC electrolysis is presented in figure 3:

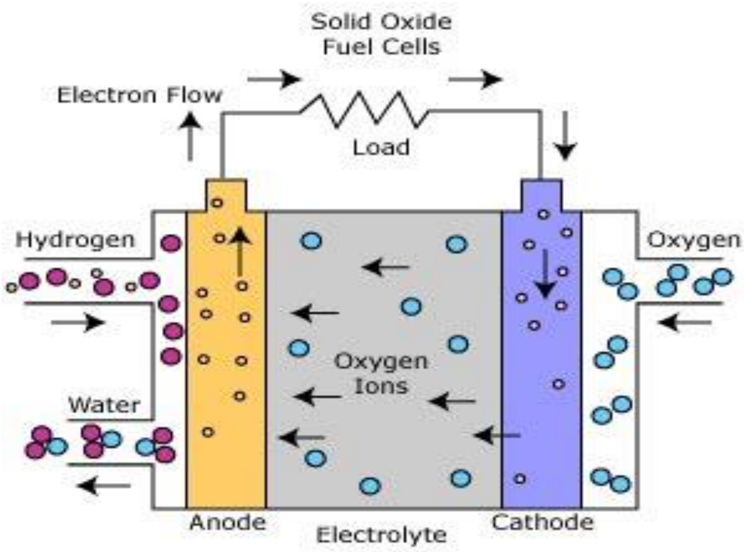

Figure 4: Working principle of Solid oxide electrolysis **(Varcoe *et al.*, 2014)**

In equations 1.11 and 1.12 are presented the electrochemical reactions taking place in anode and cathode

1.11; 1.12 $$H_2O + 2\,e^- \rightarrow H_2 + O^{2-}$$

$$O^{2-} \rightarrow \frac{1}{2}\,O_2 + 2\,e^-$$

The operational temperature of SOEC cells is very high and ranges between 700 to 1000 ° C and normally uses atmospheric pressures. The reported efficiency of this technology is very high and is around 90%. One of the main advantages of SOEC is revered operation mode, when the device functions as a fuel cell. Additionally, with SOEC exists a possibility of dynamic operation when the temperature control is sufficient, if not stability problems with fluctuating electricity resources have been reported (Varcoe *et al.*, 2014). Due to the high operating temperature and a shortage of robust materials SOEC appliances degrade very fast. This is the limit of this technology; once it is solved it will be broadly commercialized (de Boer *et al.*, 2014).

3.5. Methane

In power to gas process the methanation is not a mandatory itself, as the hydrogen to store and distribute energy in gaseous form. Nevertheless, the available applications for synthetic natural gas (SNG) make it an interesting process, despite of the additional loss of efficiency and technical complexity. The process where hydrogen and carbon dioxide react in order to form methane is called Sabatier reaction which is described in the following equation 1.13

1.13 $$CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O \quad \Delta H = -165.0 \text{ kJ/mol}$$

In the Sabatier reaction, hydrogen reacts with carbon dioxide and form intermediate carbon monoxide in an endothermic reaction described in the following equation 1.14

1.14 $$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H = +41.2 \text{ kJ/mol}$$

Consequently, carbon monoxide reacts exothermically with gaseous hydrogen and produces methane in the following equation 1.15

1.15 $$CO + 3\,H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H = -206.2 \text{ kJ/mol}$$

From equations 1.7 and 1.8 and it can be clearly seen that both CO2 and CO can be used as a carbon source in methanation process. In still dominating application of methanation, the carbon is brought into the process from gasification product of coal (de Boer *et al.*, 2014). In the power-to-gas technology the carbon dioxide is an important input of the reaction. Carbon dioxide can be extorted from the atmosphere or from the biogas plant. The atmosphere is the richest source of CO2. The extraction from the atmosphere can make the process to become carbon free, but it needs a considerable amount of energy and significally decreases the efficiency of the process. The use of concentrated CO2 source would increase the efficiency of methanation process itself. Today, biomass and biomass gasification are the most auspicious sources of CO2.

Currently existing methanation methods entail fairly steady inputs of feedstock. Thus, because of intermittent hydrogen output from electrolysis, the intermediate storage of hydrogen is required. In different power to gas concepts, the specifications of the design are very varied. These specifications are intermediate storage of feedstock gases, the quality requirements of the natural gas grid, the peak output of electric power and its fluctuation range as well as the source of CO2. All these specifications limit the scalability and flexibility of power-to-gas concepts. Today, the process of methanation is in experimental phase and is on its early development stage. Current existing projects generally are exhibit plants, which were built in order to gain experience and acquire data for their commercial use in the future (De Joode *et al.*, 2014).

3.5.1 Catalytic methanation

The Sabatier reaction requires high temperatures, elevated temperature and presence of a catalyst. Today the most widely used catalyst in methanation is nickel, when other such as iron and cobalt are under investigation. The catalytic methods that are developed for industrial use typically require steady inputs, which go in discordant with a power-to-gas concept when renewable energy sources of power for P2G are by themselves fluctuating. Thus, this fact situates particular requirements to control the process. The high temperatures that occur during exothermal reactions make it easier to use waste heat in power and steam production in order to improve process efficiency. Chemical efficiency of catalytic methanation can reach up to 78% (Varcoe *et al.*, 2014)**.** Catalytic methanation reactors are divided into three main types: Fixed-bed, Fluidized-bed and Bubble column reactors. Detailed description of these reactors is not of importance in this study.

3.5.2 Biological methanation

Biological methanation involves microorganisms that form methane and chemical catalyst is not needed. Inputs used in this process are carbon dioxide and hydrogen, this reaction is generally equivalent to the Sabatier reaction, the reaction is taking place in anaerobic conditions in an aqueous solution of the cell culture, dissolved gases and maintenance reagents. The operating temperature is about 60-65 °C, when the carbon conversion efficiency is extremely high at up to 98.6% and the process is taking place in typical atmospheric pressure. Of the main advantages of the process, is that it is very responsive to fluctuating inputs in a certain range and is tolerable for impurities. Nevertheless, the drawback is that the speed at which methane is formed is slower than during the catalytic process.

Figure 5: Biological methanation reactor. **(Hafenbradl CTO, 2016)**

In the case if released heat is recovered, power-to-gas efficiency in biological methanation can reach to up to 78%, when without the heat recovery the efficiency is about 58%. There is not much utilization way for the waste heat, because of its relatively low temperature level (Gahleitner, 2013).

Additionally, biological methanation can efficiently be coupled with biogas plant. Here, the anaerobic decomposition of organic material and digestion forms carbon and methane dioxide, thus, the produced gas from digestions contains 50-70% methane and 30-35% carbon dioxide (Gahleitner, 2013).

4

Methodology

4. Methodology

4.1 Methodology background

The Swiss energy system is set to be renovated from now on till the year 2050. The package measures called ''Energy Strategy 2050'' provided by the Swiss federal government provides a guideline to shift away from nuclear power. Additionally the energy consumption is expected to be reduced; new renewable sources should be installed as well as the already existing ones should be utilized more efficiently. With Energy System Integration (ESI) platform, Paul Scherrer Institute offers an experimental platform where promising advances can be tested, taking into account their complex connections and relations.

In fact, the requirement of efficient usage of renewable energy sources poses enormous issues for an energy system. The electrical grid cannot endure big oscillations and thus, should keep in balance of supply and demand. During the night when the sun is not shining and the wind does not blow the renewable energy installations contribute nothing to the energy system. At the same time, on many days when the sun shines to the full extent and wind blows very strongly, the amount of energy generated is immense, and since the electrical grid cannot absorb all supplies, this electricity will be lost.

4.1.1 Storing surplus power

Nowadays, increasing capacity of wind and solar power will not be necessary amount to anything useful, therefore the surplus electricity would go to waste.. The most obvious solution for this, after matching supply to demand, is to store the energy, so that this surplus energy will be possible to be used during the night. Nevertheless, at this point exists one boundary condition: electric power is extremely difficult to store directly and it cannot be stored in long-term as electricity. The power-to gas technology can help resolve this recently not a solvable problem. With the help of P2X electric power can be converted into gases such as hydrogen or methane. These two types of gases themselves are relatively simple to store and reconvert to electricity and inject it back into the electricity system as an electric power. Moreover, these gases can be used as renewable fuels in hydrogen or natural gas powered vehicles or also to serve as raw materials for industry. ESI platform allows investigating in details these storages and the conversion processes of electricity in gaseous form.

4.1.2 ESI Platform

ESI platform is a test platform for research and industry, which is designed for power output of 100 KW and is open for research and industry partners of PSI as an experimental platform. ESI offers the possibility to investigate the technical viability of different methods and processes, consequently new ideas can be tested on a small scale, therefore the future potential of the industry can be explicitly evaluated. The PSI uses ESI platform to broaden its expertise in energy research. Direct expertise is as much in focus as incorporating results in order to develop scenarios for potential future energy systems. IT is believed that ESI platform will help to overcome energy challenges in Switzerland's energy future.

Today, PSI is highly interested in future partnerships with industry where they can use the vast experience of ESI platform. Thanks to the flexible structure of the platform it offers industrial companies an assortment of different possibilities for testing their innovative ideas (*ESI Plattform | Paul Scherrer Institut (PSI)*).

4.1.3 Modeling Objective

The tool that is going to be described called PEStO, which was created by Antriksh Singh. The modeling objective of this tool was to develop techno-economic optimization tool to assess power-to-X (P2X) systems which will be used in modular, dynamic and scalable models for constituent components. Additionally, the objective is the optimization at high temporal resolution for life-cycle of systems as well as to optimize plant design and a assess business potential of ESI-1 (100kW) , ESI-2 (future, MW) and other potential price-taking projects which will ease the modelling and optimization process of P2X. ESI platform is P2X plant located in PSI, Switzerland.

4.1.4 Platform Design

In order to understand how the system works it is necessary two describe the system layout:

The following is the basic ESI platform layout which is located in Paul Scherrer Institute (PSI) (*ESI Plattform | Paul Scherrer Institut (PSI)*)

