UNIVERSITY OF TWENTE.

Internship Report

Feasibility Study of Power to Gas Technology at Twence

A report of a three months internship at Twence Waste Processing Plant in Hengelo, the Netherlands

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PREFACE

This report in front of you is the result of my internship assignment, as a requirement to fulfill the curriculum of Sustainable Energy Technology at the University of Twente. My internship takes place at Twence, a waste processing plant in Hengelo, The Netherlands. During the internship, I was assigned to a team of business and strategy development.

It has been great working experience at Twence and I have learned many things especially in the field of sustainable energy technology. Firstly, it shows me the working culture of Dutch people. My impression is that not only they are very professional and smart, but also they do not forget to maintain their work life balance. I would recommend that the Netherlands particularly Twence is one of the top places to work as an engineer. Second, working at Twence has inspired to be always optimist with the green technology because there are so many business opportunities for being green. After all, it was a very precious time to be part of Twence.

With the given topic, I have dealt with many challenges but it gave me interesting tasks as an engineer. At first, it worried me a little bit because the main core technology at Twence is about chemical engineering, while my major background is mechanical engineer. However, the smart philosophy of Power to Gas has kept me enthusiastic with the topic. Basically, I was given much free time to explore all of the research possibility and I really enjoyed the brainstorming session. Besides, this topic also has given me opportunities to learn the thermodynamic flowsheet model, financial budgeting study, and energy market analysis. After all, I can say it has been valuable experience for my master study and for my career.

I would like to thank my mentor, Henk Fikkert, for his continuous support and kindness, Leender Tamboer for the internship opportunity he gave to me, T.H. van der Meer for his guidance, and other friendly and supportive colleagues.

Last but not least, I would like to thank my lovely wife, Fikria Karinanur, who is always supporting me in every single moment of my life, my child, Airafilah Nabiha, who is always smiling at me when I get back home, and my parents, who are always praying for the best of my life.

Bima Anggun Putra

Enschede,

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EXECUTIVE SUMMARY

The business of selling electricity is becoming less profitable at Twence, as the wholesale electricity price tends to continuously drop. In responding to this problem, it is important for Twence to find any of new possibilities to create a business case that can offer benefits by using the low price electricity. For this purpose, Power to Gas (P2G) technology can be one of the candidates and it is becoming a topic of feasibility study at Twence.

P2G is a potential business case at Twence. The P2G technology could be well collaborated with biomass/waste processing plant, thus it fits with the main business of Twence. The final products of P2G are also very flexible such as hydrogen, methane, or methanol. This flexibility makes P2G adaptable with the future energy market.

In accordance to above, it is worthy to do an investigation regarding the possibility to apply P2G at Twence. During three months internship, several investigations have been done. The result of investigation is provided in this report in which the structure consist of the following chapters.

Chapter 1 gives a brief introduction into the subject. First, a short description is given to the existing plants at Twence that are likely to have a relation with P2G. It is then followed by definition of problems, objectives, and methodology.

The aim of investigation is to identify possible routes of P2G and to define probability operation scenarios as well as business case. To achieve the objective four methodologies are used: (1) literature reviews, (2) analysis of electricity price, (3) thermodynamic and flowsheet modeling, and (4) financial calculation.

Chapter 2 provides a vision of the P2G technology. Basically, P2G takes important role in making a new sustainable carbon cycle. This cycle has a process that can convert CO_2 to synthetic fuels. In addition, the fundamental theory of important reactions such as gasification, methanation, and methanol synthesis are introduced.

Chapter 3 explains the summary of literature reviews. It mainly describes the state of the art of power to gas, the different routes of P2G, and the latest development of plasma gasification. The main result of this chapter is that Power to gas plays a role in the decarbonization scenario. In this scenario, P2G is more likely to act as a chemical converter instead of energy storage. As a chemical converter, P2G offers the routes of methanation or methanol synthesis from CO_2, biomass, or waste. Through these routes, it is possible to create business cases of replacing fossil based chemicals/fuels. These renewable fuels can be distributed to mobility sector or industry.

Chapter 4 provides analysis of spot electricity price using frequency curve. The data of the Netherlands, Sweden, Norway, and Denmark are taken for the analysis. As a result, it is revealed that the high penetration of wind based electricity production positively affects the electricity market price for P2G. This effect of high wind penetration is represented by Denmark spot price in comparison with the other three markets. From this result, it can be discussed that Dutch market will evolve toward a condition similar with DK1, because the Netherlands as well as other European countries has set a higher target of RE production for the next decades.

Chapter 5 describes the process of making flowsheet model. In short, the flowsheet model was successfully created and it can be used for comparison analysis between different input variables, routes, or operation scenarios of P2G system.

Chapter 6 presents the simple mass calculation using ideal stoichiometric ratio. The calculation is done to compare the difference between the output quaintly of methanation and methanol synthesis. From this chapter, it is concluded that the process of methanol synthesis is more efficient than methanation.

Chapter 7 elaborates the route of methanol synthesis. Three scenarios are investigated: (1) methanol synthesis using CO_2, (2) low yield methanol synthesis using biomass, (3) high yield methanol synthesis using biomass. From the investigation, it appears that the case no.2 is the most efficient process, because it has optimum methanol production while keeping the electrolyzer capacity at minimum value. In addition, it is also found that the use biomass (the biomass case) led to a higher production of methanol, compared to the use of waste (the waste case). Nevertheless, the waste feedstock has a negative price in which it may improve the net cash flow. In the end, further investigations about the financial feasibility of both the waste and biomass case shall be done

Chapter 8 presents the result of the financial calculation. The waste case shows a better result than the biomass case. In the waste case, profitable business case is noted (IRR>0), but the NPV has not fulfilled the Twence minimum requirement yet. Following this result, the sensitivity analysis is done to investigate which factor could significantly affect the value of NPV and IRR. It is found that NPV and IRR are sensitive to the investment cost of gasifier. Also, intermittent operation (winter summer cycle) has negative impact on NPV. This is because the growth of cash flow by intermittent operation does not compensate the larger capital cost.

Chapter 9 explains the overall conclusion and recommendation. The conclusion combines all important messages and results from previous chapters. Most importantly, this study has revealed that the route of waste to methanol is the most feasible business case for Twence. Furthermore, The accomplishment of this study has opened various possibilities for further investigations such as the prediction of energy market, the improvement of the model accuracy, etc.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

The definition of Power to Gas Technology (P2G) may differ, depending on different perspectives. Commonly, P2G is defined as an energy system used to convert the electricity to gas. This meaning might be misinterpreted because it is impossible to transform the energy to a mass. However, from a different point of view, the electricity is in fact used to convert hydrogen and/or carbon containing feedstock to more valuable products such as gas or liquid fuel. The produced synthetic fuel is then used for instance as an energy carrier or a final chemical product. After all, P2G is the technology that may involve several chemical reactions including electrochemical, thermochemical, and/or biological reactions.

Twence might be a suitable place for realizing the P2G technology due to its availability of electricity and the chemical source (carbon, hydrogen, and oxygen) from municipal waste and biomass. Therefore, the feasibility of applying P2G at Twence Waste Processing Plant is discussed in this report. As an opening, general introductions of this study are explained in this chapter. The introduction includes the overview of Twence, problem definition, objectives and research questions, and methodology.

1.1. General overview of Twence

Twence is a waste processing plant producing raw materials and renewable energy. The raw materials are recovered from the waste by means of the separation process as well as the biological or chemical reaction processes. Meanwhile, the renewable energy is generated in a form of electricity and heat by burning the non-recyclable municipal waste and woody biomass. Located in Hengelo, Province of Overijssel, Twence has been delivering 50% of the steam production to a neighbor factory namely AKZO Nobel. Additionally, Twence is also providing heated water for district heating to the city of Enschede, FC Twente Football Stadium and University of Twente. The name of customer of the district heating is *EnNatuurlijk*. In 2014, the electricity production supplied to the public grid is approximately 401.8 GWh. This is comparable with the consumption of 15.000 households. Moreover, the heated water and steam production reached 169 GWh and 475 GWh respectively. This resulted in saving of around 95 million cubic metres of natural gas along with CO2 emission savings of more than 168,000 tons [1].

Several waste processing plants have been installed at Twence. The photograph of the entire plant layout is shown in Figure 1. It consists of the Energy from Waste Plant (EfW Unit 1,2,3), Biomass Power Plant (BPP), Bio Fermentation Plant, Bioconversion Plant (Digesting and Composting Plant), Waste Separation Plant, and a Landfill. In this introduction, high attentions are given to the EfW, BEC, and Bio Conversion Plant, since these plants may offer some possibilities to be in integration with Power to Gas technology.

Energy from Waste Plant (EfW)

The energy from non-recyclable wastes is regenerated in this plant. The EfW plant processes over 600,000 tons of waste every year. Units 1 and 2 of this plant have the same design capacity and were built for the early operation, while unit 3 is designed for a bigger capacity and was established later. The waste is delivered into the furnace where the incineration process takes around 45 minutes. The combustion occurs in the furnace at a temperature of 850 -1100 ºC. With this process, various emissions are released and treated in flue gas scrubbing. Additionally for the unit 3, Carbon Capture Storage (CCS) is mounted for capturing CO_2 from the flue gas. The bottom ash/slags are also formed in the incinerator as by-products of the waste burning process. For this, the bottom ash reprocessing plant at Twence is operating to extract the valuable metal remaining in the slag after the incineration process. Until now, Twence has been able to recover around 12,000 tons of ferrous and 3,500 tons of non-ferrous metals [2]. Despite of the constant of overall steam production, the supply of heat and electricity from this plant is varying throughout the year. This is mainly because of the changing demand from Twence's main customers: *AKZO Nobel* and *EnNatuurlijk*. Since *AKZO Nobel* can also partly generate the steam and power by burning natural gas, the supply of renewable steam from Twence is fluctuating, depending on the grid electricity price. Furthermore, the demand of steam for district heating is also varying due to seasonal change.

Biomass Power Plant

Unlike the EfW, Biomass Power Plant (BPP) processes only waste wood, mainly low-grade waste wood, woody non-compostable elements, and coarse element from bioorganic waste. The biomass is combusted at 1000ºC with residence time almost the same with the EfW plant. This plant currently produces only electricity with 141.6 GWh supplied to public electricity grid in 2014 [1]. This amount is sufficient for approximately 44,000 households. This unit is recorded to have constant electricity productions throughout the year. However, there has been a development plan to improve the plant energy efficiency by delivering both steam and electricity to customers.

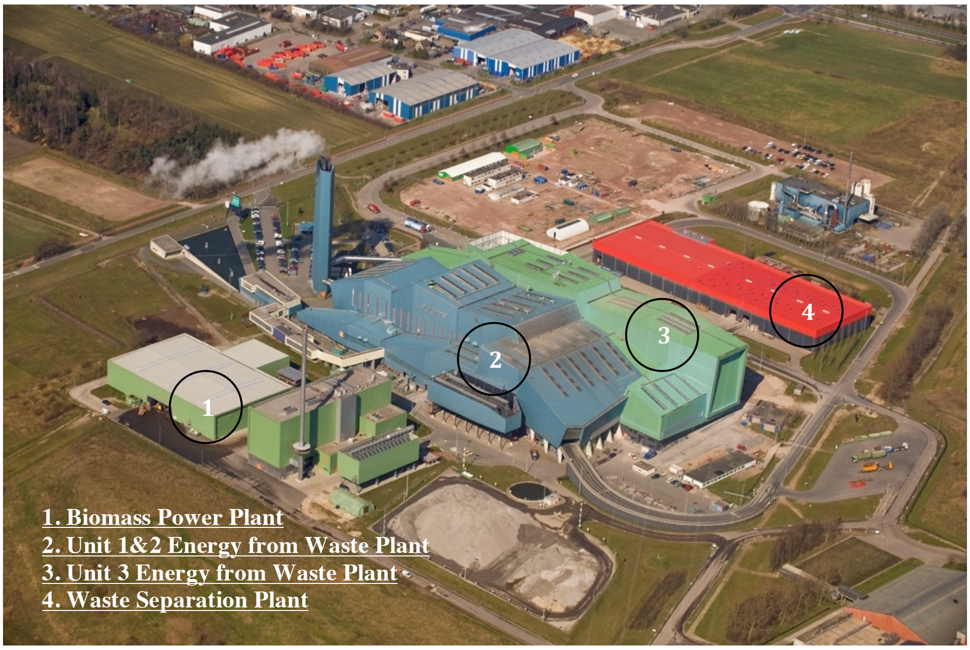

Figure 1. The layout photograph of Twence.

Bio Fermentation Plant

Bio fermentation plant, or usually called Combi Digester Plant, is a pilot plant for digesting coarse and contaminated biomass. This plant mainly consists of two types of fermenters/digesters: Container Digester and Wet Digester. With these installations, Twence enables to generate approximately 100 m^3 of biogas. The biogas is then burned in the Combine Heat Power (CHP) unit, producing 250 kW of electricity and 250 kW of thermal energy [2].

1.2. Problem definition

The idea to use Power to Gas technology is becoming an issue at Twence due to both external and internal problems. These problems include:

1. **The increasing of intermittent power supply from Renewable Energy Source (RES):** With the increase of the utilization of solar and wind energy as primary renewable energy sources, it is predictable that the intermittent power supply will grow substantially in the near decades. It is reported that the European target of Green House Gas (GHG) emission in 2050 is 80%-95% reductions from 1990 level. To support this, 75% share of RES in gross final energy consumption is required [3]. Consequently, the increasing of intermittent power source, as an impact of the inconsistency of wind and solar irradiance, may lead to a problem where the excess or deficits of power supply to electricity grids occur more often.

2. **The decreasing of wholesale electricity price:** The business of selling electricity is becoming less profitable, as the wholesale electricity price tends to continuously drop. In responding to this problem, it is important for Twence to find any of new possibilities to create a business case that can offer benefits from the cheap electricity.

3. **The high fluctuation in spot market price for electricity:** Great fluctuations of electricity price are found in the short time based market, and this would open a business opportunity for P2G. Daily ahead market or commonly called Spot Market is an hourly electricity wholesale market. The price in this market is mainly

determined by balancing the amount of supply and demand in a specific hour. Moreover, the price might significantly move to negative or very high positive level, especially if the volume of electricity is largely influenced by intermittent RE source. In addition, another short time based electricity market, so-called imbalance market, is also available. This market offers electricity trading that is used to manage the surplus or deficit of the actual power generated from a generator. The time frame is shorter than hourly spot market and the price radically and randomly varies over the time. To summarize, the great fluctuation of electricity price may open a business opportunity for P2G, since there are certain periods where the electricity price drops to a value under the level of gas.

4. **Ineffective use of organic wastes:** Some organic wastes are ineffectively used or treated at Twence. Firstly, by-product of composting plant so called Sieve Overflow has become a major problem at Twence Plant. Currently, Twence must pay taxes for dumping these materials. Although they can be sent and burned in BPP, the amount of Sieve Overflow going to the BPP is very limited. This is due to the fact that Sieve Overflow contains high composition of minerals that may lead to corrosion problems in the burner. Secondly, Twence is now searching for an effective way to treat the Organic Waste Fraction. These materials will be later separated from “other waste” in the Waste Seperation Plant. Until now, there are no options except sending the materials to the incinerator.

5. **Unstable electricity production:** The actual production, or normally called Realization, rarely match the target production, or normally called Nomination. At Twence, the contracts of steam delivery to AKZO Nobel and *EnNatuurlijk* are being made as per daily agreement. Therefore, everyday Twence set the nomination of steam production, and followed by the nomination of electricity production. The difference between realization and nomination would represent the excess or lost production per day. This instability of electricity production is now being resolved by getting involved in the imbalance market. However, the imbalance market price is very volatile. Therefore, another solution to back up the steam and electricity production is required.

After all, the proposed P2G system in this study is therefore meant to overcome the above problems.

1.3. Objectives

The main objective of this feasibility study is to find a possible solution to tackle the future energy challenges and to see if there are any of new business opportunities for the future market. With understanding of the defined problems, it is therefore important to identify possible routes of P2G and to define probability operation scenarios as well as the business case. To be more specific on to what extend this study will contribute in achieving the objectives, the following research questions are determined.

1. *Which P2G route is likely feasible to be in integration with the existing Twence Plant?*
2. *What operation scenario has the most benefits for Twence?*
3. *How much the Interest rate of Return (IRR) of the selected P2G business case?*

1.4. Methodology

This study is conducted as a requirement to complete the master program of Sustainable Energy Technology in University of Twente. Therefore, the methodology to reach the assignment goal shall be in relevant to the intended program and the scope of works shall be feasible to be accomplished within the given period of internship (three months). In this assignment, the following methodology is used.

1. **Literature review**: This includes studies about the state of the art of P2G, energy market and price, and other technologies related with waste pre processing such as high temperature of gasification.
2. **Statistic analysis of electricity price**: the history data of wholesale electricity price from different countries are collected. Using this data, statistic analyses will be made.
3. **Route modeling by a flowsheet program**: The P2G/ route will be modeled in a flowsheet program named Cape Open (COCO) simulator. The purposes of this model are to understand the mass and energy flow, to show the performance of the selected route, to analyze the sensitivity of multiple parameters, etc.
4. **Financial study**: Analyses of CAPEX and OPEX are conducted to know the economic feasibility of the selected scenario.

CHAPTER 2: FUNDAMENTAL THEORY

The fundamental theories related closely to P2G technology are explained in this chapter. First, a simple picture of a carbon cycle with a new sustainable carbon route will be introduced. It is then followed by a brief explanation about the technology pathway with respect to energy carrier and biomass conversion process. Lastly, the basic theories in modeling important reaction such as methanation, methanol synthesis, and gasification will be mentioned as well.

2.1. P2G in the carbon cycle

The importance of P2G can be seen in the new carbon cycle. To understand this, the conventional carbon cycle is introduced first. CO_2 is conventionally released to the air as a product of combustion, and the carbon is recycled by means of photosynthesis. Then, the carbon is used again as a fuel in the form of biomass or fossil fuels (coal, oil, natural gas). The rate of this cycle is slow in the process photosynthesis, as well as in the transformation of biomass to fossil fuel. Consequently, it will lead to a high concentration of CO_2 in ambient, known as the major cause of global warming. Compared to the conventional carbon cycle, the new generation of carbon cycle shows different loop and processes, as the P2G devices are utilized to convert CO_2 emission to fuel. The new carbon cycle is illustrated in Figure 2. To catch the CO_2 from the flue gas of combustor, Carbon Capture Storage (CCS) can be used. Then, the CO_2 will be transferred to a process such as methanation or methanol synthesis in which the fuel producing reaction will occur. Next, the fuel would be stored until it is released whenever the energy demand is high. In this way, the cycle rate is improved and it is now possible to increase the energy rate without releasing more carbons to the atmosphere.

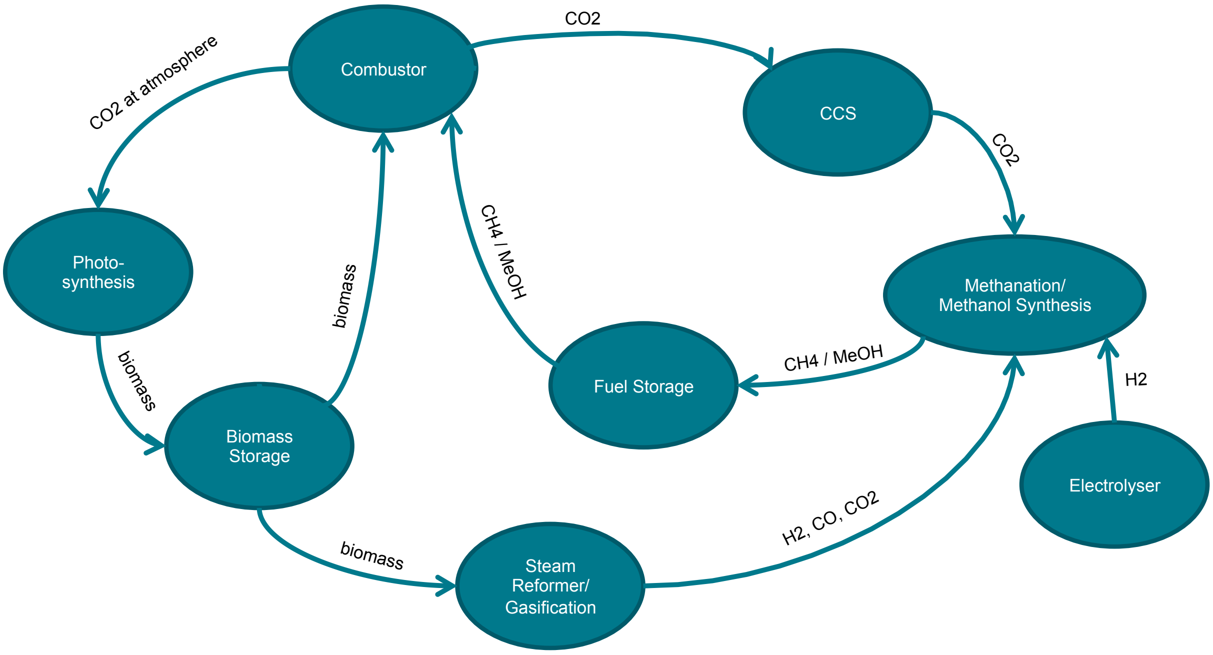

Figure 2. The carbon cycle with the use of P2G.

Recycling CO_2 is not always an efficient way to produce synthetic fuels. Unless it is extracted from the flue gas of combustion, it takes a lot of energy to catch CO_2 from the ambient air. Moreover, when it is not necessary to burn the fuel, it is meaningless to obtain CO_2 from flue gas.

Based on the above reason, it is also important to find a route to produce fuels directly from the biomass. As shown in Figure 2, it is possible to create a shortcut to generate H_2, CO, or CO_2 from biomass by means of a steam reforming or gasification reaction. This route is efficient in storing the energy, because a combustion process does not take a place.

Steam reforming and gasification have similar function but different concepts. The steam reforming reaction occurs to biomass with the addition of steam. Moreover, this reaction is done in the absence of oxygen, resulting in a highly endothermic reaction. Hydrogen and CO_2 are the final products of this reaction. On the other, gasification could become an alternative to store the energy from biomass. The main products of this reaction are CO and H_2 or so commonly called Syngas. The main difference between the concept of gasification and steam reforming is that the gasification process requires gasifying agents/mediums. Depending on the type of the agents, the gasification could become an endothermic or exothermic reaction.

The steam reforming is the most challenging process. This process needs catalyst and high amount of energy. Currently the steam reforming for biomass is still under research. In fact, the steam reforming is now being used commercially only for natural gas as a feedstock.

2.2. Technology pathway of energy carrier

Technology pathway of an energy carrier could be predicted by examining its history trend. Presented in Figure 3, H/C ratio could be the indicator to define what type of energy carrier will be demanded in the future market. As the H/C ratio is continuously increasing over the time, it is predictable that the future fuel is hydrogen. Nevertheless the world's technology has not reached yet the hydrogen economy. It is known that the C-1 fuel such as methane or methanol is currently becoming more attractive in the energy market. This condition indicates that the Power to Methane or Methanol might be feasible options for the electricity storage system.

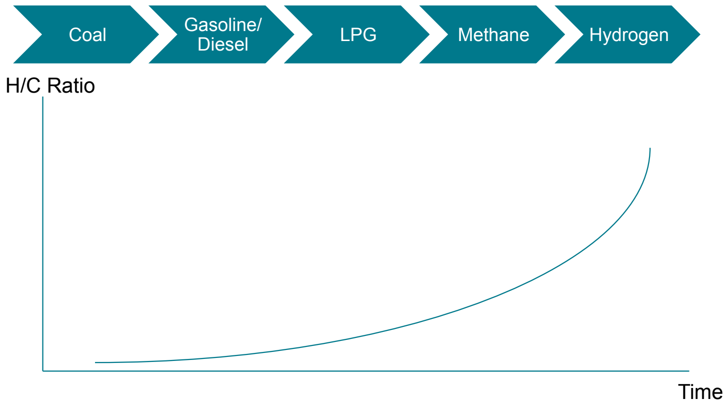

Figure 3. Technology pathway for energy carrier.

2.3. Reaction of gasification, methanation, and methanol synthesis

Gasification is the process of converting solid/liquid carbonaceous material (in this case biomass) into carbon monoxide and hydrogen or commonly known as Syngas. There are some important reactions taking places in the gasification process. Both exothermic and endothermic reactions (1) - (14) consecutively happen in the reactor. To produce gas with higher H/C ratio, the gasification process adds hydrogen and/or strips away the carbon from hydrocarbon feedstock. Therefore, the gasification requires a medium/gasifying agent to make the reaction occurred. The main gasifying agents used for gasification are oxygen, steam, or air.

In the case of conversion of CO_2 and CO to methane, the Sabatier Reaction (11) and (12) can be applied respectively. Both reactions are highly exothermic but need a catalyst to enhance the kinetic. Depending upon the application and the catalyst type, the Sabatier methanator is typically run at temperature of 250 – 400 °C [4]. At a higher temperature, the catalyst integrity could become an issue, and the reaction is likely toward the reverse direction. Methanation reaction needs H_2 as a reactant in which the H_2 could be obtained as a product of water decomposition (15). In this case, the P2G is meant for using electricity power to produce H_2 by means of electrolysis.

Methanol synthesis is a process to produce methanol from any hydrocarbon source. The reactions (16) and (17) use a solid catalyst and the global reaction of methanol synthesis is exothermic, reaching the higher conversion at a lower temperature. However, a lower temperature should compromise the small specific reaction rates. A study shows that the reactor temperature is set as 280 °C such that a high pressure steam can be produced by the reactor [5]. In this study, the input material for this reaction is syngas. Methanol from syngas involves hydrogenation of CO (16), CO_2 (17) and reversed water gas shift reactions (9).

Carbon Reactions:		
$C + CO_2 \leftrightarrow 2CO$	$\Delta H_{298\ K} = +172$ kJ/mol	(1)
$C + H_2O \leftrightarrow CO + H_2$	$\Delta H_{298\ K} = +131$ kJ/mol	(2)
$C + 2H_2 \leftrightarrow CH_4$	$\Delta H_{298\ K} = -74.8$ kJ/mol	(3)
$C + 0.5O_2 \rightarrow CO$	$\Delta H_{298\ K} = -111$ kJ/mol	(4)
Oxidation Reactions:		
$C + O_2 \rightarrow CO_2$	$\Delta H_{298\ K} = -394$ kJ/mol	(5)
$CO + 0.5O_2 \rightarrow CO_2$	$\Delta H_{298\ K} = -284$ kJ/mol	(6)
$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$	$\Delta H_{298\ K} = -803$ kJ/mol	(7)
$H_2 + 0.5O_2 \rightarrow H_2O$	$\Delta H_{298\ K} = -242$ kJ/mol	(8)
Water-Gas Shift Reaction:		
$CO_2 + H_2 \leftrightarrow CO + H_2O$	$\Delta H_{298\ K} = +41.12$ kJ/mol	(9)
Methanation Reactions:		
$2CO + 2H_2 \rightarrow CH_4 + CO_2$	$\Delta H_{298\ K} = -247$ kJ/mol	(10)
$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$	$\Delta H_{298\ K} = -165.0$ kJ/mol	(11)
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	$\Delta H_{298\ K} = -206.0$ kJ/mol	(12)
Steam Reforming Reactions:		
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$\Delta H_{298\ K} = +206$ kJ/mol	(13)
$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	$\Delta H_{298\ K} = -36$ kJ/mol	(14)
Water Decomposition:		
$2H_2O \leftrightarrow 2H_2 + O$	$\Delta H_{298\ K} = +285.8$ kJ/mol	(15)
Methanol Synthesis Reactions:		
$CO + 2H_2 \leftrightarrow CH_3OH$	$\Delta H_{298\ K} = -90.55$ kJ/mol	(16)
$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$	$\Delta H_{298\ K} = -49.43$ kJ/mol	(17)

CHAPTER 3: LITERATURE REVIEW

In this chapter, literature reviews that support the idea to apply P2G are described. This chapter is started with a brief description of the state of the art of P2G from multiple literatures such as books, scientific papers/journals, and presentation slide of several companies involved in P2G business. It is then followed by brief insights about the importance and the opportunity of utilizing waste/biomass to produce methanol. Next, information summary about the latest development of high temperature gasification using a plasma heater is provided. Lastly, the overall summary of this chapter is given.

3.1. Power to gas: state of the art

Power to Gas is a distinctive route to tackle the future energy challenge. From an exergetic perspective, electricity should always be utilized as electricity. However, when problems occur in the electricity sector (such as congestion, negative electricity price or physical damage) or an electricity infrastructure is lacking at the production site, the electricity can be converted into hydrogen (gas). Power to Gas could also be used to overcome continuous transmission capacity constraint (grid specific) or to transport energy over long distances [6]. P2G is distinctive from other power storage technologies because of the characteristic in which the gas is being produced as an intermediate product. Generally, there are two possibilities of hydrogen conversion: (1) hydrogen from electrolysis is stored and reconverted to electricity by fuel cell, or (2) hydrogen/methane is accommodated in the gas infrastructure and reconverted into power by conventional technology. This way, electrical grid expansion can be avoided when stored energy is transported away through the gas distribution system. However, it shall be noted that the amount of hydrogen that can be fed into a natural gas grid is limited. The maximum allowed hydrogen fraction in the Dutch gas transmission grid is 0.02 vol% [7]. From 2021 onwards, the maximum allowed hydrogen fraction would be 0.5 vol% [8].

Different performances of P2G system are reported in many literatures. A study by [9] concluded that the overall efficiency of different P2G systems is in the range of 77% in case of power to hydrogen, to as low as 18 % in case of power to methane (CO_2 source is from atmosphere). Nevertheless, efficiency is less important in the wider point of view in which the P2G is enabling the delivery of renewable gas in other sectors, such as the industry or mobility sector.