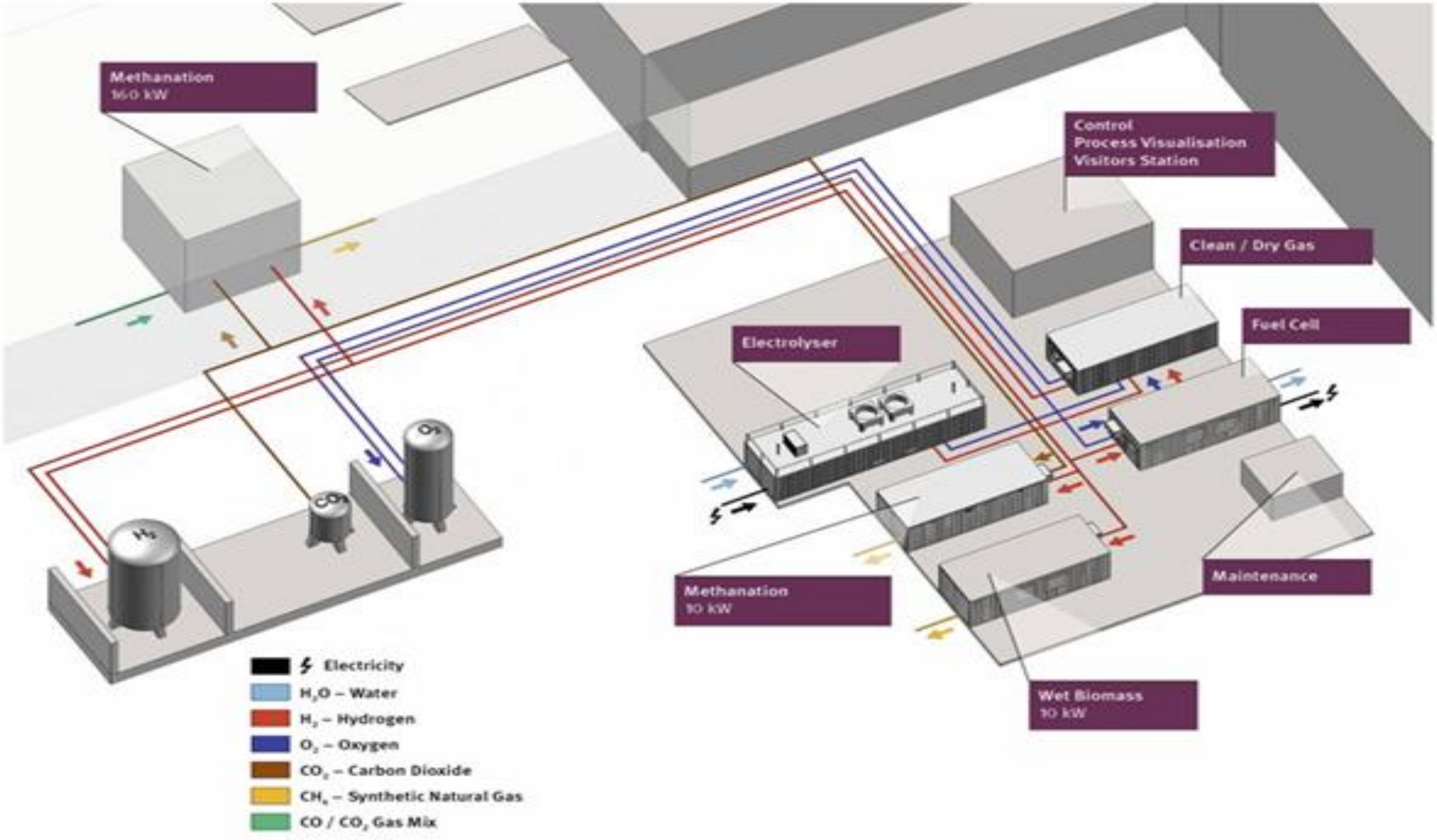

Figure 6: ESI Platform

The following is the schematic layout of Model ESI

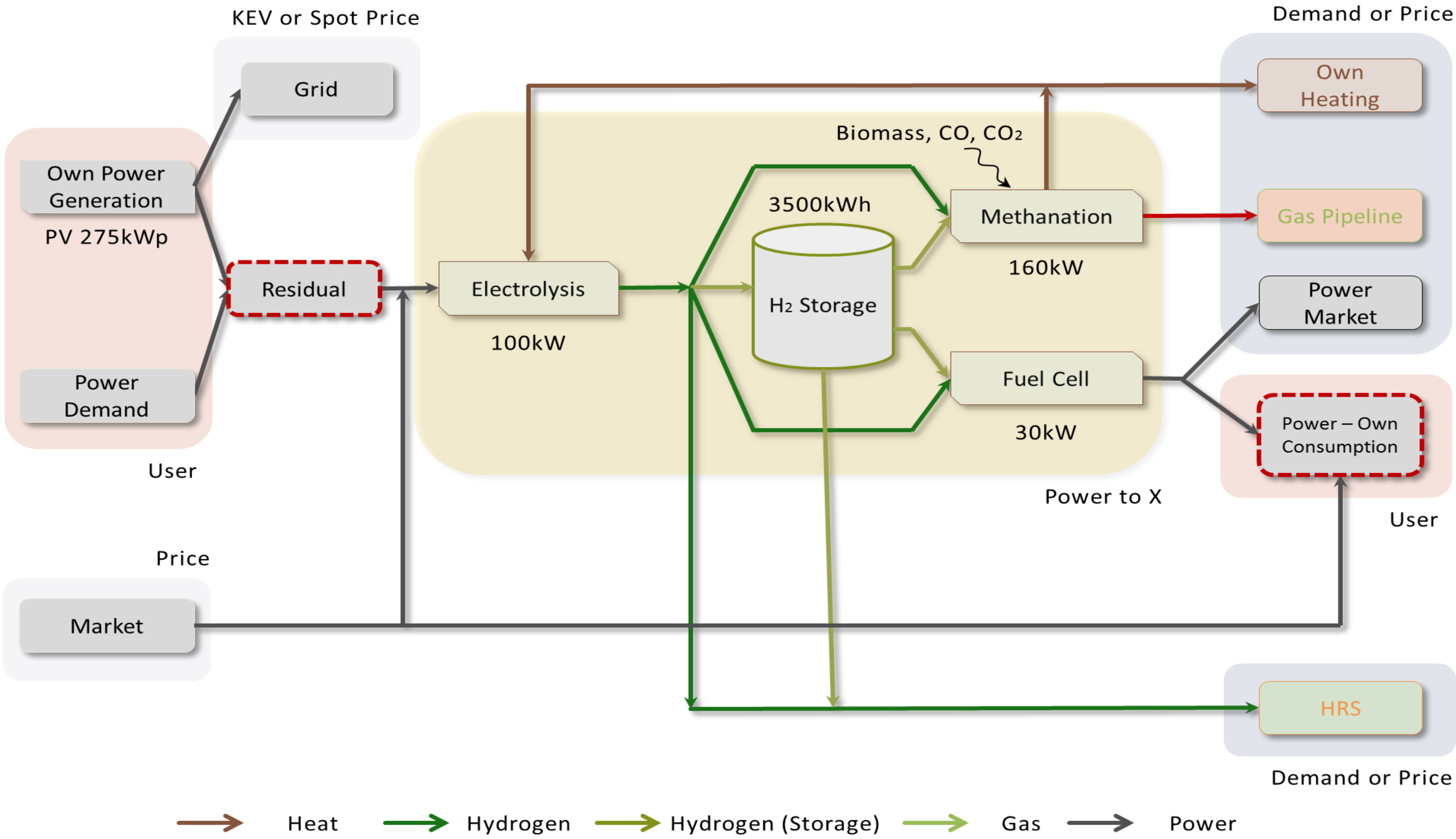

Figure 7: Model ESI

Subsequent will be given detailed qualitative analysis of ESI platform and P2X process.

4.1.5 Operational Schemes

The system can work in different operational schemes. Depending on the needs it can change its output in the form of gas, hydrogen or power. These outputs in their turn can be used for different purposes.

- **Power-to-gas** (SNG)
    - intermediate storage
    - without intermediate storage

- **Power-to-power** (via electrolysis and fuel cell)
    - Battery
    - Heat

- **Power-to-Hydrogen**

- Other conversion processes
    - SNG from wood
    - SNG/synthetic fuels/chemicals from wet biomass
    - Methane from industrial CO_2 & H_2

4.2 Layout analysis

4.2.1 Electricity Supply and Electrolysis

Own power generation in the presented layout is the energy produced by any energy plants in order to meet the power demand. This energy can from renewable energy sources as well as from any conventional energy plants. Afterwards, when matching power generation with power demand, the surplus residual power from wind or solar generation (or any other source), is injected into the electrolyser, where the process of electrolysis is taking place with having hydrogen and oxygen (O2) as an output. In our case, ESI platform has 100 kW of capacity.

Additionally, in times of a scarcity of residual power, the electricity can be bought from the Spot Market and be injected into the electrolyser as well.

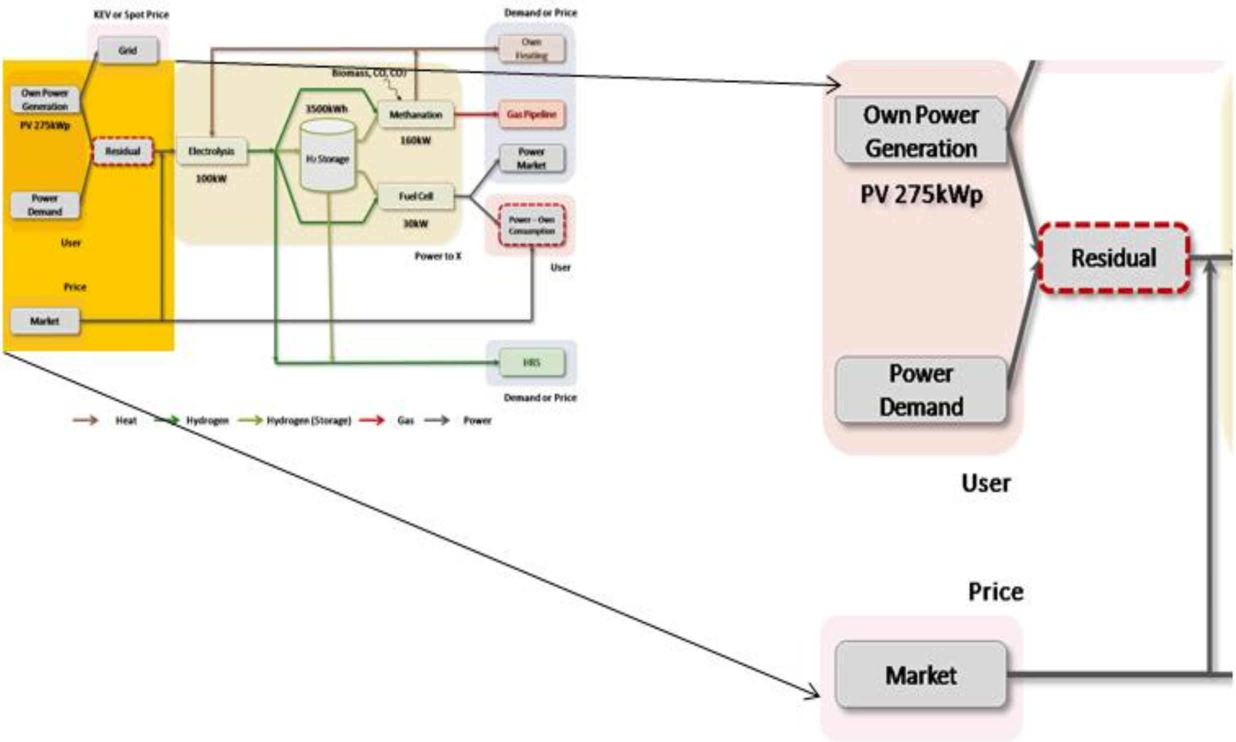

Figure 8: Electricity Supply and Electrolysis

4.2.2 Storage

Electricity, after going through the electrolysis provides the system with hydrogen. In times when gas, electricity or hydrogen prices are high enough on the market, hydrogen can surpass the storing process and be directly injected into methanation or fuel cell conversion processes and be sold directly on the market.

Otherwise, when having low prices of gas, electricity and hydrogen on the market, hydrogen can be stored and afterwards be injected into methanation or fuel cell conversion processes with a future purpose of selling it on the market when having higher prices.

In order to be stored hydrogen is injected into H2 storage, which capacity, in ESI case is 3500 kWh.

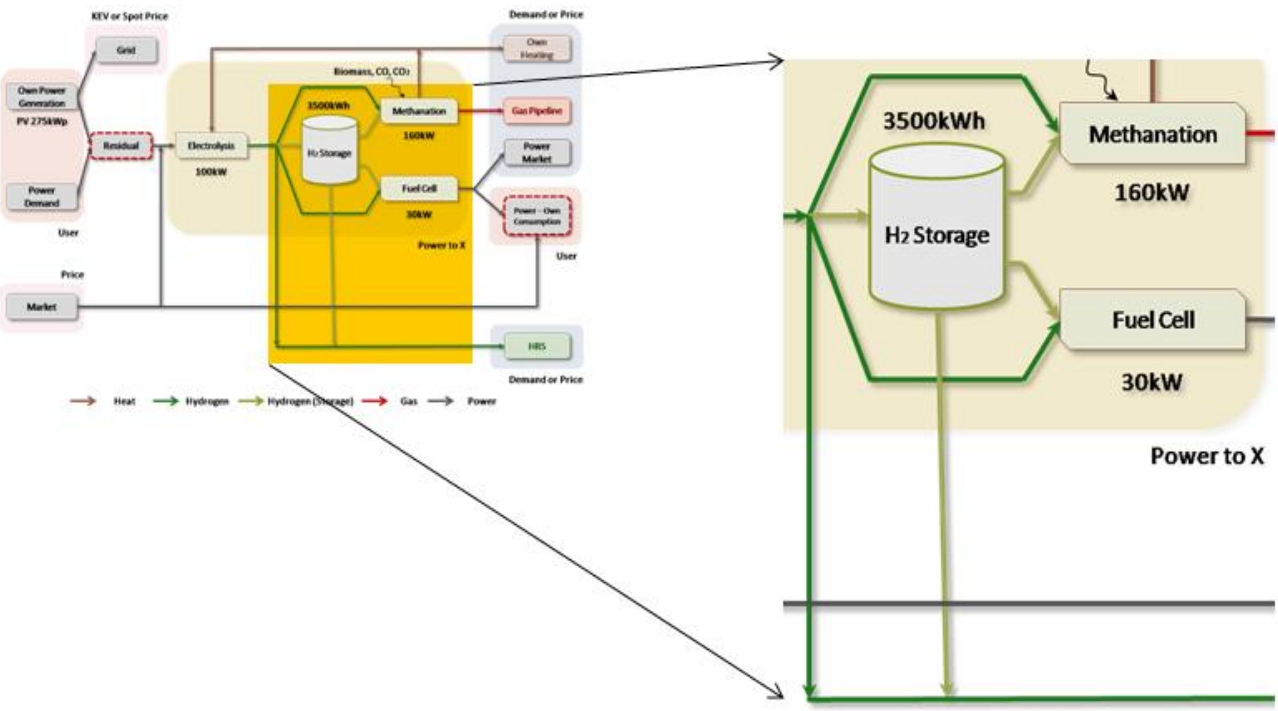

Figure 9: H2 Storage

4.2.3 Power-to-Gas (P2G). Methanation

In P2G setting of the system, hydrogen, entering into the methanation process is converted into Synthetic Natural Gas (SNG) that can be easily injected into existing natural gas pipeline infrastructure. The methanation process is taking place with the help of capturing CO or CO2 from the air or any other sources, this process is described in details in Section 4.5.

It is widely known that when converting hydrogen to SNG through Methanation process, a particular amount of heat is released. This heat can be sold on the market and be used as a own heating by households or any other entities. Moreover, the heat can be also be sent back to electolyser, where High temperature electrolysis (HTE or steam electrolysis) can take place. In this case the heat, instead of electricity is used in order to produce hydrogen. The main reason for this is that the heat is cheaper than electricity, and because the electrolysis reaction is more efficient at higher temperatures (Badwal, Giddey and Munnings, 2013).

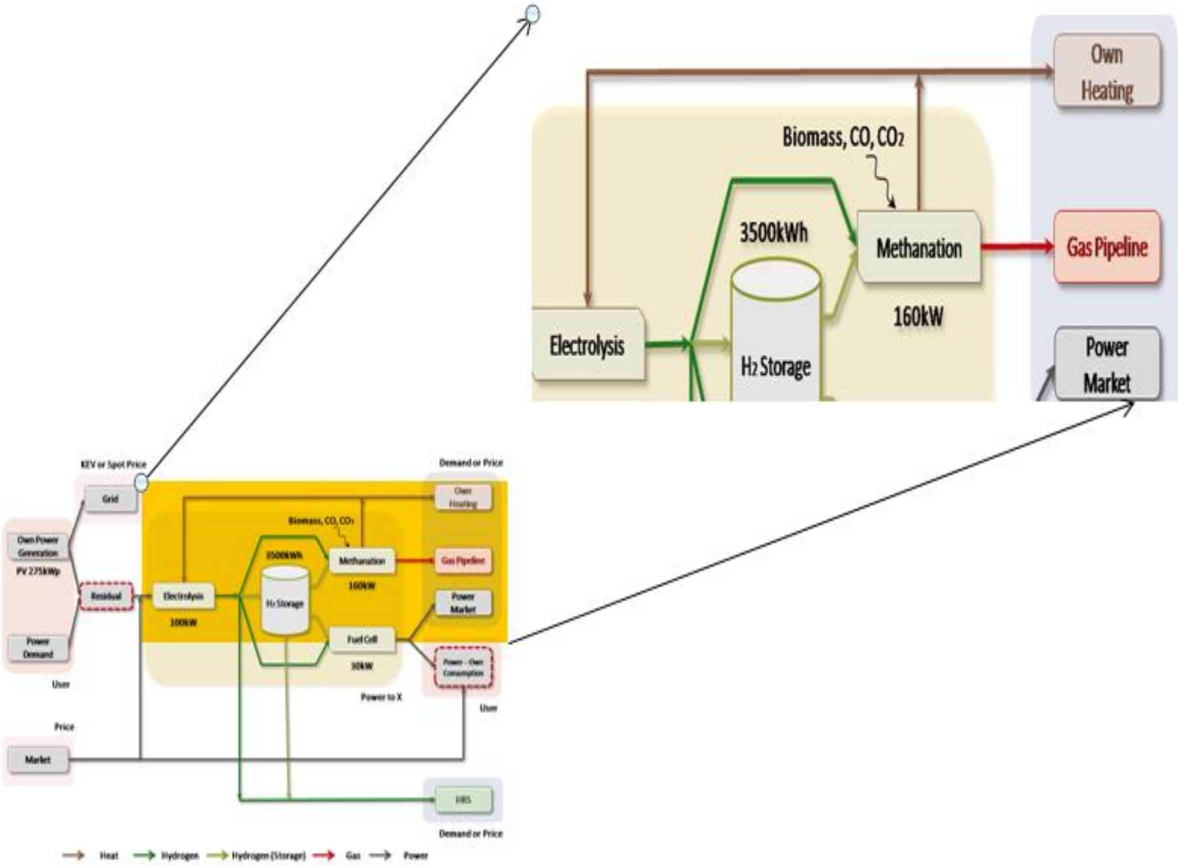

Figure 10: Power-to-Gas (P2G)

4.2.4 Power-to-Power (P2P). Fuel Cell

In P2P system configuration Hydrogen enters the fuel cell, where fuel cell converts hydrogen back into electrical energy with particular efficiency, which further can be sold in Power market. , this process is described in details in Section 4.5. Additionally, there is a possibility to use the power for own consumption purposes.