Research and development on P2G is being followed by the progress of development in Methanation process. Generally, the methanation process can be performed in chemical and biological process. Chemical process is a matured technology that is currently available in different industrial application. However, the development on a biological process shows a significant progress as it could offer more advantages, and it is now started being commercialized [10] [11]. Table 1 shows comparison of characteristics between chemical and biological methanation.

The electrolysis is believed as the major technical and economic challenge for the P2G system. Currently, there are three main water electrolysis technologies available, namely Alkaline Electrolysis (AEC), Polymer Electrolyte Membrane Electrolysis (PEMFC), and Solid Oxide Membrane Electrolysis (SOEC). The SOEC, operating at 700-1000ºC, has the highest efficiency potential but currently is the least developed technology. It deals with an issue in the material degradation. The AEC is the oldest and the most mature technology but it deals with a limitation on the flexibility of an intermittent operation which it is highly required for P2G technology [12][13]. A great significant progress of development has been shown for PEMFC. This technology could offer various advantages such as the compact design, high current densities, high operation temperature, high flexibility with respect to operation mode and wide partial load ranges. However, it has several drawbacks such as its high cost, the limited materials, and scaling up problem. Regardless the type, the major challenges of electrolyzer are the limited capacities, degradation behavior and high investment as well as operating cost of electrolyzer systems[12]. Regarding the Intermittency load for electrolyzer, batteries are suitable for short-term energy storage and minimize the cycling of electrolyzer. Besides, they can manage load transients and intermittent power peaks, provide bus stability and smooth out the power output of renewables [13].

The largest share of the investment cost of P2G plant is clearly in the electrolyzer and methanator. The specific cost of the respective devices can only be made with approximate standard values because the actual cost depends on the intended use of the system. The costs including all electrolyzer peripherals are between 1,500 euro/kWe and 9,000 euro/kWe, but it is predicted to be less than 1,000 euro/kWe in 2030 [14]. For the methanator, the future investment cost for comparison is between 130 – 300 euro/kWe [12]. Although the P2G costs are currently still high, the costs of power to gas can achieve market competitiveness in the long term by including additional cost such as energy infrastructure cost [12]. Power to Gas should not be restricted exclusively on the storage option. It can be useful for other system functions, such as the transportation energy.

There are multiple landscapes/environments observed to have major and minor impacts on the application of P2G technology in the future. Firstly, P2G plays a big role in case of an increasingly large role for renewable source in the deep decarbonization energy system. It is found to play a role in a cost-optimal mix of energy technologies in 85% of CO2 reduction scenario. Secondly, The availability of Biomass and CCS has a large impact in which a reduced biomass and CCS potential lead to a larger investment in electrolysis. Methanation is an option to achieve a significant CO_2 emission reduction when the available capacity for CO_2 storage is fully utilized. Thirdly, a lower investment cost has a moderate impact on the role of P2G. Moreover, the need for the flexibility in a larger intermittency power supply is not the key driver as it has less impact than the deep decarbonisation setting. Moreover, an increase or decrease in fossil fuel price is not a game changer for the role of P2G [15].

Table 1. Comparison between chemical and biological methanation.

Characteristic	Chemical	Biology	Reference
Process temperature (oC)	200-750	35-70	[16], [17], [10], [11]
Delivery Pressure (bar)	4-80	1-3	[17], [10], [18]
Maximum Production Capacity (MW_{CH4})	<500	15	[19], [6]
Maturity	Commercial for large plant	Pre-commercial	[6] [10]
Cold Start Time	hours	Minutes	[20], [6]
Annual Availability	85%	90%	[21] [6]
Efficiency (excl. electrolysis)	70-85%	95-100%	[16], [17], [6]

3.2. Waste/biomass to synthetic fuel: integration with power to gas

Understanding the integration of P2G with biomass/waste processing plant is one of the objectives in this chapter. Therefore, the literature review regarding the route of Waste/Biomass to Synthetic fuel as well as the possibilities to be in integration with P2G is performed. It shall be noted that the P2G here refers to hydrogen production with the use of electrolyzer.

The route of waste/biomass to synthetic fuel is essential for Twence in developing a new method to recycle the waste or to utilize the green materials. It can be said that both power to gas and waste/biomass to fuel have the same operation philosophy. This means that there is a possibility to apply integration between these two routes. Figure 4 illustrates the flexibility of using renewable gas storage facility, in a way to combine the route of P2G with the route of waste/biomass to syn-fuel. In addition, the route of making methanol from waste/biomass looks attractive.

Methanol economy shows some opportunities and advantages over methane or hydrogen. As the final energy carrier hydrogen or methane are interesting because of its clean combustion and high HHV especially for hydrogen, but in practice they deal with a storage problem due to the low volumetric density. By contrast, methanol is in a liquid form under normal condition and is easier in handling and transporting. This way, power to liquid technology is defined as the process of making methanol from the hydrogen produced by water electrolysis. The interest of using methanol in energy and transportation sector has been continuously growing. As a fuel for internal combustion engines (ICE), methanol also provides a number of benefits pertaining safety and engine performance (high octane rating, heat of vaporization, flame speed), and its combustion is cleaner than petrol. Besides, the synthetic methanol could replace fossil-derived products for electricity generation in conventional power plants and the chemical industry [22]. Hence, in this study the route for producing methanol as well as the integration with P2G route will be investigated.

3.3. High temperature of gasification

High temperature gasification could become one of the promising technologies for supporting the P2G system. The utilization of pure oxygen from the by-product of electrolysis is the key concept of the integration between the gasification and the P2G system. As explained in the previous chapter the oxygen can be an option for gasifying medium. Oxygen based gasification offers advantages over air based gasification such as lower capital cost or similar operating cost and higher calorific value of syn-gas product [23]. The latest development of gasification technology indicates that the high requirement of clean syngas with controlled composition has led to a very high temperature process with an external energy source. Thermal plasma (plasma with local thermal equilibrium) offers extreme properties with very high temperature of reaction, which can be applied for waste/biomass gasification. Thermal plasmas are dominantly generated by either an electric arc or by a radio-frequency induction discharge [24]. In waste treatment, the DC arc is mostly used. However, the use of some AC plasma torches in biomass gasification are known [25].

Several researches have been conducted for technology conversion of electrical energy to chemical equipped by Argon, Air and water steam DC current plasma torch. The arc temperature of a DC plasma torch varies between 5000 and 1000 K [26]. An experimental investigation by [27] has been performed for a reactor operating at hundred pascal and temperature of 1200-1400 ºC. The throughputs of the tested biomass materials (sawdust, pellets, waste plastics, and pyrolysis oil) for the gasification ranged between 9 and 30 kg/h. The result indicates approximately 90% of CO and H_2 in the syngas with the torch input power of 100 kW. A similar research of plasma gasification by [28] was also established for Refused Derived Fuel (RDF). It is revealed that the thermodynamic equilibrium model works very well for plasma gasification. Experiment data shows that the product gas contains small amount of Volatile Organic Compounds (VOCs) and tars. These results are very close to the thermodynamic equilibrium simulation.

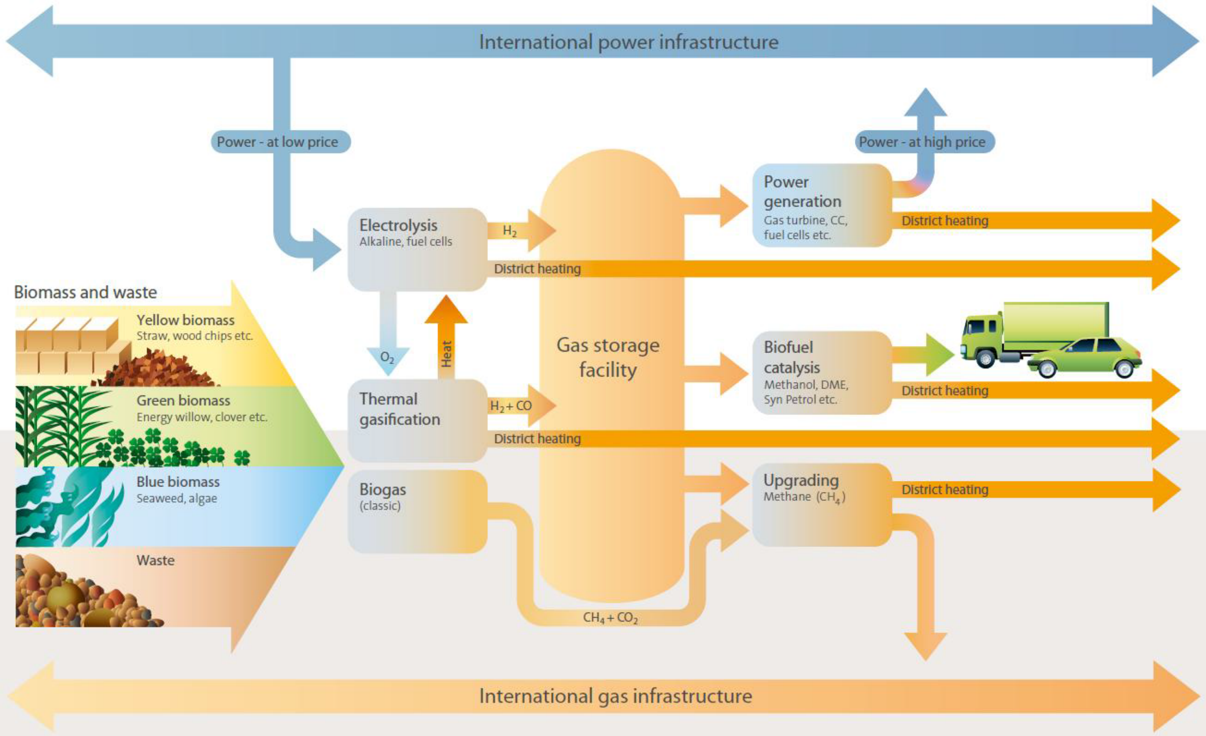

Figure 4. Schematic route of P2G and waste/biomass to synthetic fuels [29].

3.4. Summary

The P2G offers different routes for its application. Using electrolyzer as the hydrogen generator, it provides great flexibility to use the hydrogen as the intermediate medium. Multiple ways to use the hydrogen are known, such as reconverting hydrogen to electricity using fuel cell, delivering hydrogen to natural gas grid (the amount is limited), or converting hydrogen to other types of fuel. Each hydrogen route has different energy efficiency varying within 18 - 77%. Nevertheless, the energy efficiency may not be the first priority, in case of P2G is used for distribution of renewable energy source to industry or mobility sector.

The latest development of P2G technology can be seen in the methanation process. It is found from the literatures that the biological methanation could offer higher efficiency than the chemical methanation due to its capability to operate at low pressure and temperature.

Electrolyzer is still the major challenge for the technical and economic feasibility of P2G. The most mature technology of Alkaline Electrolyzer (AEC) is dealing with the problem of limitation in intermittent power input, while PEMFC, which works well in flexible load, has some drawbacks such as the high cost, scarce material, and scaling up problem. With the investment cost around 1,500 - 9,000 euro/kWe, the electrolyzer may not become a feasible solution. However the use of electrolyer in P2G shall not be limited for energy storage, It may show competitiveness if the P2G is meant for energy distribution system using gas grid.

Despite its multiple drawbacks, P2G can still play a big role under certain landscapes. The relevant literatures mentioned that it is not the lower investment cost, the larger intermittent energy supply, nor the change of fossil fuel price that will significantly affect the role of P2G in the energy market. It is a landscape of deep decarbonization that can raise the importance of using P2G. In this case, P2G will significantly contribute to reach the target of 85% CO_2 reduction from 1990 level. This can be done by recycling CO_2 and replacing the fossil fuel with RE hydrogen, RE methane, etc.

It is known that renewable gas, so called syn-gas, is the key item in making a well integration system between P2G and waste processing plant. The characteristic of syn-gas in such that its components can be supplied from biomass (via gasification), water (via electrolysis), or organic waste (via biogas fermenter) makes it really flexible to become the connection bridge between the different processes.

As a product of P2G, methanol offers some advantages over the methane and hydrogen. Its easiness in handling, storing, and transporting is the major benefits of methanol. Moreover, wider uses of methanol in energy generation and transportation sector have been found in the literatures. Besides its function as an energy carrier, methanol is also largely used in chemical industry as the basic chemical feedstock.

In terms of conversion of biomass to syngas, the high temperature of plasma gasification could provide more benefits. This technology is mainly developed for processing the waste. With temperature of around 1200 ºC, it is claimed that the plasma gasifier enables the conversion of waste/biomass to syngas with large improvement in carbon conversion. It is reported that the reactions occurred in such gasification almost reach it thermodynamical equilibrium condition. Plasma gasification can works well with P2G because it uses oxygen from electrolyzer.

3.5. Discussion and conclusion

It is worthy to do an investigation about the feasibility study of P2G technology at Twence. Despite the fact that the technology is still immature, the progress of development is accelerating in the recent times. Moreover, the technology could well collaborate with the biomass/waste processing plant and this certainly fit with the main business of Twence. The final products of P2G are also very flexible, making it adaptable with the future energy market.

Most importantly, instead of seeing P2G as an energy carrier, a much bigger business opportunity can be seen from a perspective that P2G plays an important role in reducing CO_2. The products of renewable syngas, methanol, methane, etc. can be synthesized using P2G technology. These sustainable products will soon take a place in the global market, replacing the fossil based products. In addition, P2G enables the CO_2 recycling by using the CO_2 as the carbon feedstock for methanation or methanol synthesis. To summarize, P2G will be highly demanded for deep decarbonization scenario and the opportunity of making a business from P2G will increase.

In summary, the literature review in this chapter has gained the insight about the possible investigation and development of P2G application. Based on this literature review, the further analysis and investigation about P2G related to the existing market and technology of Twence will be done in the next chapter, where the main objective is to identify whether the P2G is able to provide a good business case for the future of Twence.

CHAPTER 4: STATISTIC ANALYSIS OF ELECTRICITY PRICE

Statistic analysis of electricity price of Netherlands as well as other European countries is provided in this chapter. This is done as a part of investigation to identify in which and what kind of market P2G is likely more applicable. To do the analysis, the historical data of the energy market price in 2014 is collected. The data includes spot electricity, methane, methanol, and CO_2 price. The analysis of spot electricity price is done for both day ahead hourly electricity price and imbalance price. In addition, the effect of seasonal changes on electricity price is also investigated. Lastly, the discussion and conclusion of this chapter are given.

4.1. Data collection: energy market price

Energy market price is crucial input data for investigating a business of Power to Gas. The need to store the electricity can be indicated by the decrease in the electricity price. Therefore, the data of electricity price should be examined thoroughly. Furthermore, the methane and methanol market are also taken into account, in order to investigate the competitiveness of the synthetic methane/methanol price in the global market. Besides, Data of CO_2 price is also very important because the implementation of P2G is highly supported by a high target of decarbonization landscape.

In this study, the energy market price is intended for electricity, methane, methanol, and CO_2. It shall be noted that there are two types of electricity price data namely daily ahead hourly price and imbalance price. The graphs of yearly historical data of all mentioned market prices are attached in Appendix A and each market price will be further elaborated below.