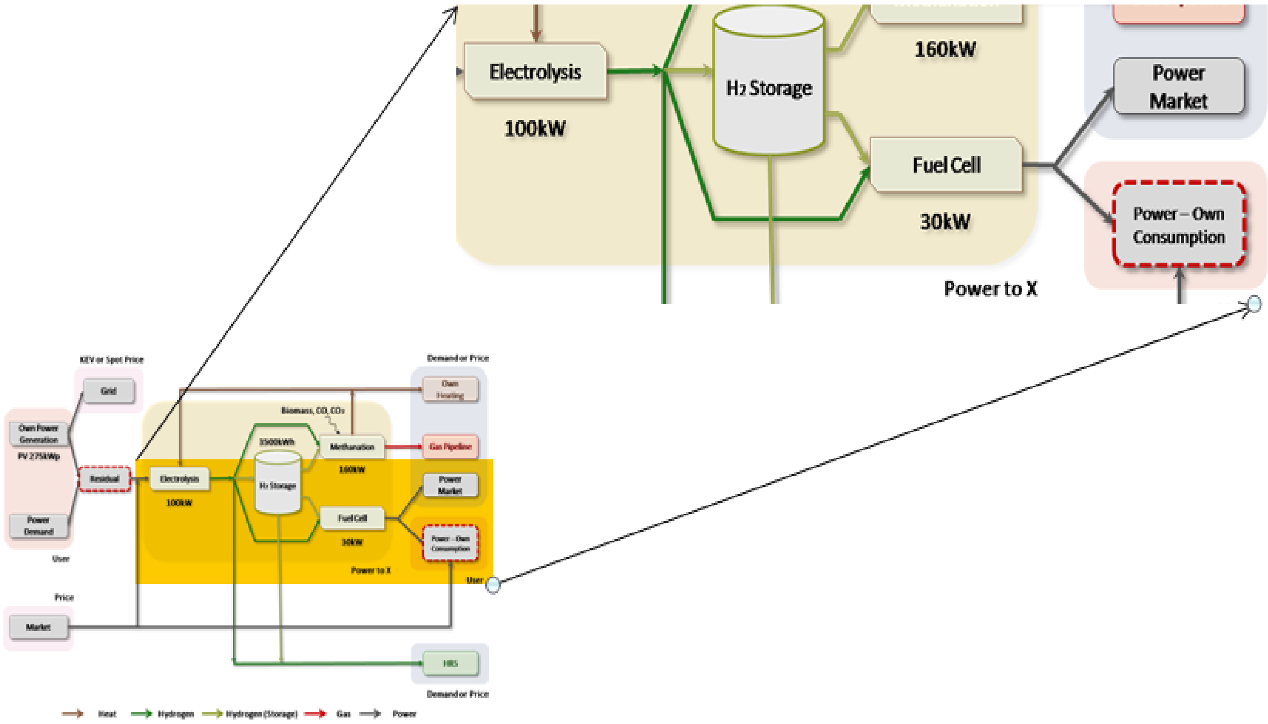

Figure 11: Power-to-Power (P2P)

In the same way, in case of need the power bought from the spot market can be directly used for own power consumption passing all P2X systems.

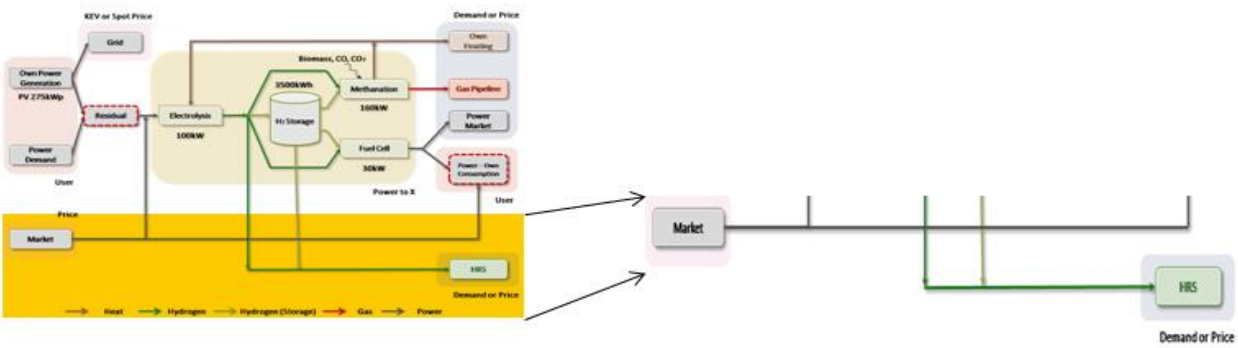

Figure 12: Power-to-Power (P2P)

4.2.5 H2-to-Market

Hydrogen can be sold in the market with two possibilities. Firstly, hydrogen can be directly injected into the market in case of higher prices or, secondly, be stored and sold in the future in case of higher prices on the market.

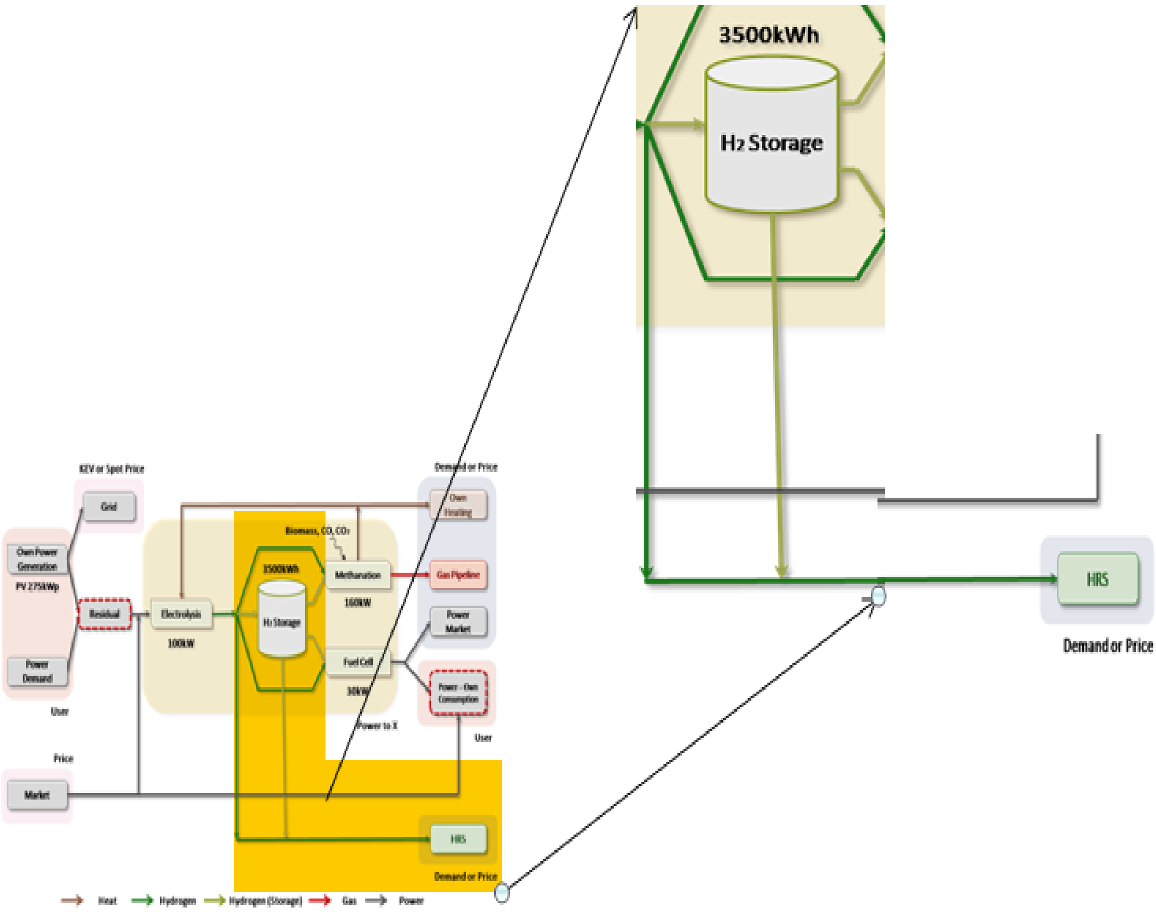

Figure 13: H2-to-Market

4.2.6 Demand and price

Demand and price of Own heating, Gas, Power and Hydrogen are the variables of the system and are set exogenously. These and other variables will be described in more details in the following sections.

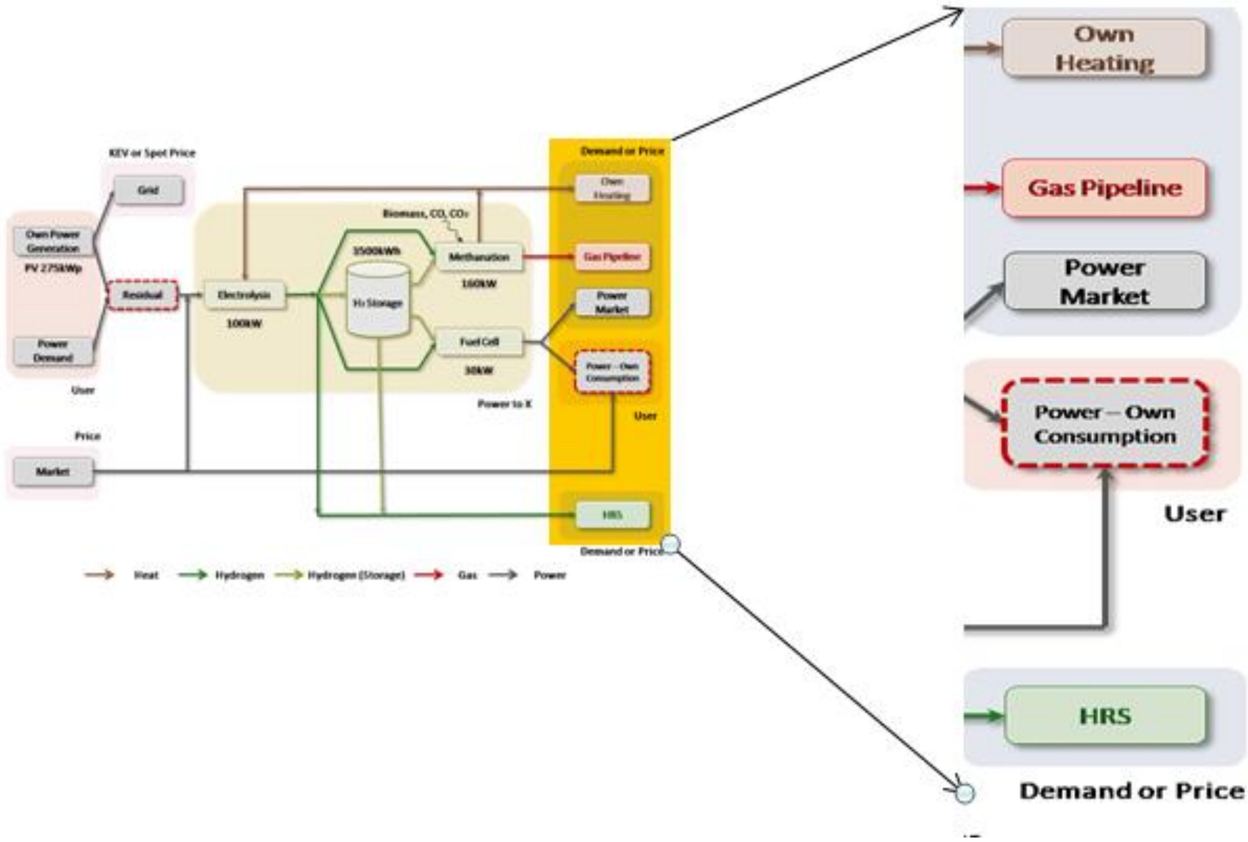

Figure 14: Demand and price

4.3 Tool description

- Maximize own profit through optimized design and operation
- Price-taker from economic environment (prices, taxes, etc.)
- Demand for commodities are exogenous
- High temporal resolution – multiple years at hourly resolution
- Business valuation – detailed project finance model
- Non-linear optimization using Interior point (IP) methods - IP methods are best suited for very large-scale problems with many degrees-of-freedom (design variables)
- License free and multi OS

The purposes of the tool is to maximize own profit. The revenue is generated by selling commodities (hydrogen, SNG, power, heat). Costs include costs for purchasing commodities, and variable cost, when Negative opportunity cost is additional revenue due to "time shifting".