Daily ahead hourly price of electricity

A representative data of daily ahead hourly price of electricity has to be taken for the analysis. For this, data of APX hourly in 2014 was obtained, as Twence is usually involved in this market.

For comparison analysis, data from different countries were taken. As known previously that the P2G will play a role very well in a market with high supply of electricity from intermittent RE source. In 2013, Denmark was reported to be the country with the highest wind energy penetration, as 32.2% of its electricity was being supplied by wind turbines [30]. This condition may already represent the trend toward a situation in which power to gas is becoming more applicable. Hence, the data of Denmark is obtained for comparison with the data of Netherlands. In addition, the historical 2014 data of Sweden and Norway were also taken due to respectively the highest total RE consumption and the highest energy production from hydro potential.

Besides historical data, it was previously considered to use a prediction data of electricity price as a function of wind energy penetration. From literatures, there are in fact numerous mathematical models developed to predict the future electricity market price. However, due to many uncertainties of landscape that may affect the electricity price, it is then decided to examine only historical data of electricity price.

Imbalance price of electricity

It is not necessary to obtain the imbalance market price from different countries. This is because the imbalance price does not correspond with the amount of renewable energy supply. As previously mentioned, this electricity-pricing scheme is basically meant for settling the discrepancies between the amounts of electricity in which a company has contracted to generate or consumed and the amounts that are actually generated or consumed. As a result, the data of the imbalance market price was obtained only from Tennet (2014), a market that Twence usually deals with.

The time frame of the price settlement can be very short, for instance, in half or quarter-hour. However in this study, the imbalance prices of Netherlands by [31] is settled in quarter hour basis.

Gas/methane price

The historical data of European market price of gas/methane was obtained. Unlike the day ahead hourly electricity price, no significant fluctuations have been recorded for the global market price of methane. According to ICE ENDEX market, the yearly ahead gas price is likely to drop from 25 euro/MWh to 20 euro/MWh in 2014. For quarterly and monthly ahead price, the market shows a difference between winter and summer. However, the average trend is going in the same direction as yearly ahead price. In this study, the methane price unit is converted to a mass basis (euro/ton) by assuming that the Low Heating Value (LHV) is 40 MJ/kg. This is done to make the methane price comparable with the methanol price unit.

Methanol price

The history data of European market of methanol shows an opposite trend, compared to gas price. It is found that the price fluctuation exists over the year, however since 2000 the average contract and spot price are continuously growing until they reach at the level around 250 euro/MT in 2012 [32]. Moreover, the recent data shows even higher price, as it is reported that the price per September 2015 is 355 euro/MT [33].

CO_2 price

Despite the fact that the carbon price had dropped due to the European crisis, they are likely to rise again in the coming years due to strong actions by the European government. The extent of the price hikes is unclear, but European targets are around €30/metric ton CO_2 in 2030. An assumption of around €12/metric ton in 2020 seems prudent, compared to €8/ton right now.

4.2. Analysis of day ahead hourly electricity price

Using the data obtained, the histogram/frequency graph can be plotted for each sample, as shown in Figure 5. As stated earlier, there are four samples of spot market: Denmark DK1, Sweden SE1, Norway (Oslo), Netherlands (APX). It is seen that all samples follow the normal distribution, although the statistic variables of each sample are different. The Oslo market indicates a steep profile with the lowest average value. This profile is reasonable because Norway has the biggest share of hydro-based electricity production. In contrary, the APX shows wider frequency distribution but with the highest average value. Although there may be various factors affecting the electricity price, it can be argued that the low RE share in Netherlands has led to a different frequency profile, compared to the other three markets. An interesting fact is revealed from DK1 spot market. It is visible that the DK1 has a small slope around and its average value is comparatively low. Moreover, it also shows a range of frequencies where the electricity price is negative. From this, an argument could be made that the high penetration of wind-based electricity is the major factor of such a frequency profile to occur. The negative price occurs only in the condition of which the energy generation could not be stopped during low load demand. This condition does not occur in Norway because the water potential energy can be quickly stored or released. To summarize, the DK1 is found to be the most suitable market for applying power to gas since it shows the highest probability to have low electricity prices. It is also proved that higher wind penetrations would shift the electricity market to a feasible environment for P2G.

For quantitative comparison, the statistic variables of each market are summarized in Table 2.

Table 2. Statistic variables of the energy prices 2014.

Study case	Denmark (DK1) Hourly Spot Price (Euro/MWh)	Norway (Oslo) Hourly Spot Price (Euro/MWh)	Sweden (SE1) Hourly Spot Price (Euro/MWh)	APX-NL Hourly Spot Price (Euro/MWh)	Tennet Quarterly Hour Imbalance Price (Euro/MWh)
Mean	30.67	27.33	31.42	41.18	44.04
Standard Deviation	10.24	6.16	6.31	10.7	57.46
Maximum Value	160.03	70.68	105.39	96.69	446.12
Minimum Value	-60.6	0.59	0.59	0.12	-442.20

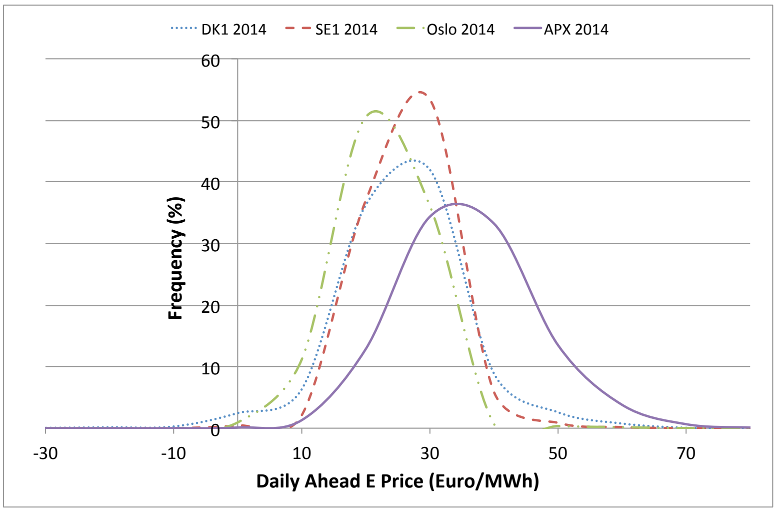

Figure 5. Frequency graph of the hourly electricity price 2014.

4.3. Analysis of imbalance electricity price

In addition to hourly electricity price, the frequency profile of imbalance market by Tennet in 2014 is plotted separately in Figure 6. It is seen that imbalance market does not fully follow the normal distribution. There are some growths of frequency in both left and right side of the graph. It could be said that such a shape appeared because of unknown factors affecting the inconsistency in the performance of the power plant. There are too many uncertainties in imbalance market, resulting to an unpredictable situation the following year.

The data shows a very disperse data of which Power to Gas Technology might play a role. However, it should be kept in mind that the interval time of price settlement is only 15 minutes. If P2G is applied to this market, it must have a capability to work very flexible in such extremely short time.

The statistic variable of Tennet imbalance market is also given in Table 2. It is revealed that the standard deviation of Tennet is around six times higher than the data of hourly electricity price. The imbalance price could drop very far to -442 euro/MWh or jump to 446 euro/MWh. Nevertheless, Tennet has the highest average price (44 euro/MWh) among all the markets.

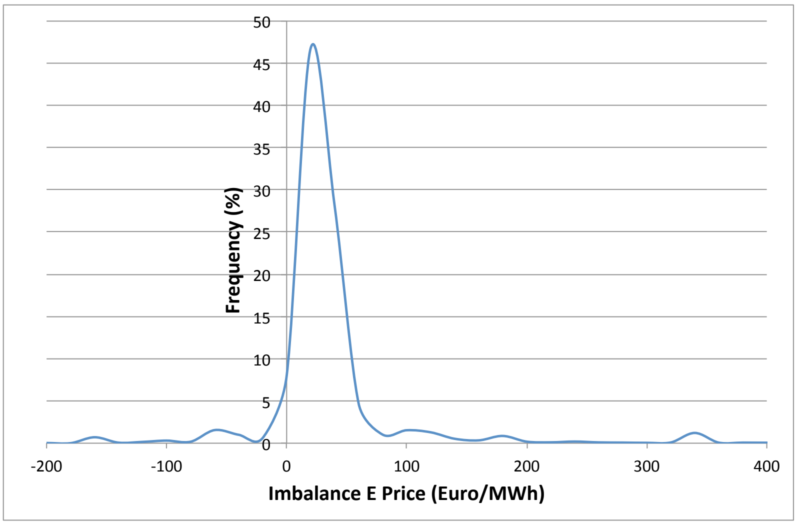

Figure 6. Frequency graph of Netherlands (Tennet) imbalance market price 2014.

4.4. The effect of seasonal changes

The effect of seasonal changes may differ, depending on the countries. In this section, the electricity price market of DK1 will be used as an example for the analysis.

The seasonal changes have influenced the price of DK1 in 2014. This becomes visible in the graph of price electricity vs time, provided in Appendix A. The significant difference occurs between winter and summer. Based on the data, the price in the winter season has a greater fluctuation (higher amplitude) and reached a negative value. On the other hand, the price in the summer shows lower fluctuation and the highest prices were recorded. This difference appears due to the fact that wind is much available in winter. By understanding the characteristic of the wind, it can be suggested that P2G shall operate only during the season with high availability of wind or winter season in the case of European countries. To visualize the seasonal effect on the frequency graph, the data for one year is breakdown into four groups of seasons, and then the frequency curve is plotted again for each group, as it is presented in Figure 7.

One may suggest that winter and spring seasons are the good time to run the P2G in DK1. It is visible that only in spring season, the peak frequency is significantly shifted toward lower electricity price. This will indeed gain the cash flow of P2G. Furthermore in the winter, despite the peak frequency occurs at the price around 30 euro/MWh, it shows a lower frequency for high price but higher frequency for low or negative price. To summarize, running P2G in winter and spring may offer more profitable business case.

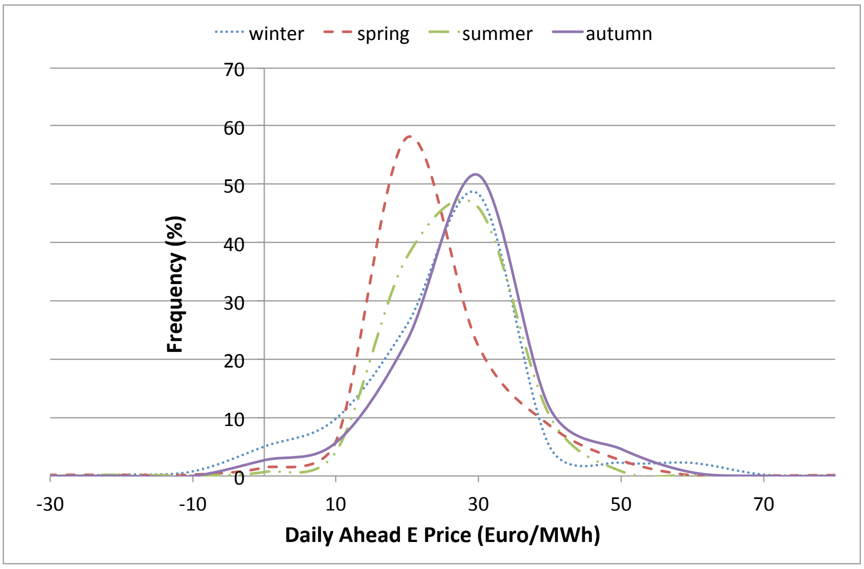

Figure 7. DK1 frequency curves of four different seasons.

The DK1 market price data in the above analysis is selected only for an example. The same analysis can be also applied to the APX or other markets. However the analyses for other markets are not provided in this report.

4.5. Discussion and conclusion

Analyzing the historical data of an electricity price by using statistic and histogram/frequency curve can be a good methodology to understand whether the market is ready (or not) for P2G technology. Besides knowing the average price, frequency distribution of prices also plays an important role for P2G and this can be seen in the frequency curve. After all, it is very convenient to perform qualitative and quantitative analysis by seeing the histogram and static variables.

The high penetration of wind based electricity production positively affects the electricity market price for P2G. This is known by comparing the histogram/frequency curve of DK1 and other countries. Denmark, which is now having the highest wind energy share in its electricity production, has shown a different histogram of electricity price. It is revealed that DK1 2014 has lower average price and higher distribution, compared to APX, Oslo, and SE1. The shape of DK1 frequency curve compared to other countries has given a positive impact to the feasibility of P2G.

The main message from the analysis of the effect of seasonal changes is that it is important to break down the data in a seasonal time frame. By doing so, it is possible to know the most profitable season to run P2G. Furthermore, from the analysis it is possible to conclude that running the system within a specific season would give more benefits than other seasons. For example, spring and winter seasons are the best period to run P2G for DK1 market.

Nevertheless, running the system in a seasonal basis time frame is not always an ideal solution. Ideally, the hourly electricity price should be applied to an hourly-operated P2G system. However, this may lead to flexibility problems such as the long time requirement for start up or shut down. To overcome this problem, the operational time frame shall be lengthened to a daily, weekly, monthly, or seasonal basis time frame. From this, it could be known that the seasonal basis time frame is merely one of the options, not the best/ideal case.

Finally, a judgment on the operational time frame shall be made by not only considering the electricity price distribution, but also the flexibility of the P2G system.

CHAPTER 5: THE MAKING OF FLOWSHEET MODEL

This chapter presents the possibilities of P2G route at Twence together with the process of making the flowsheet model. At the beginning, the basic theory of how to model the reaction is introduced. Then, a number of route possibilities at Twence are shown and the descriptions of each route are given. These routes are then drawn in a flowsheet modeling tool namely Cape Open (CoCo) Simulator. The explanation of the model such as the components used, assumption, design parameters, etc are mentioned. Finally, this chapter ends with discussions and conclusions regarding the model.

5.1. Basic theory: modelling reaction

Simulation or mathematical model takes an important role for the study of reactions, thermodynamic condition, chemical mass and heat balance. It may not give a very accurate prediction, but it can provide at least guidance in understanding the operating condition and the effect of changes on input parameters.

In this study, simulation by a flowsheet model is applied to visualize and analyze the proposed P2G system. This model includes multiple reactors and auxiliary equipment. One of the important steps in making the flowsheet model is to understand how to determine the proper model for the reactions involved.

A model of reaction can be classified into two groups, thermodynamic equilibrium and kinetic model. The thermodynamic equilibrium predicts the maximum conversion of reaction, without taking into account the geometry of reactor. The reaction is assumed to occur in infinitive residence time, so that thermodynamic equilibrium is always achieved. On the other hand, for practical application the kinetic model is more accurate to predict the product from a reactor that provides a limited time for reaction. This model takes into account the kinetic rate of each elemental reaction.

One of the thermodynamic equilibrium model, so-called the minimization of the gibbs free energy, is mainly used for this study. In this model, no knowledge of a particular reaction is required to solve a problem. A stable equilibrium condition is reached when the Gibbs free energy of the system is at the minimum level [34]. The Gibbs free energy, G_{total} comprising N species (i = 1, 2, 3, ...N) is expressed by eq. (18).

$$G_{total} = \sum_{i=1}^{N} n_i \Delta G_{f,i}^0 + \sum_{i=1}^{N} n_i RT \ln\left(\frac{n_i}{\sum n_i}\right) \quad (18)$$

Where $\Delta G_{f,i}^0$ is the Gibbs free energy of formation of species i at standard pressure of 1 bar. The equation (18) has to be solved for unknown values of n_i to minimize the G_{total}.

5.2. Possible routes of P2G at Twence

There are basically multiple ways of utilizing electricity for chemical conversion. As P2G is always identic with the process of electrolysis, it is commonly known that P2G refers to the conversion of water to hydrogen. However, P2G could also be differently defined as a process to produce syngas from biomass, namely gasification. This way, the electricity is used to generate heat to reach the temperature of gasification. Besides, the electricity is needed to run the auxiliary equipment in the sub-system/plant such as the compressors in methanation plant or methanol synthesis plant.

To be simple, any systems can be called P2G as long as the system is consuming power and producing gas. With this definition, there are several possible chemical routes of P2G that can be applied at Twence. All these possibilities are depicted in Figure 8. To be more detail, a number of alternatives are given below.

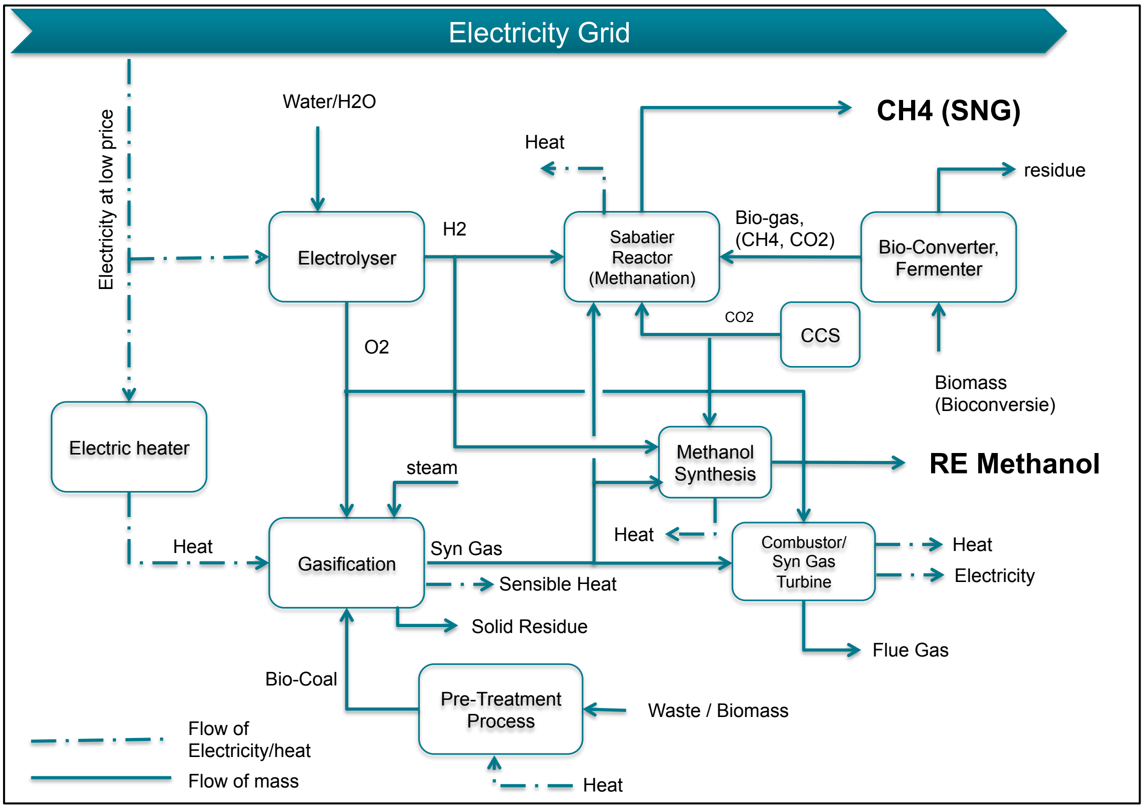

Figure 8. Possible routes of power to gas at Twence.

- **<u>Route no. 1: Hydrogen + CO_2 emission → CH4</u>**: This is a simple route, consisting only two of pure reactants: the hydrogen from electrolysis and the CO_2 from CCS. This route has the highest energy consumption, since the hydrogen is extracted only from water. It is suitable for chemical process with big capacity. Assuming the water is abundantly available, the limited amount of CO_2 becomes a constraint of this route. This route may also have a good integration with the bio-fermenter plant.

- **<u>Route no. 2: Hydrogen + Syngas → CH4</u>**: Replacing CO_2 emission with syngas offers multiple advantages. The component of hydrogen in the syngas reduces the supply of hydrogen from electrolysis. Furthermore, the use of CO as reactant leads to a higher yield of CH_4, as the stoichiometric ratio can be seen in reaction (12). Nevertheless, this route requires the process of waste/biomass gasification, resulting to an increase in plant capital cost.

- **<u>Route no. 3: Hydrogen + CO2 emission → CH_3OH</u>**: This route is basically same as the route no. 1 unless the product of reaction is methanol. This route can provide higher product yield than route no.1 because of the oxygen containment in methanol. However this route may not be well integrated with the bio fermenter plant, since the methane in biogas would become an inert gas and must be discharged from the system.

- **<u>Route no.4: Hydrogen + Syngas → CH_3OH</u>**: This route includes a methanol synthesis process using syngas. The process of making methanol from syngas has become a mature technology nowadays. As long as the stoichiometric ratio between CO, CO_2, and hydrogen are maintained, it is possible to generate highest methanol yield without the presence of water as by product.

- **<u>Route no. 5: Syngas + O2 → Power</u>**: This is an additional route, where oxygen is mixed with syngas to produce power by means of combustion. The oxygen will raise the combustion efficiency because it replaces the air as an oxidant. The supply of oxygen for this route is from electrolyzer. However, it shall be noted that the oxygen from electrolyzer is primarily sent to the gasifier. If the amount of oxygen is exceeding the need for gasification, the excess will be directed to this route.

In order to find the best route for Twence, the above five alternatives shall be investigated thoroughly, for instance, by looking its thermodynamic performance. To do so, a flowsheet simulation is required and the making of the flowsheet model will be described in the next section.

5.3. The making of flowsheet model

The flowsheet model is created based on the possible route of P2G at Twence, as mentioned previously. The flowsheet model mainly consists of five major segments: (1) water electorlysis (2) gasification, (3) methanation plant, (4) methanol synthesis plant, (5) syngas power generation. These segments are combined in the model, so that the change of input or operating condition of one process will automatically affect to the other processes. In the end, it is expected that the model enable many variations of P2G route.

The details of each segment are described below.

Segment no. 1: Water Electrolysis: This process is modeled in such that the stoichiometric reaction of water decomposition (15) occurs. The model is equipped with a fixed conversion reactor, a pump, and a compound splitter. The power input of electrolyzer is set as the input parameter, controlling the water federate to reach its stoichiometric ratio. The water is pumped from atmospheric pressure to 20 bars before it enters the electrolyzer. Then, the products (H_2 and O_2) are separated afterward through a compound splitter. Beside the ideal stoichiometric reaction, several assumptions are applied to the model, for instance the pump isentropic efficiency of 0.9, the electrolyzer efficiency of 0.83 at operating temperature of 25 ºC, and no heat and pressure loss. The flowsheet diagram of the model is shown in Figure 9.

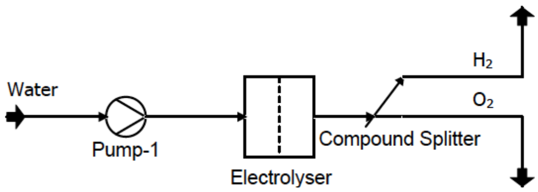

Figure 9. Flowsheeting diagram of water electrolysis.

Segment no. 2: Gasification: The thermodynamic equilibrium reaction is implemented in the gasification model. This way, the reactor/gasifier is modeled as gibbs minimization/non stoichiometric reactor, where all of feed streams are converted into defined gases at the minimum gibbs value. In this model, the solid biomass is decomposed to certain composition of gases (Raw Gases). This is done because the Cape Open Simulator has a constraint of in which the gibbs minimization reaction can only work with the gas phase. The mass fractions of each element (such as carbon, hydrogen, and oxygen) in the raw gas are set to be equal as if it is in the solid phase. Both water and oxygen from electrolyzer are used for the gasifying medium, and their flow rate are adjusted to a value of which it leads to an endothermic reaction. This condition is expected because the main objective of the system is to create a power consuming system. The temperature of reacting zone and the operating pressure are set to 1200ºC and 20 bar. The gasification temperature is based on several literatures regarding the experiment of a new developed gasification process using DC arc plasma heater [27][35]. In addition, two heat exchangers/recuperators are placed to utilize the sensible heat of the product gases. The flowsheet diagram of the model is shown in Figure 10.

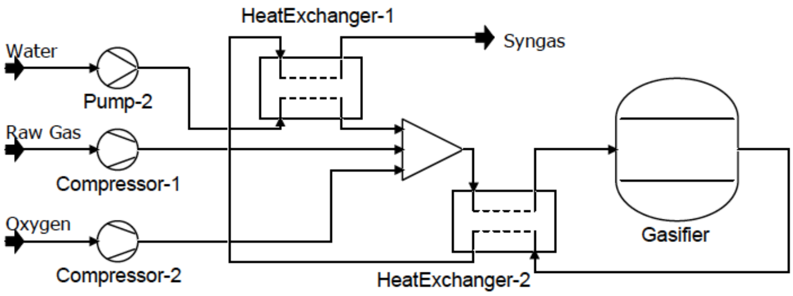

Figure 10. Flowsheeting diagram of gasification.

Segment no. 3: Methanation Plant: The model of methanation basically apply a fixed conversion reactor, a flash tank, a compound splitter, and some auxiliary equipment (heater/cooler sand compressors). The reaction temperature is 300ºC, based on the experiment with the use of a commercially available methanation catalyst (Haldor Topsøe PK-7R). The experiment result shows that the conversion and CO_2 at such temperature could reach 60% with the stoichiometric ratio of H_2:CO_2 4:1 [4]. Since the reaction is limited by its kinetics, a single recirculation line is provided to recycle the unreacted gases. The flash tank is used to separate water and non-condensable gas after expansion by the throttling valve. Afterward, the compound splitter splits the methane from the unreacted gases. A vent line is used in case of applying non-stoichiometric ratio of the reactant. The flowsheet diagram of the model is shown in Figure 11.

Another possible route of methanation is to use CO as the carbon source and this could be extracted from the syngas by the gasification. However, it is decided in this study to not utilize CO because the presence of CO promotes the undesired water gas shift reaction (9) [36]. The flowsheet diagram of the model is shown in Figure 11.

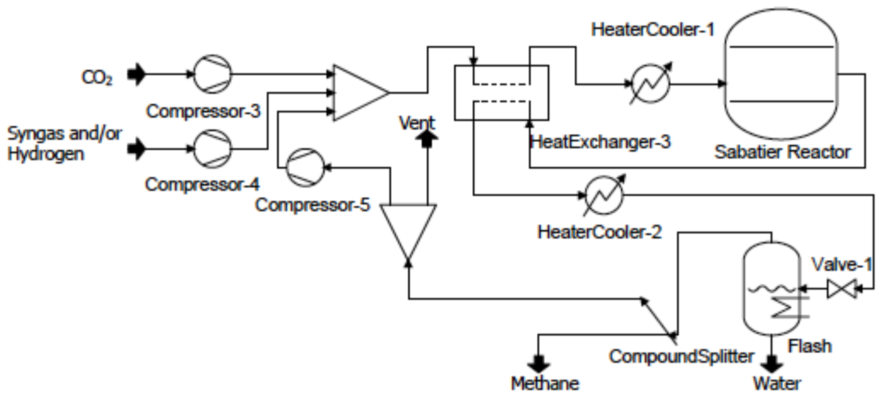

Figure 11. Flowsheeting diagram of methanation.

Segment no. 4: Methanol Synthesis Plant: The flowsheet model of methanol synthesis plant is basically adopted from the model by [5]. The components are almost similar with the methanation plant, except the fact that the final product is in a liquid phase. After condensed in flash tank, the methanol is separated from water by using compound splitter. A fixed conversion reactor is used with assumption that the conversion of CO to CH_3OH and CO_2 to CH3COOH are 64% and 17% respectively. A single recirculation line is provided to return the unreacted gases to the reactor. The flowsheet diagram of the model is shown in Figure 12.

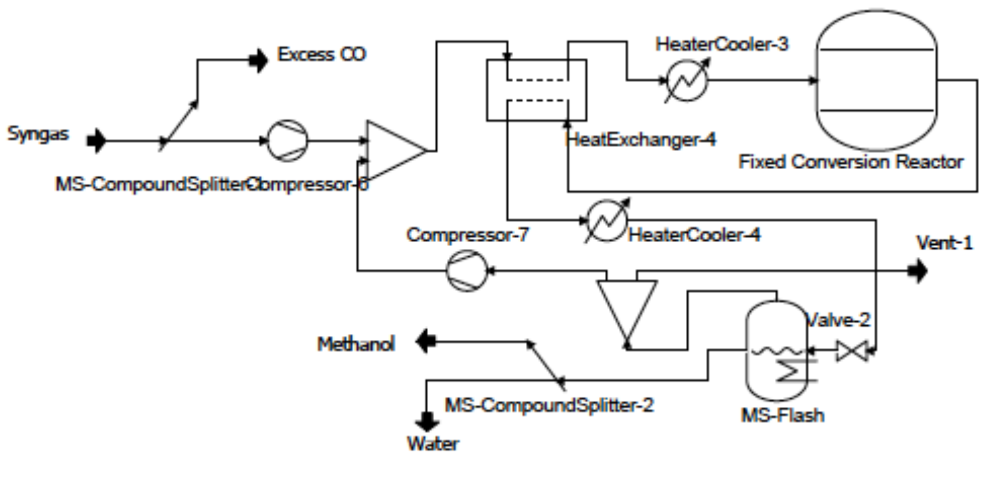

Figure 12. Flowsheeting diagram of methanol synthesis.

Segment no. 5: Syn Gas Power Generation: The flowsheet model is similar with the conventional brayton cycle. It consists of compressors, a combustor, and a syngas turbine. As a special feature, the additional oxygen inlet stream is provided. The oxygen comes from electrolyzer and is available when the oxygen production rate exceeds the oxygen consumption rate by gasification. The combustor is modeled as a gibbs minimization reactor, which means the combustion of syngas is assumed to reach its thermodynamic equilibrium. The burning temperature is set to be at 1200ºC. Other assumptions are the compressor isentropic efficiency of 0.9, the turbine isentropic efficiency of 0.9, and the combustion pressure of 20 bar. The cooler is placed at the downstream of turbine and used to extract the heat from the flue gas. The flowsheet diagram of the model is shown in Figure 13.