1.16 $$\textbf{Maximize} \rightarrow \sum_t \textbf{Profit} = \sum_t \text{Revenue} - \underbrace{\sum_t (\text{Costs}_{\text{with P2X}} - \text{Costs}_{\text{without P2X}})}_{\text{Opportunity Cost (Provided: Demands pre-existed)}}$$

Leveraged profits or the net cash flows (CF) for each year of life-cycle is discounted to evaluate project finance indices such as NPV, IRR, LLCR, etc.

1.17 $$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \dots + \overbrace{\frac{CF_n}{(1+r)^n}}^{\text{Terminal Value}}$$

CF = Cash Flow

r = Discount Rate (WACC)

Simulation of renewables generation, using Re-analysis data. Processed and calibrated results

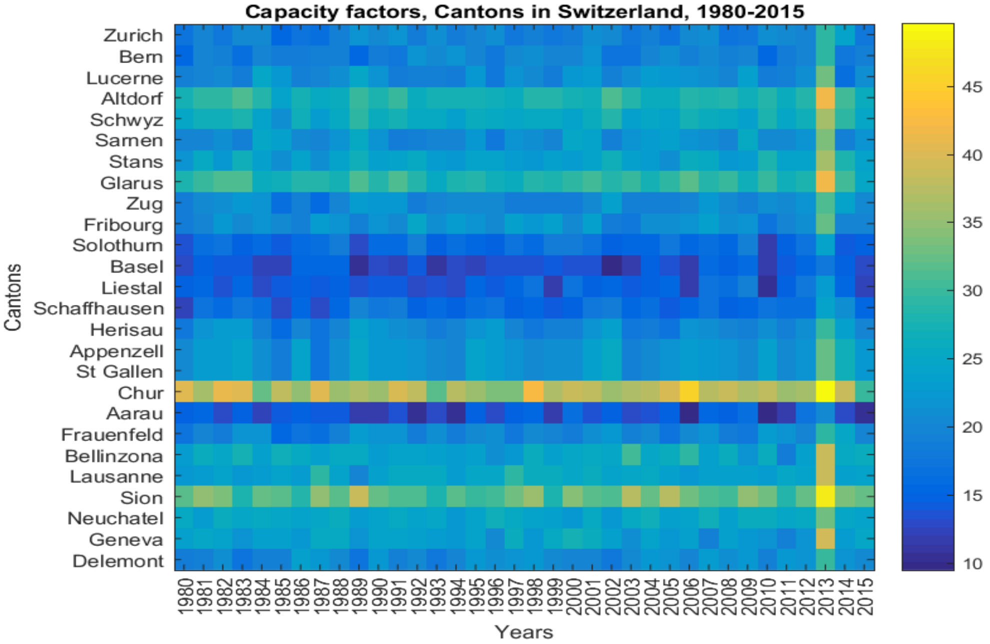

Figure 15: Derived Cantonal Wind potential (1980-2015)

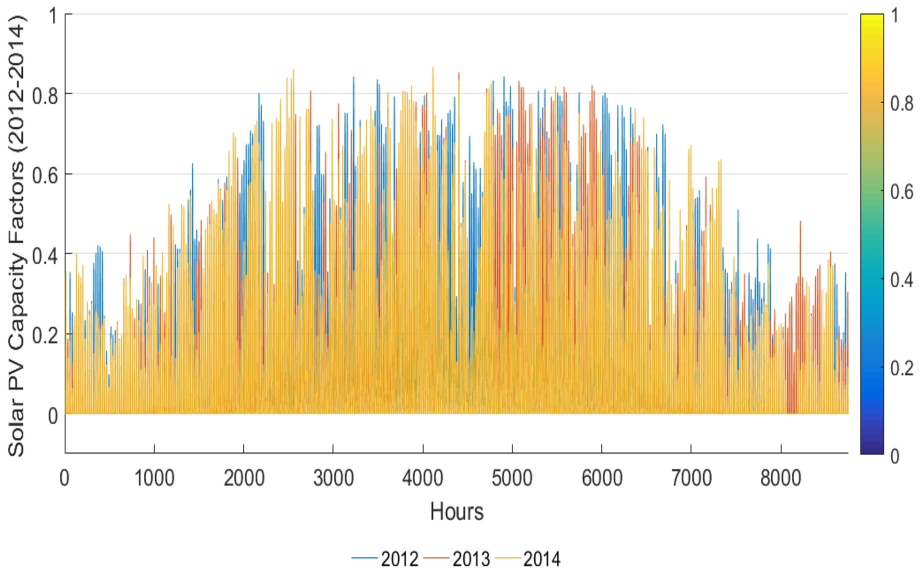

Figure 16: Hourly Solar PV Potential (2013-2015)

Advantages

- High Spatial and temporal resolution of variable renewables generation
- Long-term historical records (30+ years)

Natural gas for industry
(per megawatt hour GCV)

	Ex-tax price	Excise tax	VAT	Total tax	Total price
2006	52.19	0.35	-	0.35	52.54
2007	59.03	0.46	-	0.46	59.49
2008	66.77	2.67	-	2.67	69.45
2009	63.15	2.62	-	2.62	65.77
2010	52.56	6.79	-	6.79	59.35
2011	57.51	6.81	-	6.81	64.33
2012	60.45	6.75	-	6.75	67.23
2013	60.23	6.74	-	6.74	66.97
2014	56.22	11.08	-	11.08	67.30
2015	52.21	11.08	-	11.08	63.29
2016	45.40	15.53	-	15.53	60.93
1Q2016					
2Q2016	46.77	15.53	-	15.53	62.30
3Q2016	46.00	15.53	-	15.53	61.53
4Q2016	45.07	15.53	-	15.53	60.60
1Q2017	43.77	15.53	-	15.53	59.30

Source: OECD

Figure 17: Prices of Commodities

4.3.1 Parameters, Constrains, Variables

The model includes a set of parameters, constraints and variables. Depending on the case parameters and constrains are changing, consequently variable and the output of the system change as well.

Parameters

- Own power supply - Temporal scope of 8760 hours is taken. The electricity supply time series data is provided by PSI's solar energy supply of a particular year
- Own power demand
- Cost: own power supply: the cost of own power
- Cost of buying power from Sport market
- The cost of electrolysis and the cost of operating storage facility are taken as open assumptions.
- Cost of P2G and P2P conversion.
- Prices of gas and hydrogen on the market are taken exogenously. Price of heat and heat demand are set as open assumptions
- Selling price of electricity (Sport Price + KEV (Swiss Feed-in Tariff))
- Efficiencies of Electrolysis, P2P, P2G and conversation factor of P2P to heat
- Feed in Tariff for curtailed power
- Benefit to power from P2P over spot
- Solar Power Capacity
- Investment costs for Storage, PEM, Fuel cell and Methanation process.

Constrains (Units: kWh)

- **Storage**
- Min. and Max. Storage level (Max: actual ES platform capacity)

Storage Flows

- Min. and Max. inflow to Storage (open assumption)
- Min. and Max. outflow from Storage (open assumption)

Storage

- Initial level of Storage (t=0, open assumption)

Flows in Conversion Processes

- Min. and Max. power input to P2X (Max: Rated Power of PSI electrolyser = 100kW)
- Min. and Max. H_2 input to P2P (Max: Rated Power Fuel cell = 30kW, efficiency=70%)
- Min. and Max. H_2 input to P2G (Max: Rated Power Fuel cell = 160kW, efficiency=80%)
- Min. and Max. H_2 directly Electrolysis to P2P (open assumption)
- Min. and Max. H_2 directly Electrolysis to P2G (open assumption)

Market Limits

- Min. and Max. H_2 Storage to market (open assumption)
- Min. and Max. desired/constrained output Gas (open assumption)
- Min. and. Max. desired/constraint output H_2 (open assumption)

Variables

- Residual, Power for own use, P2P power for own use, Power spot market: own use

- Power from spot market, Power in P2X, Power from spot market: P2X, Hydrogen from electrolysis

- Hydrogen to storage, Storage level, Hydrogen direct to gas, Stored H2 to Gas, Hydrogen direct to Power, Stored H2 to Power, Hydrogen direct to market, Stored H2 to Market

- Hydrogen for Gas, Gas to Market

- Sink of Supply, Use of Supply

- Total cost: P2G, Total cost: P2P, Unit cost of Power from P2X, Total cost buying power: spot market, Total cost: electrolysis, Total Cost: Operating storage facility, Total cost: own power supply

- Total revenue from P2G, Total Revenue: Heat, Total revenue: Power, Total Revenue: Hydrogen, Total Revenue, Profit

- Power sold to market, Power produced from P2P, Hydrogen sold in market

- Costs after P2X, Costs before P2X

- Spot Price Power

- KEV P2P

4.3.2 Business Model Valuation

This part of the tool displays the detailed project finance model of the system. The main parts of the Business Valuation will be described hereafter.

Assumptions:

- Fixed O&M Costs
- Revenues - Variable O&M Costs
- Initial Investment Costs

It is important to look on the section ''Outputs'' in order to understand the profitability of the project.

Outputs:

- Project Pre Tax IRR
- Project After Tax IRR
- Equity IRR
- Min DSCR

In future business cases will be presented the ''Assumptions'' and ''Outputs'' parts for each regarded case.

Building Blocks and Performance

Building Blocks

- Algebraic modelling language – Pyomo (Python)
- Data interface – Excel (Solver Studio), VBA
- Solvers – **IPOpt**, Couenne, CBC, etc. (COIN|OR projects)

Performance

- Non-linear problem with more than 350,000 variables and 100,000 parameters
- Optimization time of 5-15 minutes on PC
- Open-source programming language and solvers → Independent of licensing or OS
- Batch simulations via command line

5

Business Cases

5. Business Cases

5.1. First case. Changing the prices of commodities

In this section the main variables and the results of each case are incorporated in one single excel file. This is done in order to have a clear view and to be able to compare the results of the system. Hereafter the variables will show, qualitative description will be provided and plots supporting the discussion will be exhibited.

Following, the base case and its sensitivity analysis will be conducted. Sensitivity analysis will be carried out 4 times, by increasing the price of commodities (hydrogen, power, gas) twice by +25% and +50% and decreasing two times by -25% and -50% with regards to the base case.

For the following Tables and Figures the units will be:

- Annual Profits, Initial Investment Cost s- **CHF**
- Equity IRR - **%**
- Hydrogen for Power, Hydrogen Direct to market, Stored H2 to Market, Hydrogen for Gas, Storage Level - **kWh**
- Selling Price for Electricity, H2 Price, Gas Price , Heat Price - **CHF**

The base case for P2P, P2H and P2G configurations of the system is presented:

Price Default	P2P	P2H	P2G
Elc.Supply	286321,86	286321,86	286321,86
Elc. Demand	0	0	0
Annual Profit	10045,8526	31829,35884	1616,574512
Initial Investments Costs	284728,50	258646,5	338134,5
Equity IRR	-18,88%	3,90%	#NUM!
Min DSCR	0,38	1,38	0,04
Hydrogen for Power	189452,272		
Hydrogen direct to market		206368,4879	
Stored H2 to Market		141658,688	
Hydrogen for Gas			189451,7728
Storage Level	2073,3052	2063,737505	1375,122947
Selling price for electricity	0,14029607		
H2 Price		0,2	
Gas Price			0,059966384
Heat Price			0,05

Table 1: Base Price (CHF)

In this Base Case when the prices are not changed, we can clearly see all the necessary outputs and variables we need in order to understand which system in which configuration is profitable.

In the above mentioned case the most profitable is P2H configuration with 31829 CHF Annual profit, Equity IRR of 3.9 % and Min DSCR* of 1.38 when having the least Investment costs. Additionally, the hydrogen used to make revenue of P2H process is the highest.

Now we will consider a +25% price increases for Power, Hydrogen and Gas on the market and see which case is the most profitable.

Price +25	P2P	P2H	P2G
Annual Profit	14806,69	53015,26	3964,01
Initial Investments Costs	284728,50	258646,50	338134,50
Equity IRR	-11,98%	16,63%	#NUM!
Min DSCR	0,58	2,36	0,15
Hydrogen for Power	189452,193		
Hydrogen direct to market		251661,4248	
Stored H2 to Market		186338,5791	
Hydrogen for Gas			189451,9785
Storage Level	2066,56707	2132,105497	1352,675126
Selling price for electricity	0,17537009		
H2 Price		0,25	
Gas Price			0,074951461
Heat Price			0,05

Table 2: Base Price +25% (CHF)

As in the base case, we can clearly see that the most profitable configuration of the system is still P2H with 53015 CHF annual profit, 16.63% Equity IRR and 2.36 Min DSCR, while the other two configurations are still not profitable. Nevertheless, the P2P configuration did a considerable improvement in annual profits and Equity IRR.

Now we will consider a +50% price increases for Power, Hydrogen and Gas on the market and see which case is the most profitable.

**Debt-service Coverage Ratio (DSCR) - It is a measure of the cash-flow available to pay current debt obligations. The ratio states net operating income as a multiple of debt obligations due within one year, including interest, principal, sinking-fund and lease payments. A DSCR greater than 1 means the entity – whether a person, company or government – has sufficient income to pay its current debt obligations. A DSCR less than 1 means it does not (Debt-Service Coverage Ratio (DSCR), no date)*

Price +50	P2P	P2H	P2G
Annual Profit	19568,19	74910,30	6312,49
Initial Investments Costs	284728,50	258646,50	338134,50
Equity IRR	-6,97%	27,63%	#NUM!
Min DSCR	0,78	3,36	0,25
Hydrogen for Power	189451,8023		
Hydrogen direct to market		251657,5175	
Stored H2 to Market		186292,3263	
Hydrogen for Gas			189452,1047
Storage Level	2066,17953	2131,502941	1376,427498
Selling price for electricity	0,21044411		
H2 Price		0,29996969	
Gas Price			0,089941752
Heat Price			0,05

Table 3: Base Price +50% (CHF)

As expected P2H configuration of system makes the most profit with 74910 CHF, Equity IRR of 27,63% and Min DSCR of 3.36, when P2P and P2G configurations, although improved their profit, Equity IRR and Min DSCR, are still not profitable.