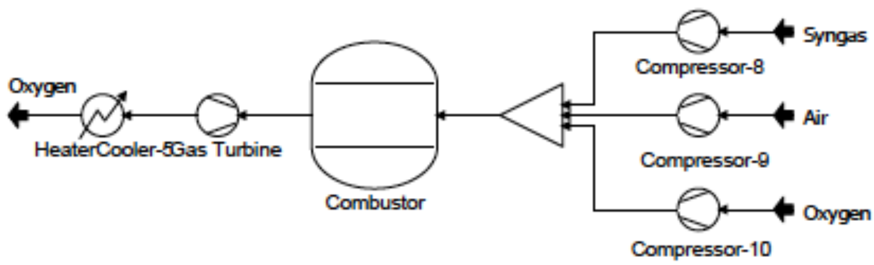

Figure 13. Flowsheeting diagram of syngas power generation.

Design optimizations are made for each segment. To understand the level of performance, indicators are determined for each process, for instance the syngas yield (Y_{syngas}) for the gasification, the methane yield (Y_{CH_4}) for the methanation plant, the methanol yield (Y_{CH_4}) for the methanol synthesis plant, and the electrical efficiency ($\eta_{elect.}$) for the syngas power generation plant. The definition of each indictor is expressed in eq. 24-27. To provide an optimum design, the targets are set for each indicator. Firstly, the Y_{syngas} is controlled to be more than 0.9, by changing the mass flowrate of steam ($\dot{m}_{H_2O,in}$) and mass flow rate of oxygen ($\dot{m}_{O_2,in}$). Secondly, the $Y_{CH_4}$is controlled to be more than 0.3, by changing the vent flow rate as wellas maintaining the stoichiometric molar ratio of H_2:CO_2 4:1. Thirdly, the Y_{CH_3OH} is controlled to be more than 0.9, by changing the similar variables, except that the stoichiometric molar ratio of the feed stream is H_2:CO 2:1. Lastly, the efficiency of the syngas power generation can be improved by adding more pure oxygen. However, since the oxygen supply depends on the operation of electrolyzer, no specific target is set for the electrical efficiency of the syngas turbine.

$$Y_{syngas} = \frac{\dot{m}_{CO,out} + \dot{m}_{H_2,out}}{\dot{m}_{Raw\ Gases,in} + \dot{m}_{H_2O,in} + \dot{m}_{O_2,in}} \tag{19}$$

$$Y_{CH_4} = \frac{\dot{m}_{CH_4,out}}{\dot{m}_{CO_2,in} + \dot{m}_{H_2,in}} \tag{20}$$

$$Y_{CH_3OH} = \frac{\dot{m}_{CH_3OH,out}}{\dot{m}_{CO,in} + \dot{m}_{CO_2,in} + \dot{m}_{H_2,in}} \tag{21}$$

$$\eta_{elect.} = \frac{P_{turbine} + P_{compressor}}{[h_{out} - h_{in}]_{combustor}} \tag{22}$$

5.4. Results

The result of this chapter is the final blueprint containing all five segments above. The final blueprint is available in Cape Open file format (.fsd). Its print version can be seen in Appendix B.

5.5. Discussion and conclusion

The created flowsheet model can be a useful tool for doing investigation on P2G route. The model is comprehensive because all possible routes of P2G are combined into one sheet. Despite containing many assumptions, the model is convenient for making preliminary analysis. The program used (Cape Open Simulator) is an open source program, making it available for any users. In addition, the model is created to have its own output data processor. For example it is possible to have the total plant water consumption calculated by the model. This way, the model is useful not only as a flowsheet solver but also as an information calculator. Besides, the possibility to have many variations is also the strength of this model.

The flowsheet is widely open for many variations. There are multiple variables in the model such as operating temperature and pressure, waste/biomass input feedrate, electrolyzer power input, etc. By varying these variables, it is possible to identify the changes in the system performance. Moreover, the stream flow can be easily directed to a specific route. This makes it easier to identify different routes

Nevertheless, there are some remarks regarding the use of variables. As for the methanation and methanol synthesis, the reactor model used is a fixed conversion reactor. This model has a fixed conversion value based on specific temperature and pressure from the literatures. This means that the conversion value is not valid anymore if the reaction temperature and pressure are different from the literature. Consequently, the temperature and pressure in methanation and methanol synthesis plant should not be treated as variable.

Another important note for the model is that the flowsheet model is only suitable for output data trend analysis. Model simplification as well as ideal assumption indeed leads to an inaccurate output. Hence, the output value from this value shall not be used for conclusion. What should be analyzed from the model is only the output data trend, for instance the trend of methanol production as a function of biomass feedrate. In short, This model is only applicable if it is used to perform comparison analysis between different input variables, routes, or operation scenarios.

To summarize, the flowsheet models have been successfully created as a tool to investigate the route of P2G. By using this model, the system performances of each possible P2G scenarios can be compared and analyzed. In the following chapter, this model will be used to investigate the output of a specific route of P2G for Twence.

CHAPTER 6: IDEAL STOICHIOMETRIC CALCULATION

This chapter presents the simple mass calculation of the P2G reaction using ideal stoichiometric ratio. This calculation is meant to investigate the maximum mass production of methane and methanol, with the use of available CO_2 as a carbon source.

6.1. CO_2 source at Twence

The carbon feedstock for methanation or methanol synthesis process can be taken from the CO_2 emission. This way, several benefits such as incentives or subsidies can be obtained due to the contribution in reducing the amount CO_2 in ambient. At Twence, the CO_2 can be harvested from the flue gas of EfW, BPP plant, or bio gas plant (Bio-Fermentation Plant). In addition, Twence currently has an installation of carbon capture storage (CCS) for EfW unit 3. As this installation can be used to provide pure CO_2 to P2G system, a well integration can be made between P2G with the existing plant.

Based on the above background, the investigation on the availability of CO_2 at Twence is performed. Table 3 summarizes the data of CO_2 source from all existing installation. From this table, it can be calculated that the total amount of CO_2 available ($\mathrm{CO_{2,available}}$) is 107.8 ton/h.

Table 3. Data of carbon sources at Twence.

Sources	Total Flow Rate	CO_2 Composition	CO_2 Flow Rate
Flue Gas EfW unit 1	115 kNm^3/h	11%vol	23.3 $tonCO_2/h$
Flue Gas EfW unit 2	115 kNm^3/h	11%vol	23.3 $tonCO_2/h$
Flue Gas EfW unit 3	220 kNm^3/h	10%vol	40.52 $tonCO_2/h$
Flue Gas BPP	120 kNm^3/h	9%vol	19.89 $tonCO_2/h$
Bio-gas	0.8-1 kNm^3/h	45%vol	0.83 $tonCO_2/h$

6.2. Maximum potency of methane and methanol production by recycling CO_2

Unlike hydrogen and oxygen, which are relatively much available (i.e. water), the carbon source becomes the limitation factor for P2G system. Using the data of CO_2 source, it is possible to calculate the maximum potency of methane or methanol production by recycling CO_2.

In case of applying methanation, calculation of maximum flowrate of CH_4 ($\dot{m}_{CH_4,max}$) and H_2 ($\dot{m}_{H_2,max}$) is done using formula (23) and (25) respectively. These formulas basically apply the ideal stoichiometric ratio between product and reactant as per reaction of methanation (11).

$$\dot{m}_{CH_4,max} = \frac{\mathrm{M_{CH_4}}}{\mathrm{M_{CO_2}}} \times \mathrm{CO_{2,available}} = \frac{16}{44} \times 107.8\ \mathrm{ton/h} = 39.2\ \mathrm{ton/h} \tag{23}$$

In case of producing methanol from the CO_2 reactant, the stoichiometric ratio refers to methanol synthesis reaction (17) and the maximum flowrate of CH_3OH ($\dot{m}_{CH_3OH,max}$) and H_2 ($\dot{m}_{H_2,max}$) are calculated in eq. (24).

$$\dot{m}_{CH_3OH,max} = \frac{\mathrm{M_{CH_3OH}}}{\mathrm{M_{CO_2}}} \times \mathrm{CO_{2,available}} = \frac{32}{44} \times 107.8\ \mathrm{ton/h} = 78.4\ \mathrm{ton/h} \tag{24}$$

The maximum amount of methanol is twice of the methane. The difference occurs due to the presence of oxygen in the methanol compound. Moreover, the hydrogen consumption of each reaction is different. In the methanol synthesis reaction, one mole CO2 reacts with three moles hydrogen, meanwhile the methanation needs one extra mole of hydrogen. Therefore, the power input for producing hydrogen reaches the maximum in the case of methanation and could be estimated by using eq. (26). For simple calculation, the Low Heating Value of H_2 ($\mathrm{LHV_{H_2}}$) and efficiency of electrolyser ($\eta_{\mathrm{elect.}}$) are assumed to be respectively 120 MJ/kg and 0.83. The efficiency of electrolyser is nothing else than the maximum efficiency at normal pressure temperature (298 K, 1 atm), as expressed in eq. (27).

$$\dot{m}_{H_2,max} = \frac{4 \times M_{H_2}}{M_{CO_2}} \times CO_{2,available} = \frac{4 \times 2}{44} \times 107.8\ ton/h = 19.6\ ton/h \quad (25)$$

$$P_{max} = \frac{\mathrm{LHV_{H_2}} \times \dot{m}_{\mathrm{H_2}}}{\eta_{\mathrm{elect.}}} = \frac{120\ \mathrm{MJ/kg} \times 19.6\ ton/h}{0.83} = 787.1\ MW \quad (26)$$

$$\eta_{\mathrm{elect.}} = [\eta_{\mathrm{max}}]_{\mathrm{1atm,298\ K}} = \left[\frac{\Delta \mathrm{G}}{\Delta \mathrm{H}}\right]_{\mathrm{1atm,298\ K}} = \frac{237.1 \mathrm{kJ/mol}}{285.8\ \mathrm{kJ.mol}} = 0.83 \quad (27)$$

6.3. Discussion and conclusion

The calculation result above shows that Twence can accommodate the capacity of electrolyzer up to 781.1 MW. This value indicates a huge potential of making synthetic methane and methanol but the process required high amount of electricity, compared to Twence total electricity and steam production. Nevertheless, Twence is receiving different types of waste and biomass feedstock of which numerous possibilities of extracting hydrogen and carbon can be discovered.

From calculation above, it is also possible to conclude that the process of methanol synthesis is more efficient than methanation. This is clearly seen from the result that methanol production rate is twice of the methane. As the market price per ton of methanol and methanation are about the same, from the economic perspective it is more profitable to run business of methanol synthesis. In contrary, the business of Power to Methane is not feasible at all unless there is a supportive policy or incentives.

In accordance to the conclusion above, it is finally decided that the option of Power to Methane shall be eliminated. From now the investigation will be more intense on the route of methanol synthesis. Nevertheless, using CO_2 to produce methanol is not the only way. The use of the carbon feedstock as well as other alternative process of methanol synthesis shall be investigated further.

Beside emission, biomass and organic waste could also be an option for carbon feedstock. Using waste/biomass as reactant, the reaction will be not as simple as the reaction of hydrogen with CO_2. As shown in Figure 8, gasification is one of the alternative processes to harvest the carbon in biomass or waste. A detailed investigation about route of gasification as well as methanol synthesis from syngas will be done in the following chapter.

CHAPTER 7: ROUTE OF METHANOL SYNTESIS

In this chapter, the route of methanol synthesis is elaborated. Generally, the routes are classified into two different feedstock. The first route uses CO_2 and mainly consists of an electrolyzer and a methanol synthesis plant. Meanwhile, the second route uses biomass/waste and is equipped by a gasifier and a syngas turbine. For both routes, the flowsheet model (described in earlier chapter) is used to investigate the output performance. Then, the result/output of flowsheet calculation from both routes are presented. Finally, a discussion and conclusion regarding the result are made.

7.1. Methanol synthesis using CO_2 feedstock

The operation philosophy of this route is very simple. The hydrogen from electrolyzer is mixed with CO_2 at the stoichiometric ratio of H_2:CO_2 4:1. To achieve the stoichiometric ratio, automatic controller is placed to control the amount CO_2, based on the power input of electrolyzer.

As an example, the electrolyzer capacity is set to be 3MW and the CO_2 consumption is automatically regulated to 0.66 ton/h. Subsequently, the calculation is solved the outputs are obtained from the flowsheet model.

7.2. Methanol synthesis using waste/biomass feedstock

Biomass and waste have complex chemical compositions and this becomes a major challenge for modeling tool. To simplify this condition, an assumption is made to chemical elements of the feedstock. In the model, biomass is assumed to be a mixture of pine wood ($C_6H_9O_4$), water (H_2O), and inert material. Meanwhile, waste is defined as a mixture of the same elements but the fractions of each element are different from biomass. Table 4 shows the fraction of each element. The difference of composition between biomass and waste would later represent the difference in performance.

It is important to note that the chemical composition of waste in Table 4 is assumed in such a way that the composition is similar to what Twence will obtain from new feedstock so called "Organic Waste Fraction". This feedstock will soon be available as a byproduct of the Separation Plant.

Table 4. Assumption of chemical elements in biomass and waste.

Chemical Element	Mole Fraction in Biomass	Mole fraction in waste
Pine Wood ($C_6H_9O_4$)	72%	25%
Water	21%	53%
Inert Material	7%	22%

Regarding the operation philosophy, the main idea of this route is to use the syngas as a flexible medium. The syngas produced by gasification is flexible because it can be sent to either methanol synthesis plant or syngas turbine. The syngas is used primarily for methanol reaction. However, its application for power generation may also take an important role, especially if the produced electricity can be sold at high price.

In this chapter, the fraction of syngas going to the syngas turbine is determined to be 10%. This number is chosen only for example. Therefore, it is possible to change this number for further investigation.

The syngas from biomass/waste gasification has compositions of CO, H_2, and CO_2 and the ratio of those gases is not in the best ratio for performing methanol synthesis reaction. The molar ratio of syngas will show that CO is the dominant gas, meanwhile in stoichiometric ratio the large quantity of molar hydrogen is needed. Referring to reaction (16) and (17), five moles hydrogen is needed to react with one mole CO and one mole CO_2. Based on this requirement, an action shall be taken to achieve the stoichiometric ratio

The idea to set the stoichiometric ratio basically includes two scenarios: (1) low yield scenario and (2) high yield scenario. The further explanations about the chemical route of each scenario are provided below.

Low yield scenario

The Stoichiometric ratio of the syngas component is achieved by expelling CO. This way, the unreacted CO can be avoided. However, only less amount of methanol is produced and the excess CO is sent to syngas turbine as a fuel for combustion.

To compare the performance this scenario with the scenario of CO_2 feedstock, the same 3 MW of electrolyzer is used. Then, the biomass feedrate is adjusted to number of which the supply oxygen from electrolyzer is sufficient for gasification. For this, the biomass feedrate is the selected input parameter, the output of methanol from both alternative routes is calculated using flowsheet model.