Furthermore, the decision of decreasing the commodity prices on the market has been made. The prices are decreased by -25% and -50% with respect to the base case. Both of them are least profitable ones.

Price -25	P2P	P2H	P2G
Annual Profit	5286,05	19646,98	-729,67
Initial Investments Costs	284728,50	258646,50	338134,50
Equity IRR	#NUM!	-6,00%	#NUM!
Min DSCR	0,17	0,82	-0,05
Hydrogen for Power	189451,803		
Hydrogen direct to market		126382,3403	
Stored H2 to Market		63768,69641	
Hydrogen for Gas			189449,759
Storage Level	2068,18553	1811,115316	1369,368435
Selling price for electricity	0,10522205		
H2 Price		0,149986813	
Gas Price			0,044970876
Heat Price			0,05

Table 4: Base Price -25% (CHF)

Price -50	P2P	P2H	P2G
Annual Profit	528,20	10168,26	-2804,83
Initial Investments Costs	284728,50	258646,50	338134,50
Equity IRR	#NUM!	-18,62%	#NUM!
Min DSCR	-0,08	0,38	-0,14
Hydrogen for Power	189452,3259		
Hydrogen direct to market		126197,8908	
Stored H2 to Market		63254,40489	
Hydrogen for Gas			44933,30365
Storage Level	2081,809781	1811,009288	668,4759194
Selling price for electricity	0,070148037		
H2 Price		0,099992521	
Gas Price			0,029980584
Heat Price			0,05

Table 5: Base Price -50% (CHF)

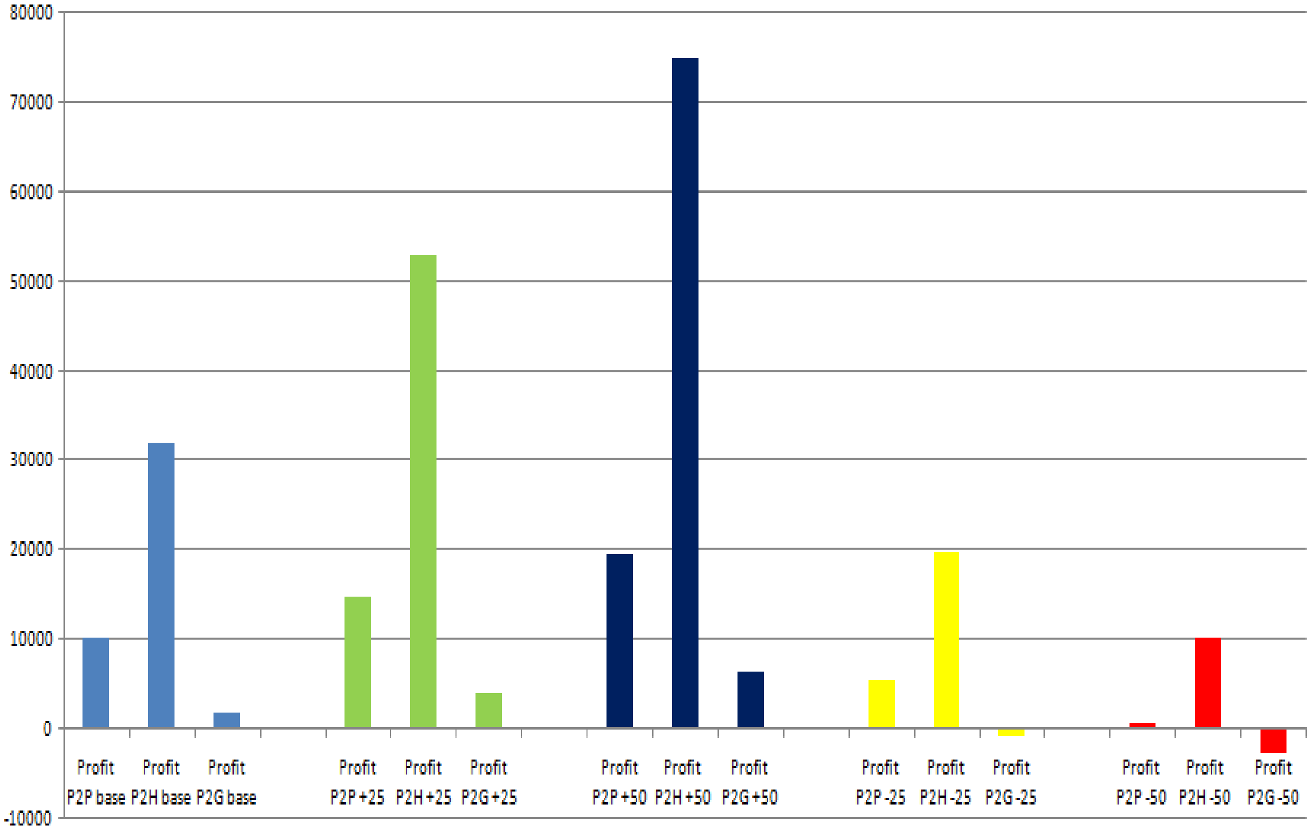

Figure 18: Comparison of Annual revenues with each price change (CHF)

As it was discussed previously the highest revenue is made in the case of 50% price increase and the lowest revenue is in the case of -50% price decrease.

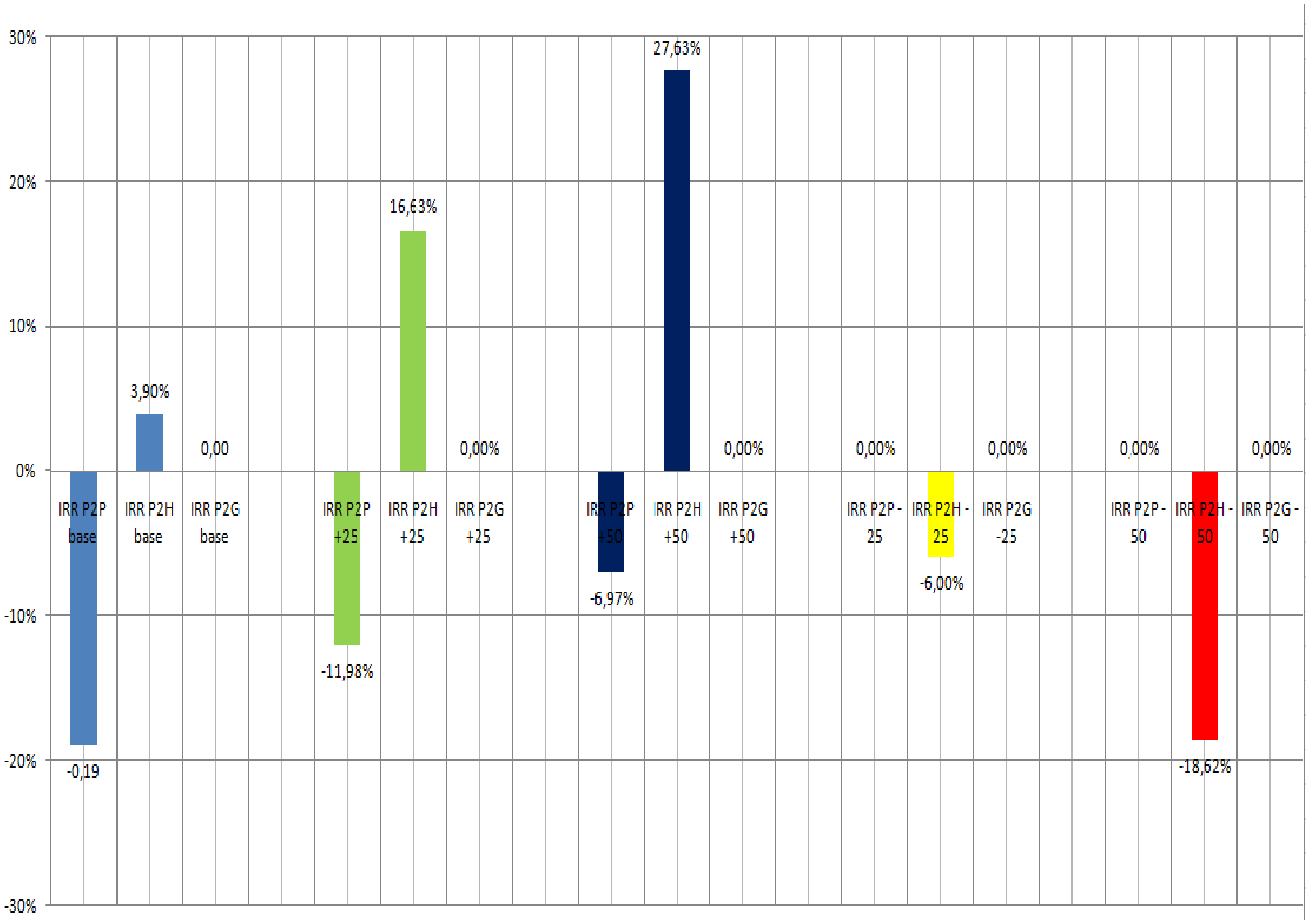

Figure 19: The comparison of Equity IRR with each price change (%)

Internal Rate of Return is the highest for P2H +50% case with 27.63% when the lowest Equity IRR has P2H case, which means that it is not profitable.

The chart below shows the relation between commodity prices on the market with their decrease and increase.

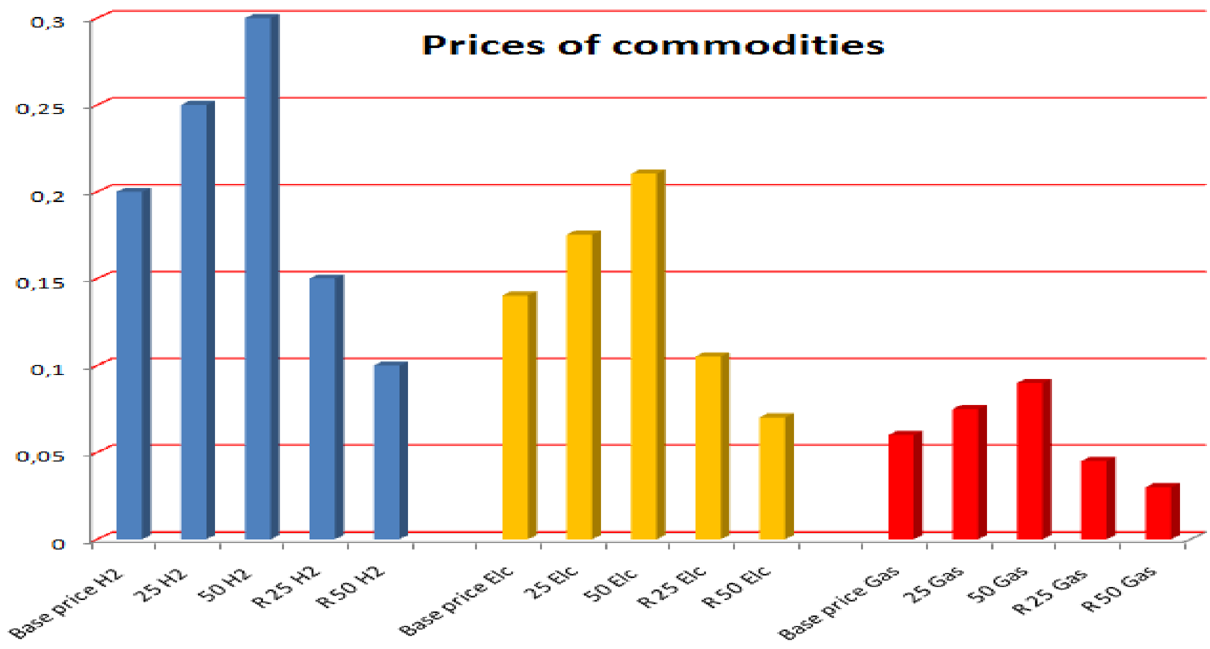

Figure 20: Prices of commodities (CHF)

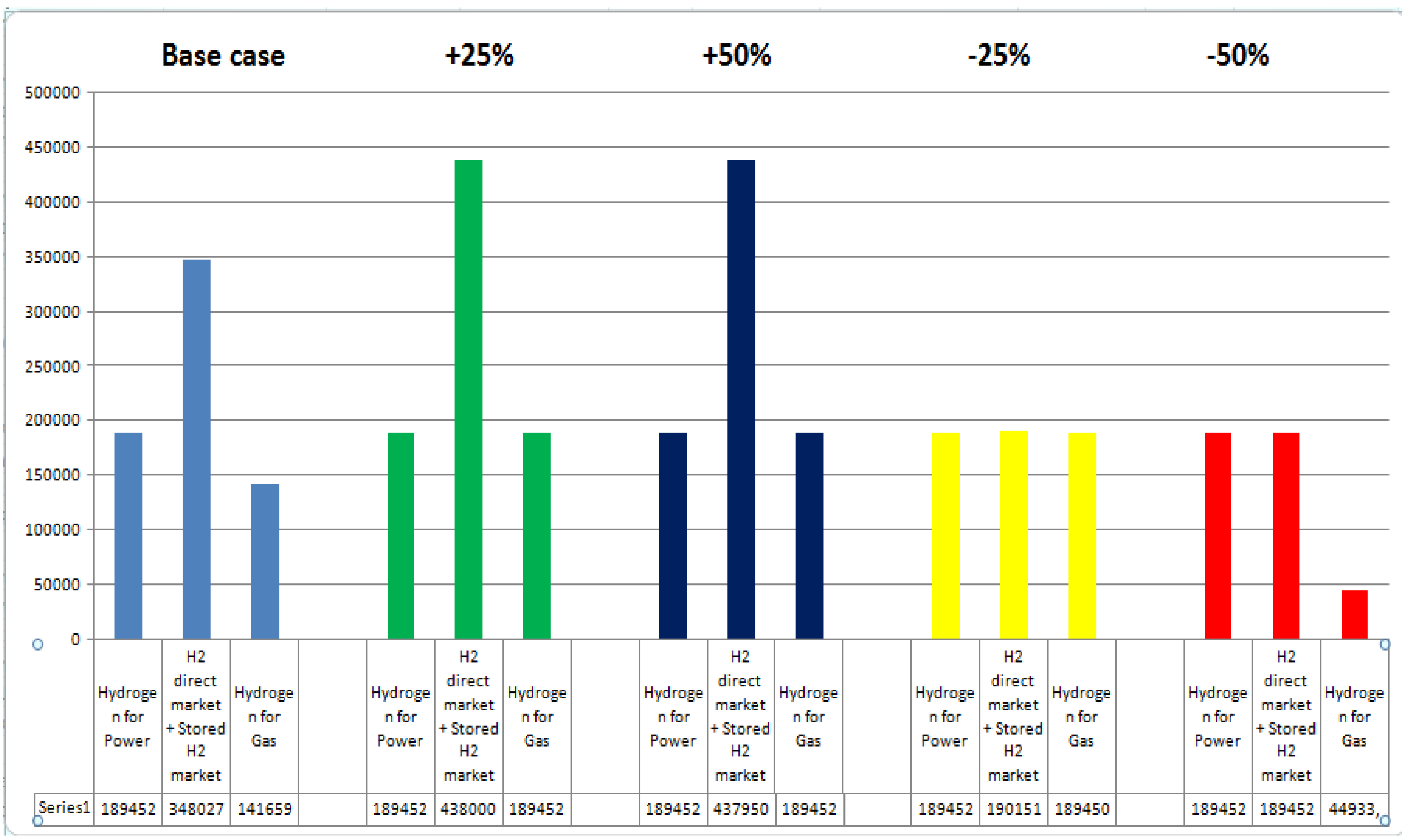

Figure 21: The amount of hydrogen going inside the system (CHF)

The amount of hydrogen going inside the system when having base, increase and decrease cases is shown. The hydrogen entering P2H system is the highest and relatively similar in +25% and +50% cases

5.2 Second case. Comparison of Solar input changes

In this section the electricity supply time series is changed from the year 2005 data to the year of 2004 data and then the results are compared. In 2005 the electricity supply was 286321,6 kWh and in 2004 is slightly higher and equals to 289504,2 kWh.