High yield scenario

The stoichiometric ratio of the syngas component is achieved by adding more hydrogen into reactant. This way, higher capacity of electrolyzer is needed and it has been calculated that the requirement of electrolyzer capacity is approximately 13 MW. In short, almost all of CO and CO_2 in the syngas react with hydrogen, producing high amount of methanol.

7.3. Simulation result and discussion

Table 5 summarizes the simulation input and output of all defined scenarios. For easy explanation, the case of using CO_2 feedstock, biomass feedstock with low yield scenario, and biomass feedstock with high yield scenario, are named as respectively case 1, 2, and 3.

Table 5. The output summary of flowsheet model for methanol synthesis route.

Output Parameters	Case 1 CO2 Feedstock	Case 2 Biomass Feedstock Low Yield Operation	Case 3 Biomass Feedstock High Yield Operation
Methanol Production (ton/h)	0.38	2.1	3.8
Electrlyzer Capacity (KW)	3000	3000	13000
Total power consumption (kW)	3663	4415	14096
Total Power Production	0	2292	1336
Water Consumption (ton/h)	0.6	0.65	3.03
CO_2 consumption (ton/h)	0.66	0	0
Biomass Inlet stream (ton/h)	0	3.6 ton/h	3.6 ton/h
Recycle Ratio	4	1	1

The first attention should be given to the methanol production of case 1. It is obviously seen that methanol production of case 1 is the lowest. This proved that synthesizing methanol from CO_2 is not an efficient process. With the same capacity of electrolyzer with case 2, case 1 can only produce less than a quarter of case 2. Although this case does not need biomass feedstock, the saving cost for not using biomass does not outweigh the decline in methanol production. After all, it could be said that case 1 is less feasible than case 2.

For case 2 & 3 it is seen that an increase in electrolyzer capacity does not significantly contribute to the increase of methanol production. In case 3, the electrolyzer capacity is four times larger than case 2 and it is only able to increase the production by 80%. To know more detail about the different cash flow between both cases, financial investigation has to be done.

Another the major difference between case 2 and 3 is seen at their water consumption. It is found that the case 3 requires water at 3 ton/h and this is almost five times higher than the amount for the case 2. This is because the higher capacitiy of electrolyzer indeed requires the higher amount of water. The water consumption can be a major issue recently, because the amount of available fresh water has limitation.

The table also shows the recycle rate in which this indicates the effect of low kinetics rate of reaction. It is found that the recycle ratio of case 2 and 3 have is within acceptable range, as recycle flow rate is more or less same with the main stream. However, a significant increase is found in case 1. This is due to the fact that conversion of CO2 is very low, compared to the CO conversion.

Sensitivity analysis of biomass and waste input quantity

Based on discussions above, the case 2 is selected as the best case and the next investigation will be focus on case 2. Previously, the flowsheet simulation is only performed for the biomass/waste feedrate of 3.6 ton/h. However, it is also important to identify to what extend the output parameter will differ due to the changes on the biomass/waste feedrate.

Figure 14 shows the graphs of biomass/waste input quantity vs plant outputs. The units of mass and energy rates are change to yearly basis. Due to a possibility that P2G will run intermittently, the technical and economical evaluation shall be carried put in yearly basis. In addition, the graph also shows that all of the outputs are moving up linearly with an increase in waste or biomass input quantity. From this relation a simple linear equation can be made to express the relation.

The different performance between waste and biomass based methanol plant can be seen by looking the gradient of both of the curves in Figure 14. The gradient of the waste case is lower than the biomass case. This represents a reduction in methanol production as well as energy production. After all, it is proved that the low quality of feedstock such as waste has negatively influenced the outputs of plant. Nevertheless, the waste case may still offer a benefit because waste actually has negative price. This means that it is possible to earn money from obtaining waste as much as possible.

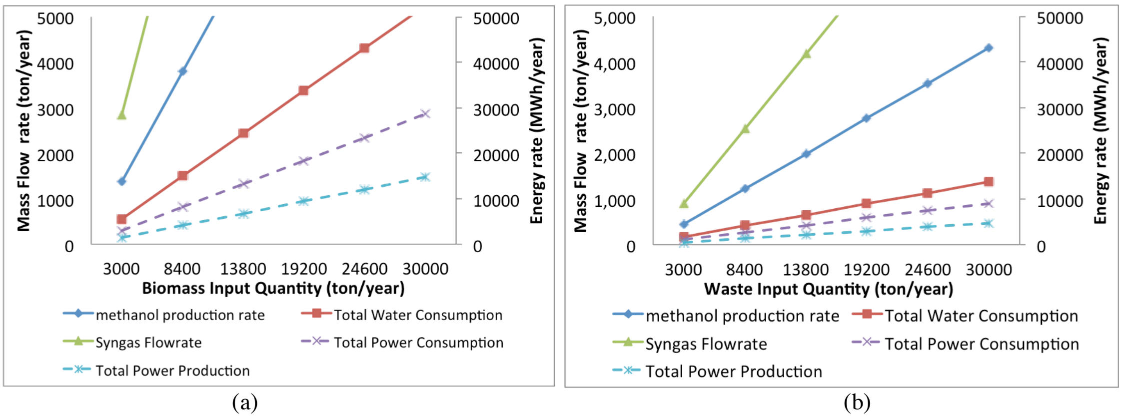

Figure 14. (a) The outputs vs biomass input quantity and (b) the outputs vs waste input quantity.

In addition to discussion above, it has been previously stated in the problem definition that by-products of organic waste processing plant, so-called sieve overflows, are currently being stored away. and becoming a problem at Twence. Through the gasification and methanol synthesi process, the sieve overflows can be used also to produce methanol. In summary, the route of biomass/waste to methanol could help Twence to cope with the problem of plant residues.

7.4. Conclusion

Despite of the inaccuracy caused by the ideal assumption or simplification, the model successfully shows reasonable results, especially for comparing the selected cases or routes of methanol synthesis. It is known from the model, that methanol production rate is mainly depending on the type of carbon feedstock, electrolyzer capacity, and the rate of carbon feedstock. This effect of modifications on these parameters can be well simulated in the model.

The flowsheet model enables to show the effect of using of different feedstock and/or electrolyzer capacity on the production rate. The use of CO_2 as feedstock (case 1) is found to be less efficient than the use of biomass (case 2) for methanol production. It is revealed that case 1 can only produce less than quarter amount of case 2. Besides, the scenario of maximizing the hydrogen production to reach the stoichiometric balance of syngas (case 3) does not significantly contribute to the methanol production. By doing so, it only increase 50% of methanol rate while it requires four times larger capacity of electrolyzer. Lastly, it is also concluded that the use biomass for methanol synthesis led to higher production, compared to the use of waste.

To summarize, the route of using biomass/waste at the minimum capacity of electrolyzer (case 2) is chosen as the preferable case. However, the conclusion of which one is the best between biomass and waste cannot be made in this chapter. A further investigation about financial feasibility of both options shall be done. This investigation is carried out in the next chapter.

CHAPTER 8: FINANCIAL STUDY

It has been concluded in the previous chapter that the process of making of methanol from waste/biomass is determined as the most preferable case of P2G at Twence. Following this conclusion, in this chapter a further investigation regarding the financial feasibility is conducted to the selected case. This is done to identify whether it is economically feasible, based on the standard requirement of Twence.

The chapter is classified into several sections. First, the basic theory about capital budgeting is briefly introduced. Second, a flowchart of feasibility study is presented. The flowchart represents the summary of important processes in doing the financial feasibility. Third, the plant capital cost is estimated, using assumption based on literatures. Fourth, the calculation of cash flow is explained. Fifth, the calculation of operational cost is described along with the used assumption. After defining all of cost component, financial calculation for entire lifespan is carried out and the important parameter such as Net Present Value (NPV), Interest Rater Return (IRR), etc are investigated. Finally, discussion and conclusion are made regarding the calculation result.

8.1. Basic theory

Several financial terms are used in this study and the definitions of each term will be introduced. In finance, the Net Present Value (NPV) is defined as the sum of present values of incoming and outgoing cash flows over a period time. As money has depreciation value over the time, the NPV is calculated using eq. (28).

$$\mathrm{NPV} = \sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{R_t}}{(1+i)^{\mathrm{t}}} \tag{28}$$

Where, t is the time for the cash flow, i is the discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk), R_t is the net cash flow (the sum of cash inflow and outflow at given time t.

Additionally, there is another important term, called Internal Rate of Return (IRR). The IRR is a rate of return used in capital budgeting to measure and compare the profitability of investments. When the IRR is same as discount rate, the NP becomes zero.

8.2. Flowchart of financial feasibility

Figure 15 presents the flowchart of financial feasibility. Certain steps in the flowchart are related to what have been discussed in previous chapter such as the input of biomass feedrate and calculation using flowsheet model. However, for financial calculation other important inputs are also shown for instance the biomass/waste price, electricity price, and methanol sales price. From the flowsheet model, the data of methanol production, power consumption, power production, and water consumption are obtained. These data are later used for financial calculation. Finally, decision shall be made based on NPV or IRR. If these parameters do not meet the Twence requirement, the process shall return to the input and/or the flowsheet model.

Twence requires a new business case to have a discount rate of 9%. This means that the IRR shall be more than 9% in order to have a positive NPV.

Using the flowchart, financial study of the route of methanol synthesis is performed in this chapter. The description of capital and operational cost will be provided in the following section.

8.3. Capital cost

The capital cost can be classified into three major equipment: (1) gasifier, (2) electrolyzer, and (3) combined heat and power (CHP). Among these three, the gasifier and electrolyzer technology are still immature especially for the application of P2G. Therefore, a high variation of investment cost can be predicted.

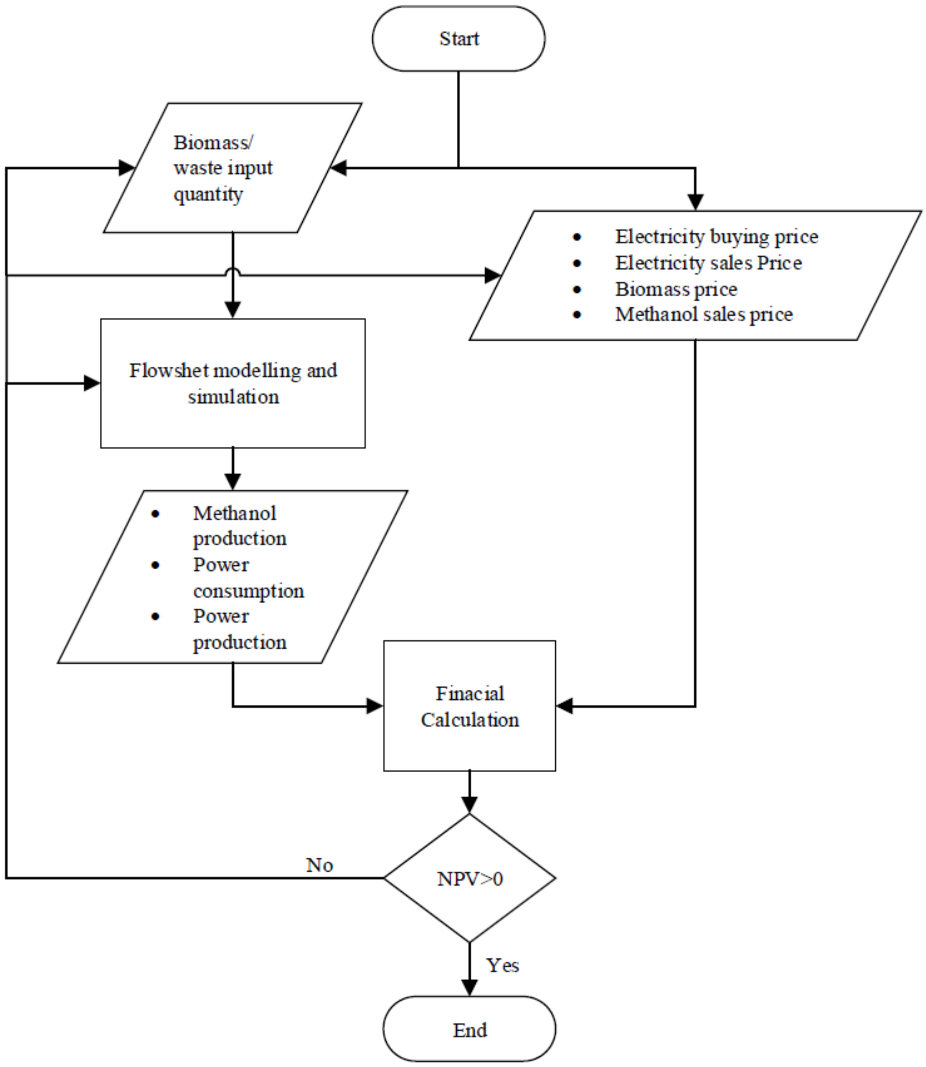

Figure 15. Financial feasibility flowchart.

Plasma gasifier is selected for this study and its investment cost is estimated based on literatures. [37] and [38] summarized the cost of all plasma gasifier that have been existing or now under construction, it appears that the capital cost varies, depending on the size of equipment. The capital cost of gasifier is expressed in the unit of Euro/ton per day of dried feedstock (Euro/TPD), and the total capacity installed in expressed TPD. From the all the data obtained, the curve fitting is made and the line equation is expressed in eq (29).

$$Gasifier\ Cost\ (euro/TPD) = 0.46 \times \{Gasifier\ Capacity\ (TPD)\}^{-0.618} \qquad (29)$$

As for the electrolyzer, the investment cost differs, depending on total capacity installed in kW. The capital cost of electrolyzer is expressed in the unit of Euro/kW and the total capacity installed in expressed kW. The relation between the investment cost and installed capacity is expressed in eq (30) [39].

$$Electrolyzer\ Cost\ (euro/kW) = 23182 \times \{Electrolyzer\ Capacity\ (kW)\}^{-0.383} \qquad (30)$$

Combined heat power is the most mature technology among all the major equipment. Depending on its capacity and operational load, different types of CHP are available for instance reciprocating engine, gas turbine, etc. For large capacity of >5MW, the capital cost is approximately 2000 euro/kW. Meanwhile for small capacity <5MW, it approximately costs 1200 euro/kW[40]. However, it is important to note that the CHP technology using syngas is currently not yet largely commercial, therefore the discrepancy from the common price of CHP might occur.

8.4. Net cash flow

The net cash flow basically incorporates the expense and income for each mass and energy stream. The expense includes the buying price of electricity ($P_{elect.buy}$), biomass ($P_{bio,}$), inert material (P_{inert}), and water ($P_{H_2O.}$). Meanwhile the income contains the sales price of methanol (P_{CH_3OH}) and electricity $P_{elect.sell}$) The cash flow of each component is then calculated by multiplying the price with the mass flow ($\dot{m}$) for the mass components and the power rate ($\dot{W}$) for energy component. Finally, the net cash flow can be generally calculated using eq. (31).

$$Net\ Cash\ Flow = (\dot{m}_{CH_3OH} \cdot P_{CH_3OH.} + \dot{W}_{elect.out} \cdot P_{elect.sell}) - (\dot{W}_{elect.in} \cdot P_{elect.buy} + \dot{m}_{bio} \cdot P_{bio} + \dot{m}_{inert} \cdot P_{inert} + \dot{m}_{H_2O} \cdot P_{H_2O}) \quad (31)$$

Next, the data of each variable needs to be defined. The mass and energy flow rate follow the result of simulation. For the electricity price, both buying and selling price are initially set as 38 euro/MWh. Then, the biomass and waste price are assumed to be constant at respectively 22 and (-)43 euro/ton, based on the information from Twence. For the price of inert material, the biomass and waste have 25 euro/ton and 18 euro/ton respectively. The inert material of waste has lower cost because it contains a higher amount of metal. For the methanol sales price, it is reasonable to assume that the price for methanol based on the recent global market because this calculation is meant for preliminary analysis. The price of methanol and methane are constant at respectively 400 euro/ton.