Solar Input Change	P2P	P2H	P2G
Elc.Supply	289504,215	289504,215	289504,215
Annual Profit	10159,21	32042,33	1729,58
Initial Investments Costs	284728,50	258646,50	338134,50
Equity IRR	-18,68%	4,04%	#NUM!
Min DSCR	0,38	1,39	0,05
Hydrogen for Power	190810,4568		
Hydrogen direct to market		210268,2138	
Stored H2 to Market		143594,3791	
Hydrogen for Gas			190810,4568
Storage Level	2214,377064	2043,777765	1335,114526
Selling price for electricity	0,140296073		
H2 Price		0,2	
Gas Price			0,059966384
Heat Price			0,05

Table 6 Solar Input Change (2004) (KWh)

The Annual Profits of P2P, P2H and P2G are shown. P2H case is the most profitable one with 32042.33 CHF. This result was predictable, due to the fact that electricity supply of the year 2005 is less than electricity supply in 2004. Consequently, if the electricity supply in 2004 is higher than in 2005, thus P2H case should make even more profit than in 2005. We can clearly see that: at the 2005 the profit is 31829 CHF and in 2004 is 32042 CHF.

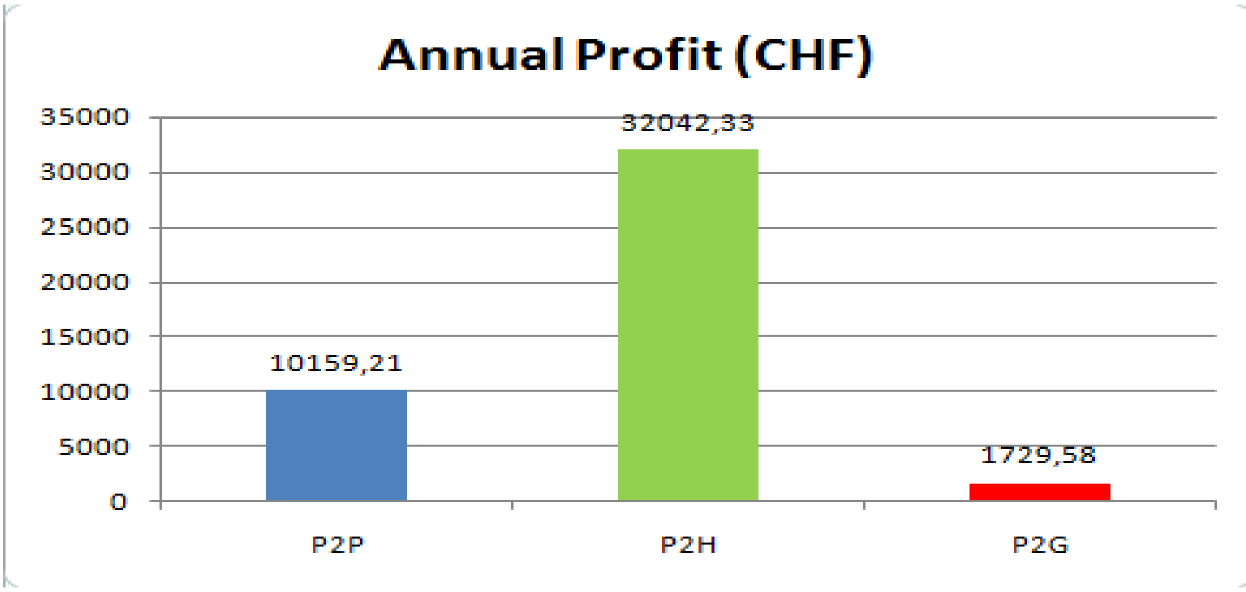

Figure 18: Annual Profit (CHF)

The Equity IRR of P2H is the highest, when P2G and P2P cases are not profitable. It is worth to mention that, although all of three configurations make a profit (as we see in the previous chart), P2P and P2G are still not profitable, since their Equity IRRs are low. Thus, in order to understand if the project is profitable or not it is necessary to look not only on Annual profit but also on Equality IRR and Min DSCR.

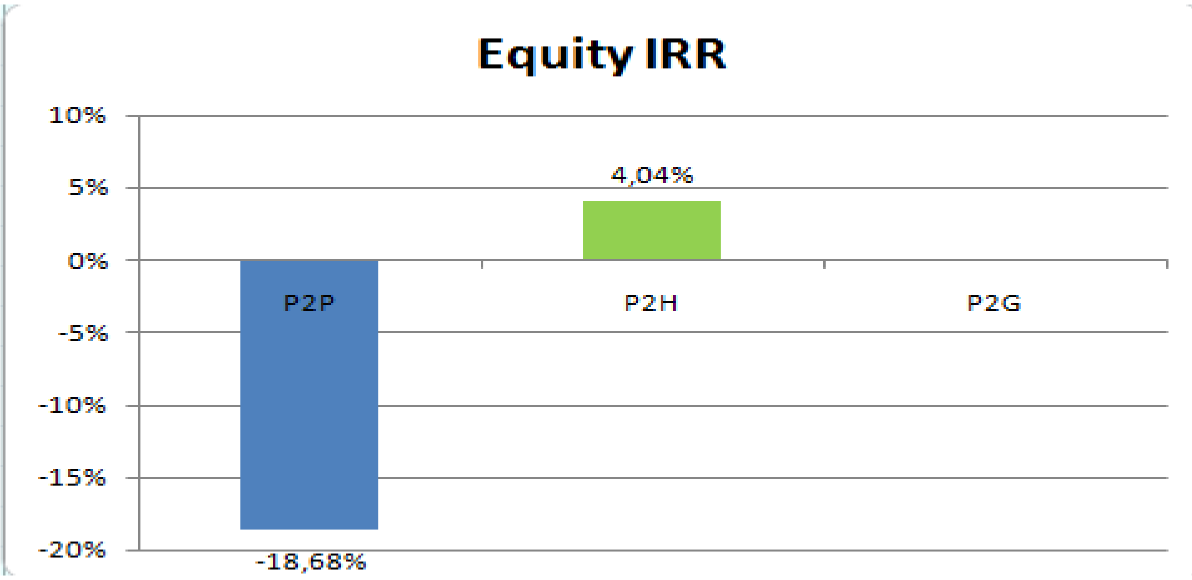

Figure 23: Equity IRR (%)

The following is the amount of hydrogen going through each configuration of the system when having electricity supply of year 2004. In 2005 the highest amount of hydrogen injected in the system was in the case of P2H configuration, which was equal to 348027 kWh. In 2004 this number is increased and equals to 353863 kWh.

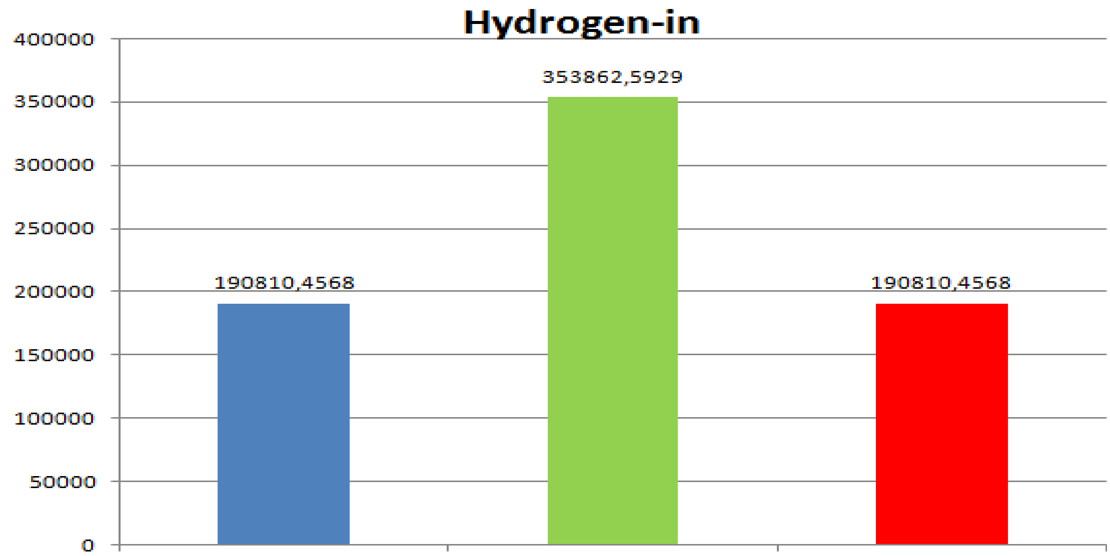

Figure 24: Hydrogen-in system (kWh)

5.3 Third case. Investment change

Following, the base case and its sensitivity analysis will be conducted. Sensitivity analysis will be carried out 4 times, by increasing the Initial investment costs of the system twice by +25% and +50% and decreasing two times by -25% and -50% with regards to the base case.

The base case for P2P, P2H and P2G configurations of the system is presented:

Inv base	P2P	P2H	P2G
Annual Profit	10045,85	31829,36	1616,57
Initial Investments Costs	284728,50	258646,50	338134,50
Equity IRR	-18,88%	3,90%	#NUM!
Min DSCR	0,38	1,38	0,04
Debt Commitment	142364,25	129323,25	169067,25

Table 7: Base Investments costs (CHF)

In all cases the Annual profit does not change and is the same as in the Base case, because changing the investment costs does not affect on the working process of the system. Nevertheless, it affects on Equity IRR and Min DSCR. In base case the highest Equity IRR=3.9% and Min DSCR=1.38 has P2H configuration.

Now we will consider +25% investment costs increase

Inv +25	P2P	P2H	P2G
Annual Profit	10045,85	31829,36	1616,57
Initial Investments Costs	355910,63	323308,13	422668,13
Equity IRR	-18,92%	0,71%	#NUM!
Min DSCR	0,38	1,18	0,12
Debt Commitment	177 955,31	161 654,06	211 334,06

Table 8: Base Investments +25% (CHF)

As in the base case, we can clearly see that P2H configuration of the system has the highest Equity IRR= 0.71% and highest Min DSCR=1.18. Nevertheless, with the increase of the investment cost we have got inverse effect. P2H still has positive IRR, but this time it dropped considerably from 3.9% till 0.71% when Min DSCR dropped as well from 1.38 till 1.18. Consequently, if the investment costs will be increase, furthermore, we can predict that even P2H system will become not profitable. In order to prove this +50% increase of investment costs will be considered.

Inv +50	P2P	P2H	P2G
Annual Profit	10045,85	31829,36	1616,57
Initial Investments Costs	427092,75	387969,75	507201,75
Equity IRR	-18,95%	-1,61%	#NUM!
Min DSCR	0,38	1,05	1,05
Debt Commitment	213 546,38	193 984,88	253 600,88

Table 9: Base Investments +50% (CHF)

As expected P2H configuration of the system dropped considerably it's Equity IRR and became -1.61% when Min DSCR equals to 1.05

Furthermore, the decision of decreasing the investment prices has been made. The costs are decreased by -25% and -50% with respect to the base case.

Inv -25	P2P	P2H	P2G
Annual Profit	10045,85	31829,36	1616,57
Initial Investments Costs	213546,38	193984,88	253600,88
Equity IRR	-18,82%	8,66%	#NUM!
Min DSCR	0,38	1,72	-0,07
Debt Commitment	106 773,19	96 992,44	126 800,44

Table 10: Base Investments -25% (CHF)

Inv -50	P2P	P2H	P2G
Annual Profit	10045,85	31829,36	1616,57
Initial Investments Costs	142364,25	129323,25	169067,25
Equity IRR	-18,69%	17,01%	#NUM!
Min DSCR	0,38	2,39	-0,32
Debt Commitment	71182,125	64661,625	84533,625

Table 11: Base Investments -50% (CHF)

As it is clearly seen, in the case of decreased investments costs, both projects with P2H configurations have the highest Equity IRRs and Min DSCRs.

The following chart shows the comparison between Equity IRRs for the base case and its sentisitivity analsyises, where it is displayed that P2H with -50% decrease of investments costs has the highest Equity IRR.

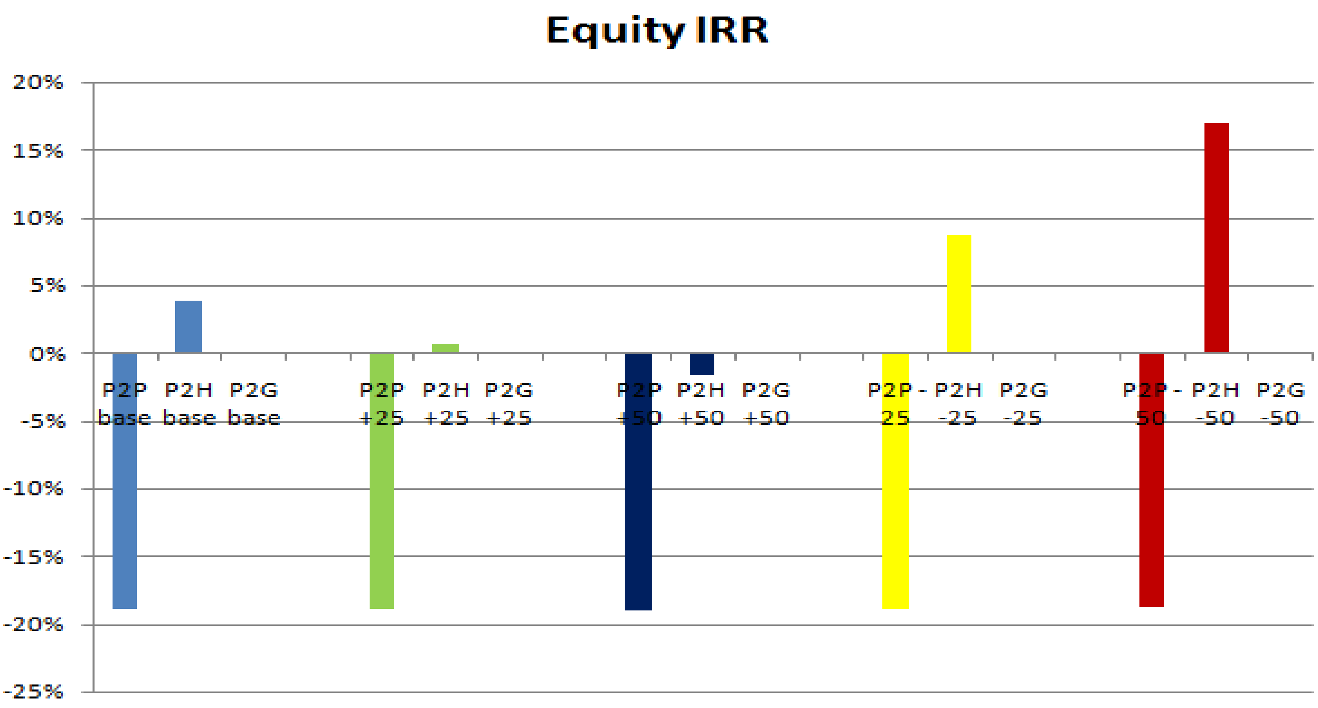

Figure 25: Equity IRR (%)

The same situation we can see when comparing Min DSCRs, where, as in previous chart the highest Min DSCR has the P2H configuration with -50% decrease of investments costs.

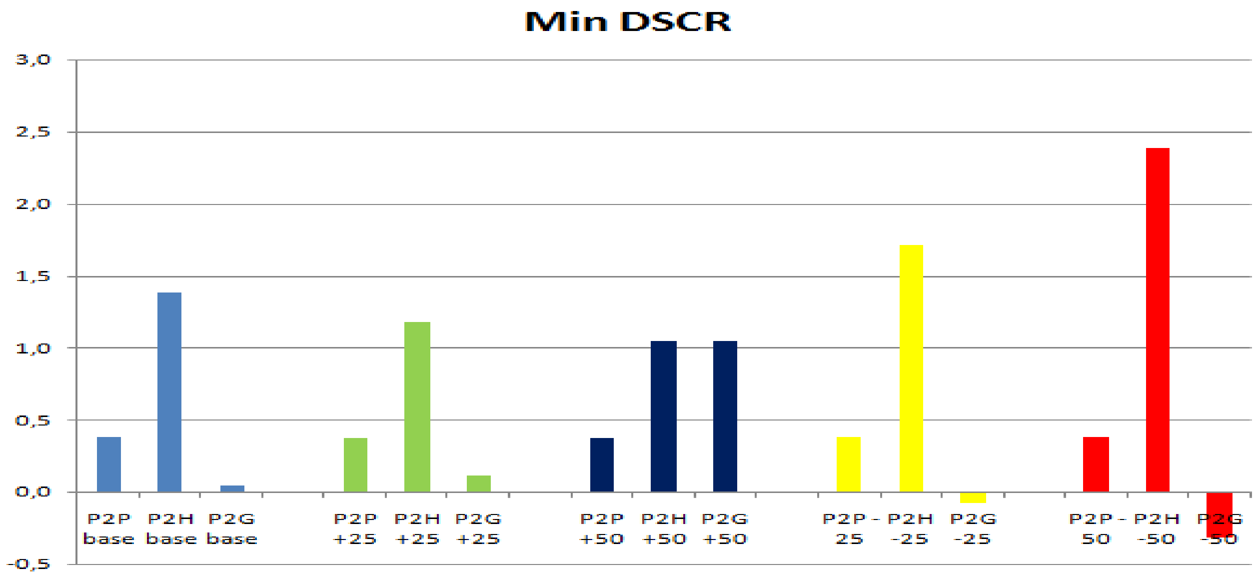

Figure 26: Min DSCR

On the following chart Investment costs are compared for base case and its sensitive analyzes

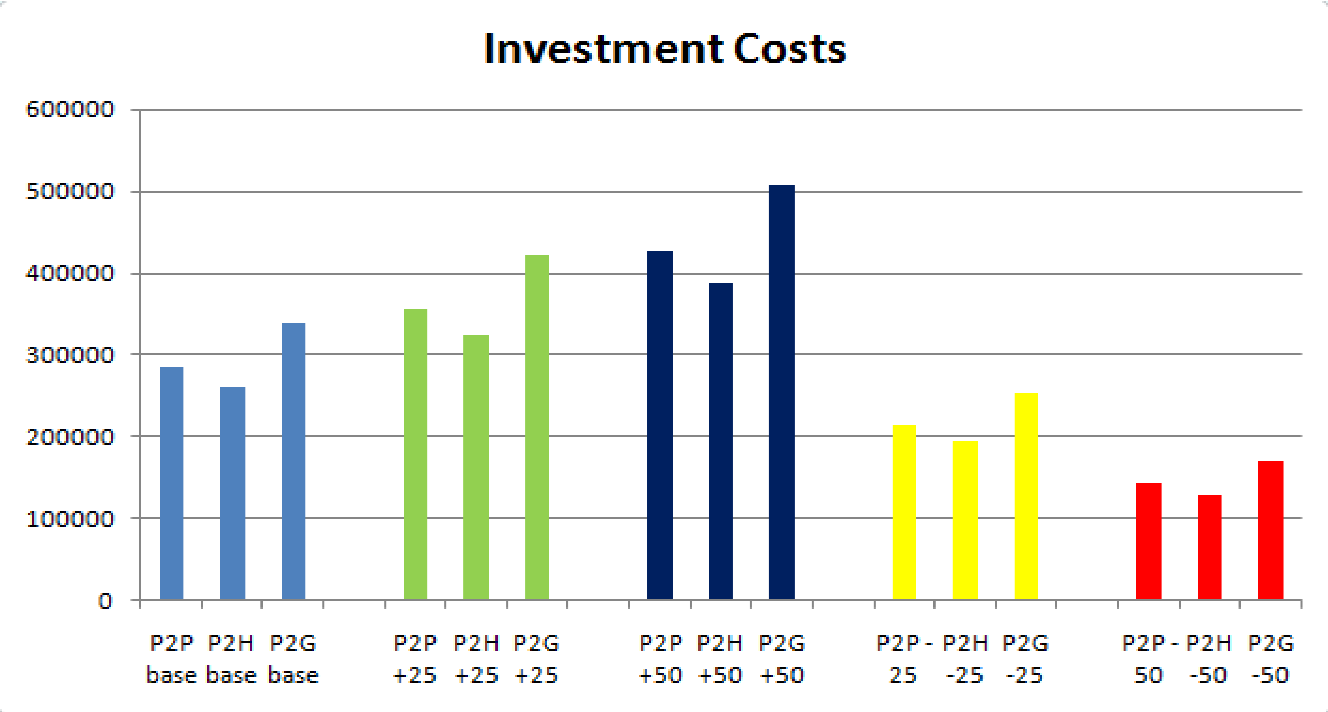

Figure 27: Investment Costs (CHF)

5.4 Fourth case. Solar power capacity is changed from 275 kW to 550kW

Electricity supply in this case is 572643 kWh. Of course, compared to other bases cases here the annual profit should be increased, so that the Equity IRRs and Min DSCR. We do not take into the consideration P2G configuration since it's Equity IRR and Min DSCR are too small, thus are not of interest to be regarded .This is clearly shown in the following table.

Price Default	P2P	P2H
Elc.Supply	572643,7	572643,7
Annual Profit	21920,67	38707,03
Initial Investments Costs	267092,10	258646,50
Equity IRR	-2,87%	8,40%
Min DSCR	0,61	1,70

Table 12: Base Price (CHF)

The annual profit, Equity IRR and Min DSCR of P2H configuration is higher than P2P's.

5.5 Fifth case. Power-to-X. P2X case

In this section we take into account all the possible configurations of the system together: P2H, P2G and P2P. This system will be called P2X. Consequently, the investment costs in this full configuration of the system will be compared to the highest investment costs of the previously mentioned cases.

P2X	P2X
Annual Profit	35768,87
Initial Investments Costs	364216,50
Equity IRR	1,34%
Min DSCR	1,22
Hydrogen for Power	0,00
Hydrogen direct to market	199 766,91
Stored H2 to Market	136 670,49
Hydrogen for Gas	6 441,18
Storage Level	2 064,70
Selling price for electricity	0,14
H2 Price	0,2
Gas Price	0,06
Heat Price	0,05

Table 13: P2X case (CHF, %, KWh)

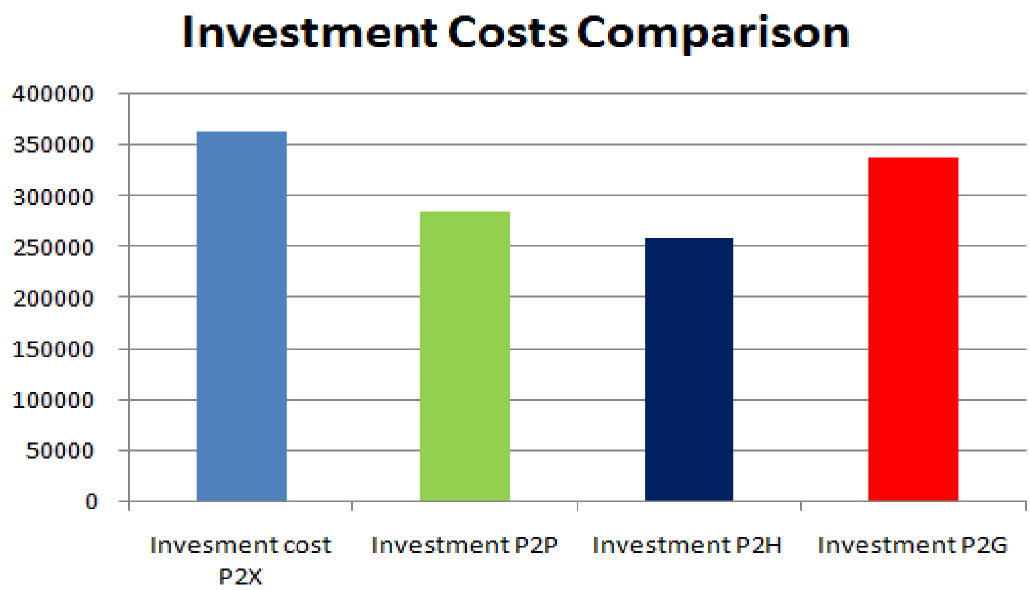

Figure 20: Investment costs comparison for P2X, P2P, P2H, and P2G (CHF)

5.6 Comparison

Here we will choose the cases with the highest Annual Profits, IRRs and Min DSCRs and compare them with Annual profit, Equity IRR and Min DSCR of P2X case.

Annual profit comparison

Annual Profit	
P2X	35768,87
Price +50 P2H	74910,30
Solar change P2H	32042,33
Inv -50% P2H	31829,36
550 kW P2H	38707,03

Table 14: Annual Profit (CHF)

The highest Annual profit has the P2H configuration with a +50% price increase, when the rest of profits are on the relatively same level, as it can be seen in the following picture.

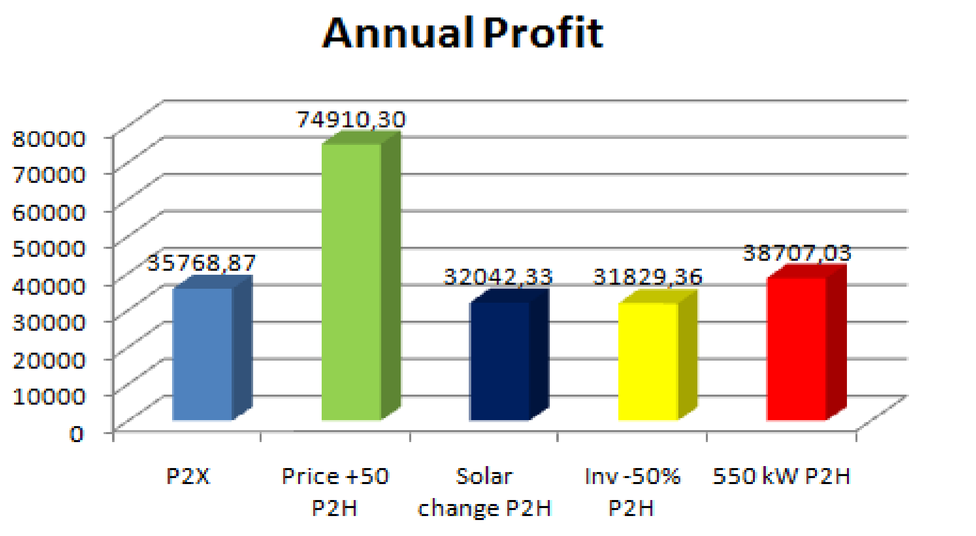

Figure 21: Annual Profit (CHF)

Equity IRR comparison

Equity IRR	
P2X	1,34%
Price +50 P2H	27,63%
Solar change P2H	4,04%
Inv -50% P2H	17,01%
550 kW P2H	8,40%

Table 15: Equity IRR comparison (%)

Here also, the highest Equity IRR has the P2H configuration with +50% price increases, when the rest of equities are on the relatively same level, as it can be seen on the following picture.

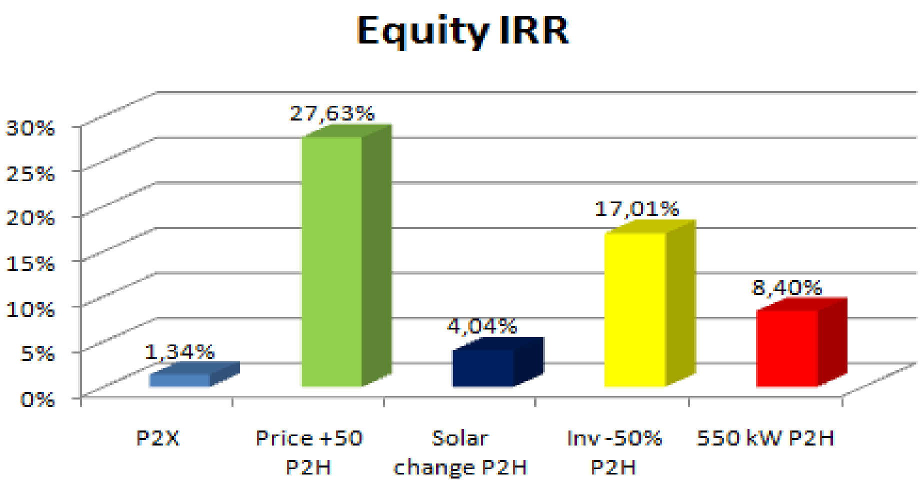

Figure 22: Equity IRR (%)

Min DSCR	
P2X	1,22
Price +50 P2H	3,362987
Solar change P2H	1,39
Inv -50% P2H	2,39
550 kW P2H	1,70

Table 16: Min DSCR comparison

Finally, the highest Min DSCR has the P2H configuration with +50% price increases, when the rest of equities are on the relatively same level, as it can be seen on the following picture:

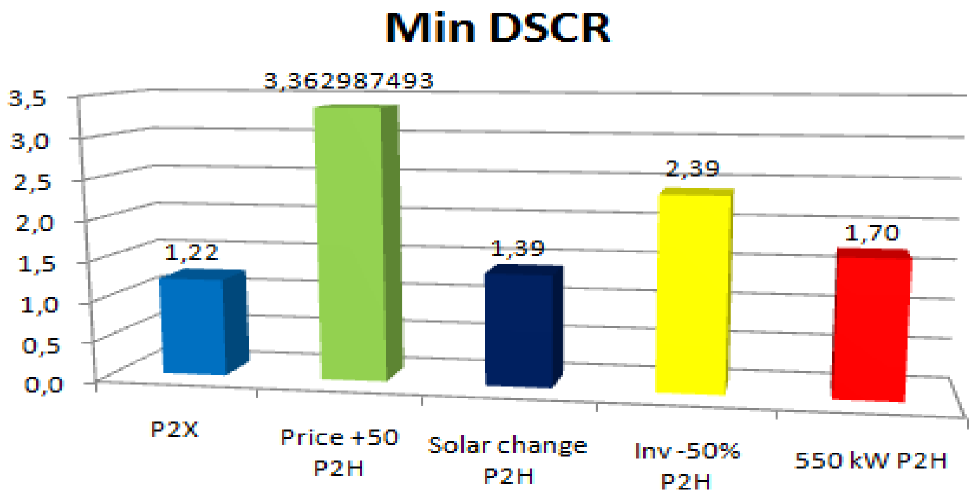

Figure 23: Min DSCR

6

Conclusions

6 Conclusions

6.1 Conclusions

For P2H, the future injection potential is mainly determined by the H2 admixture allowance, assuming that total determinants of the future need of energy storage includes the extent at which intermittent renewables will be installed domestically, the pace at which nuclear reactors will be phased out in Switzerland and keenness of the energy industry participant to build gas-fired power stations. Today, Switzerland's energy landscape is changing and there exist numerous of inconstant parts that make the modeling of future system difficult.

In this project five main cases were investigated. Additionally, in each case, sensitivity analysis was conducted.

In the first case, the prices of commodities on the market were increased and decreased four times by +25%, +50%, -25% and -50% relative to the base case prices. The study showed that P2H has the highest Equity IRR and Min DSCR (+50% scenario), by that making the most profit and the -50% price decrease has the lowest Equity IRR and Min DSCR for the all scenarios.

In the second case the Solar Input into the system was changed. Electricity supply of the base case was given by the year of 2005 time series when in the sensitivity analysis; it was changed by the year of 2004 time series. The results showed that Equity IRR and Min DSCR are the highest in the case P2H system configuration.

In the third case Investment Costs were increased and decreased four times by +25%, +50%, -25% and -50% relative to the base case investment costs. The conducted study exhibited that Annual Profit does not change with scenario and technology change, if compared with the base case. In the case of decreased Investment Costs (-25% and -50%), both scenarios with P2H configurations have the highest Equity IRRs and Min DSCRs.

The fourth case doubles the solar power capacity by increasing it from 275kW to 550kW. The results showed that Equity IRR and Min DSCR of P2H configuration is higher than P2P's.

The last case incorporates all the possible configurations of the system together and calculates the profitability of the system. Then, the highest Equity IRRs and Min DSCRs of all previously mentioned cases are compared with the same parameters of the P2X system. The study showed that in all 5 cases the highest Equity IRR and Min DSCR had the P2H configuration of the system.

This study shows the profitability of several cases and their sensitivity analyses. The outputs of the cases are compared within each other in order to show which system with which configuration, price, investment costs, solar capacity and solar input might be the most suitable one for certain stockholders. Using this data, one can decide, depending on the amount of funding available, the current prices of commodities on the market, location and the technology available, which configuration of P2X system to build in order to make the maximum profit possible.

6.2 Recommendations and Future Work

This study opens new questions to be investigated in the future. This study is capable to show what are the aspects of the project that can be improved in the future works, by the same time giving recommendations on how the stated goals can be achieved. Therefore, I emphasize that more research should be done on this topic:

- The prices of commodities in different markets can vary significantly, thus considerably affecting the outputs of the system. Hence, a new study can be conducted; taking into account specific construction location of the system and, depending on that, the assessment of the profitability of the system can be carried out.
- The solar input time series of the system can be studied. The time series from the past can be included into the system in order to assess the profitability of the system in the past, as well as time series of the future solar energy supply, derived from statistical analysis, can be used to assess potential profitability of the system in the future.
- Depending on the maturity of technologies available (efficiency of electrolysis, methanation, fuel cell, technical parameters) at the time of the construction of the P2X system, investment costs can vary. Thus, one can assume future investment costs of the system and predict future profits of that kind of system.
- Depending on the P2X system, solar power capacity can be changed. Thus, one can assess the profitability the system with each increase or decrease of the solar power capacity.
- Instead of solar, wind power can be used as an electricity supply of the system and the same cases can be run in order to observe how the system will behave. Moreover, solar power together with wind power could be used as an electricity supply for the system.
- Additional scenarios, optimizing the changes in results when P2H case is available (using electrolysis only) (increasing the efficiency when the additional step of methanation is avoided), and selling hydrogen as a product together with power

could be easily simulated with this model. In the same manner, optimizing the changes in results when P2G is available, and selling SNG and heat could be also easily simulated.

- Increasing the P2X capacity with an increased solar capacity for analyzing past and predicting future scenarios can be also simulated, which will give interesting conclusions on the most profitable P2X cases.

7 References

- Andresen, G. B. *et al.* (2014) 'The potential for arbitrage of wind and solar surplus power in Denmark', *Energy*, 76, pp. 49–58. doi: 10.1016/j.energy.2014.03.033.

- Badwal, S. P. S., Giddey, S. and Munnings, C. (2013) 'Hydrogen production via solid electrolytic routes', *Wiley Interdisciplinary Reviews: Energy and Environment*, 2(5), pp. 473–487. doi: 10.1002/wene.50.

- de Boer, H. S. *et al.* (2014) 'The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels', *Energy*, 72, pp. 360–370. doi: 10.1016/j.energy.2014.05.047.
- Clerens, P. (no date) *EASE/EERA European Energy Storage Technology Roadmap towards 2030*.

- Costa, F. C. *et al.* (2015) 'TECHNICAL PROCEDURES FOR USING SYNTHETIC NATURAL GAS AS AN ALTERNATIVE TO NATURAL GAS IN DIFFERENT SUPPLY CONDITIONS FOR INDUSTRIAL CUSTOMERS', 9(2), pp. 37–44. doi: 10.5419/bjpg2015-0005.

- *Debt-Service Coverage Ratio (DSCR)* (no date). Available at: http://www.investopedia.com/terms/d/dscr.asp (Accessed: 30 June 2017).

- *ESI Plattform | Paul Scherrer Institut (PSI)* (no date). Available at: https://www.psi.ch/media/esi-platform (Accessed: 29 June 2017).

- Gotz, M. *et al.* (2016) 'Renewable Power-to-Gas: A technological and economic review', *Renewable Energy*, 85, pp. 1371–1390. doi: 10.1016/j.renene.2015.07.066.

- Gahleitner, G. (2013) 'Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications', *International Journal of Hydrogen Energy*, 38(5), pp. 2039–2061. doi: 10.1016/j.ijhydene.2012.12.010.

- Guandalini, G., Campanari, S. and Romano, M. C. (2015) 'Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment', *Applied Energy*, 147, pp. 117–130. doi: 10.1016/j.apenergy.2015.02.055.

- Hafenbradl CTO, D. (2016) 'Biological methanation processes European PowertoGas Platform: Second Meeting 2016'. Available at: http://www.europeanpowertogas.com/media/files/Meeting June 2016/004 Electrochaea Doris Hafenbradl - Biological Methanation Processes.pdf (Accessed: 29 June 2017).

- Hansen, A. B. and Nybroe, M. H. (2012) 'Future possibilities — The gas system as flexibility provider for wind power production', in *2012 IEEE Power and Energy Society General Meeting*. IEEE, pp. 1–8. doi: 10.1109/PESGM.2012.6344741.

- Hendriksen, P. V and Energikonvertering, D. (no date) 'Energikonvertering i fremtidens effektive energisystem'. Available at: http://orbit.dtu.dk/fedora/objects/orbit:119593/datastreams/file_b0bc0418-1d10-44c0-900f-1482e566c4b3/content (Accessed: 29 June 2017).

- *Introduction to Power to Gas* (no date). Available at: http://www.powertogas.info/english/introduction-to-power-to-gas/ (Accessed: 29 June 2017)

- Jentsch, M., Trost, T. and Sterner, M. (2014) 'Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario', *Energy Procedia*, 46, pp. 254–261. doi: 10.1016/j.egypro.2014.01.180.

- De Joode, J. *et al.* (2014) 'Exploring the role for power-to-gas in the future Dutch energy system Final report of the TKI power-to-gas system analysis project'. Available at: https://www.ecn.nl/docs/library/report/2014/e14026.pdf (Accessed: 29 June 2017).

- Mohseni, F., Gorling, M. and Alvfors, P. (2013) 'The competitiveness of synthetic natural gas as a propellant in the Swedish fuel market', *Energy Policy*, 52, pp. 810–818. doi: 10.1016/j.enpol.2012.10.049.

- 'National Report Denmark 2014' (no date). Available at: http://energitilsynet.dk/fileadmin/Filer/Information/Diverse_publikationer_og_artikler/National_Report_Denmark_2014.pdf (Accessed: 29 June 2017).

- Qadrdan, M. *et al.* (2015) 'Role of power-to-gas in an integrated gas and?electricity system in Great Britain', *International Journal of Hydrogen Energy*, 40(17), pp. 5763–5775. doi: 10.1016/j.ijhydene.2015.03.004.

- Reiter, G. and Lindorfer, J. (2015) 'Evaluating CO2 sources for power-to-gas applications ? A case study for Austria', *Journal of CO2 Utilization*, 10, pp. 40–49. doi: 10.1016/j.jcou.2015.03.003.

- Renewable Energy Agency, I. (no date) 'IRENA-IEA-ETSAP Technology Brief 4: Thermal Storage'. Available at: www.etsap.org (Accessed: 29 June 2017).

- Sterner, M., Institut für Solare Energieversorgungstechnik. and Institut für Elektrische Energietechnik Rationelle Energiewandlung. (2009) *Bioenergy and renewable power methane in integrated 100% renewable energy systems : limiting global warming by transforming energy systems*. Kassel University Press. Available at: http://www.upress.uni-kassel.de/katalog/abstract.php?978-3-89958-798-2 (Accessed: 29 June 2017).

- Ulleberg, Ø., Nakken, T. and Eté, A. (2010) 'The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools'. doi:

- Varcoe, J. R. *et al.* (2014) 'Anion-exchange membranes in electrochemical energy systems', *Energy Environ. Sci.* Royal Society of Chemistry, 7(10), pp. 3135–3191. doi: 10.1039/C4EE01303D.

- *What is a Hydrogen Fuel Cell and How Does it Work?* (no date). Available at: https://www.setra.com/blog/what-is-a-hydrogen-fuel-cell-and-how-does-it-work (Accessed: 29 June 2017).

- Zakeri, B. *et al.* (1997) *Renewable & sustainable energy reviews.*, *Renewable and Sustainable Energy Reviews*. Elsevier Science. Available at: http://econpapers.repec.org/article/eeerensus/v_3a42_3ay_3a2015_3ai_3ac_3ap_3a569-596.htm (Accessed: 29 June 2017).