The net cash flow calculation is done annually, however an important parameter, so-called capacity factor (CF), shall be noted when applying intermittent operation. The capacity factor indicates how many hours it is being operated within a year. The capacity factor can be determined by looking the trend of electricity price throughout the year. For example, if winter electricity price is much lower than other seasons, it can be decided that the system only runs in winter. However, a bigger capacity of equipment is required to maintain the same yearly production as the system with capacity CF 1.

8.5. Operational and other cost

The operational cost is mostly attributed to operational maintenance cost. Based on Twence standard assumption, 5% of total capital per year is representative value for maintenance cost. Cost inflation of 2%/year is also taken into account for maintenance cost as well as other operational cost.

Beside the above major investment costs, net cash flow, and major operational cost, other components are also determined. Table 6 shows summary of all other component cost for financial budgeting. Finally all the costs are used in the Twence template of financial calculation, provided in Appendix C.

Table 6. Other component for financial budgeting.

Cost component	Value	Remarks
Project cost	10% Total capital cost	This accounts for executing the project (to hire project manager, staffs, etc)
Unforeseen investment cost	30% Total capital cost	Based on Twence's standard for the project within study phase
Investment subsidy	0% Total capital cost	No presently available SDE subsidy
Maintanence cost	5% Total Capital Cost	Based on literature [22] for preliminary investigation
Operational staff cost	300,000 euro/year	This accounts for operational teams such finance, maintenance, operational manager, etc
Unforseen operational cost	5% Total Operational Cost	Assumption
Methanol transportation cost	20 euro/ton	the value based on assumption. this cost is included in methanol sales price
Operational production lost	1% of methanol production per year	Each year the plant will lose some methanol production due to degradation of efficiency
Energy Inflation	0%	No energy inflation predicted for 2016-2020

8.6. Results and discussion

To provide a result, an example case shall be determined. For this, biomass is selected as the raw material and its feedrate is 30 kton/year. With this feedrate, simulation using the flowsheet model is conducted and the output data is retrieved. Furthermore, the biomass feedrate determines the required capital cost for gasifier, electrolyzer, and CHP. The plant operational lifetime is 20 years and the annual capacity factor is 90% (10% of year is for the maintenance). Table 7 summarizes all the important parameters.

Table 7. Important parameters for the biomass feedrate of 30 kton/year.

Parameter	Value
Lifespan	20 years
Capital cost gasifier	12.6 M€
Capital cost electrolyzer	3.6 M€
Capital cost CHP	3.7 M€
Biomass price	22 €/ton
Bottom ash price	25 €/ton
Water price	2 €/ton
Electricity price sell / buy	38 / 60 €/MWh
Capacity factor	0.9
Maintenance cost	5%/year
Discount rate	9.5%

Using the data above, it turns out that the NPV and IRR for the biomass case are respectively (-)16.8 M€ and (-)4.2%. This is clearly an unacceptable business case and does not have any profits. This result appears due to the extreme capital cost of gasifier (12.6 M€). Moreover, the huge capital cost is always followed by a high maintenance cost, resulting in low yearly incomes.

To resolve the low interest, two possible solutions are investigated. First, the net cash flow shall be improved. Changing the input material from biomass to organic waste may solve the problem, because the cost of waste is (-)43 €/ton (negative value means that the company are paid for treating waste). The second possible solution is to increase the input quantity of material. By doing this, bigger capacities of equipment are needed and it will reduce the normalized investment cost (i.e: €/kW for electorlyzer, €/TPD for gasifier)

Figure 16 shows the curves of NPV and capital cost in case of using different feedstock. There are several findings obtained from this figure. First, it is obvious that an increase in input quantity is followed by an increase in capital cost. Second, different trends of NPV are seen between biomass and waste case. For biomass case, the NPV is likely to drop, as the input quantity increases. On the other hand, the waste case shows that an increase in input quantity positively affect the NPV. Third, the capital cost in the waste case is lower than the biomass case. For example, the waste input quantity of 40 kton/year needs capital cost of 20 M€, meanwhile the biomass case needs almost twice amount of money for the same input quantity. From this, it could be said that the conversion from waste to methanol could provide a higher profit. To ensure this, a similar curve for IRR is plotted.

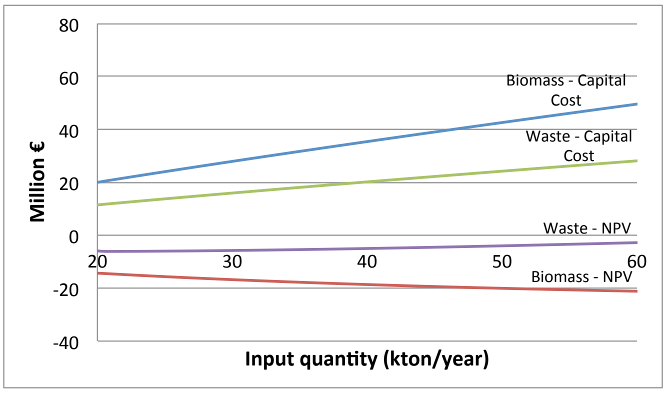

Figure 16. The capital cost and NPV as a function of biomass/waste input quantity.

Figure 17 shows the IRR, as a function of input quantity. It is now clear that the waste is more profitable than the biomass. For the input quantity of 30 kton/year, the waste case has the IRR of 3%, which is around 7% higher than the biomass case. Both cases demonstrate that the IRR grows with an increase in input quantity, and the IRR of waste case always stays above the biomass case. Furthermore, the IRR of waste has started to show a positive value at the input quantity of 22 kton/year. Meanwhile, the IRR of biomass remains at the negative value until the input quantity reaches around 50 kton/year.

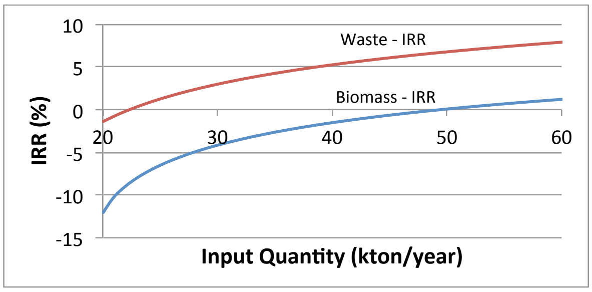

Figure 17. The IRR as a function of biomass/waste input quantity.

A discussion can be made about why the low quality feedstock could generate more profit. The negative price of feedstock is indeed the key factor in making a higher profit. Besides, there is also an advantage that the price of waste in wet basis. It is known from Table 4 that the water is the major component in organic waste (53% mass). This means that the revenues come from the water instead of the organic materials. Additionally, the capital cost of the waste case can be reduced because the input material going into the gasifier is low. Before entering the gasifier, the raw waste is sent to the dryer to get rid of the water content. At the end, only a small fraction is going to gasifier, thus reducing the gasifier capacity.

A question may arise regarding how to provide the heat for drying the waste. Theoretically, it is possible to utilize the heat residue from methanol synthesis and methanation reaction. If this is not sufficient, another possible solution is to burn the waste and extract the heat from it. This way, the more input of waste is required and the more incomes can be obtained. Regardless all the ideas, it is important to do a further investigation regarding the drying process of the organic waste prior to gasification.

From the result above, the higher amount of waste is expected, but there is actually a maximum of available waste. According to Twence's development plan, the organic waste will be supplied from the new separation plant. This plant will enable to provide organic waste approximately up to 57.76 kton/year. Based on this data, the maximum NPV, IRR, and the total capital cost are respectively -3.1 M€, 7.7%, and 27 M€.

It is known that the result of financial budgeting for 57.76 kton/year of waste does not fulfill the requirement (NPV<0). However, it is important to identify which factor does affect significantly to the changes of NPV and IRR. To understand this, a sensitivity analysis is given in the following sub section.

Sensitivity analysis NPV and IRR

The NPV and IRR are calculated from multiple variables, but for sensitivity analysis only some of important variables are identified. The variables include investment cost gasifier, investment cost electrolyzer, investment subsidy, waste input quantity, methanol price, electricity price, maintenance cost, life span, and option of winter/summer cycle. Among these variables, the winter summer cycle has a unique definition.

The option of winter summer cycle is defined as a modification on capacity factor. As the business case is suitable at low electricity price, one may suggest that it is more effective to run the system only when the electricity price is low. This is called winter summer cycle because the methanol synthesis plant only operates during summer (low E priece) and the CHP only generates electricity during winter (high E price), based on APX market price. This seasonal operation represents a system with yearly capacity factor of 20% (to operate only 20% the year). Additionally, it shall be noted that a decrease in capacity factor shall be followed by an increase in equipment capacity. This is required to maintain the yearly production of methanol and electricity.

Figure 18 and Figure 19 depict the sensitivity analysis of NPV and IRR respectively. The basis values of NPV and IRR are taken from the waste case of 57.76 kton/year. The modifications on each variable are measured in percentage except the life span and capacity factor (the option of winter summer cycle). For example, the movement of NPV as a result of ± 20% changes in each variable is visible in the chart. However, the life span and maintenance cost are altered ±5 year and ± 5%.

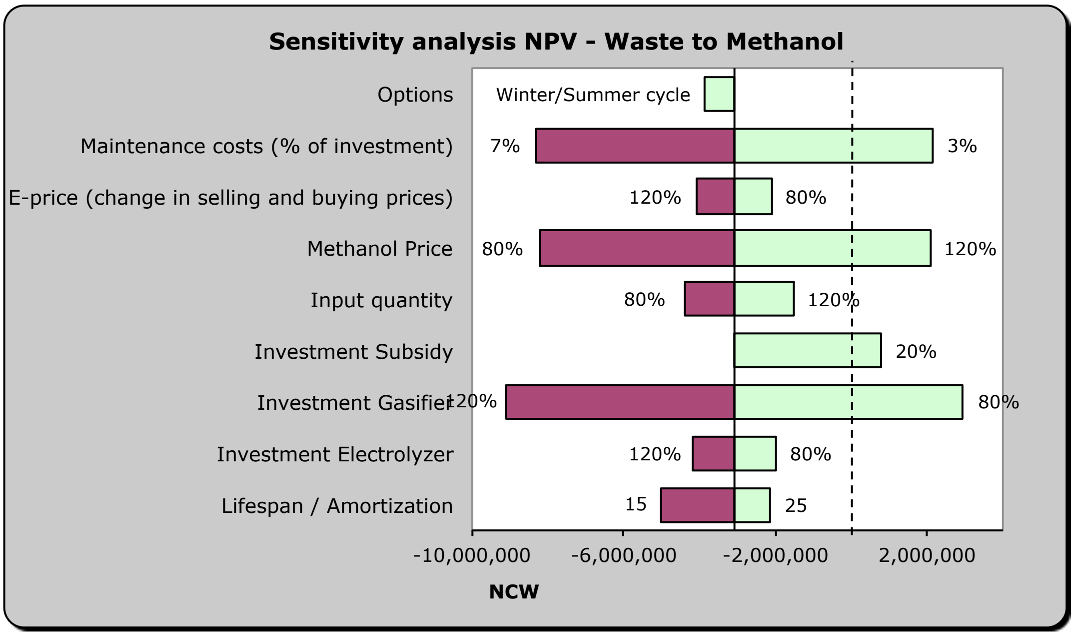

Figure 18. Sensitiviy analysis NPV.

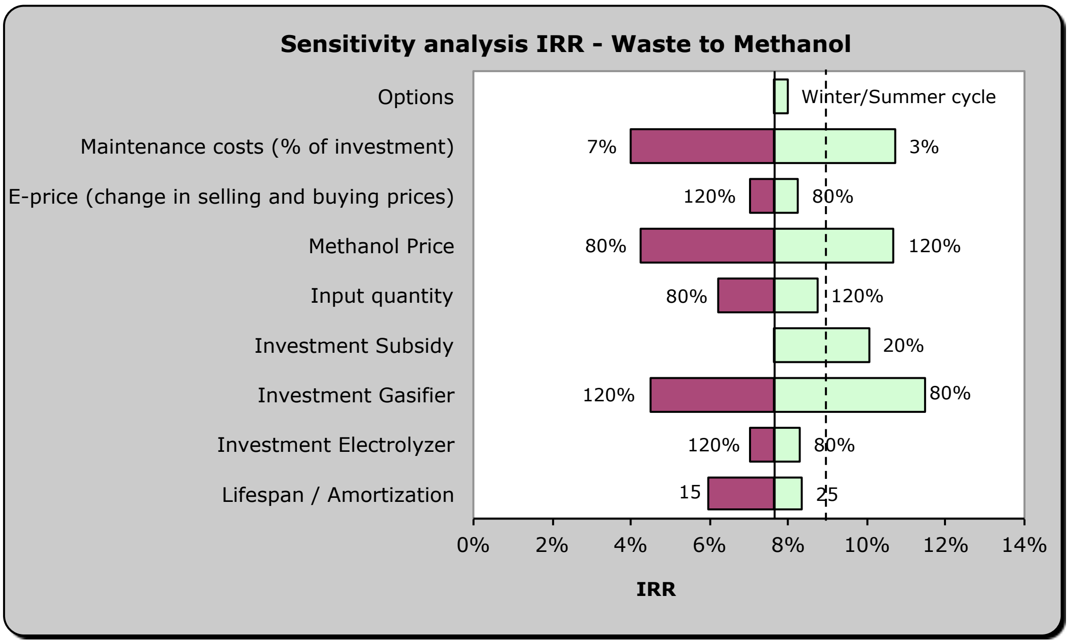

Figure 19. Sensitivity analysis IRR.

The most decisive variable can be identified from the two charts. First, the NPV is very sensitive on the investment cost of gasifier. It is shown that NPV rises to almost 3 M€ if the investment cost of gasifier can be reduced to 80% of basis value and this is the highest among all variables except maintenance cost. It is true that changing only 2% of total maintenance cost could affect the NPV and IRR significantly. However, it is assumed that the maintenance cost is a function of the investment cost. Therefore, the most decisive factor shall be attributed to the investment cost.

An interesting result is also shown in the charts regarding the effect of applying winter summer cycles. It is exposed that this option has negative impact on NPV. This condition does not correspond with the common expectation that P2G is more applicable for intermittent operation. In fact, the methanol synthesis route using waste is not sensitive to the change of electricity price. As a result, the difference in the net cash flow does not compensate the increase of capital cost.

8.5. Conclusion

The route of waste to methanol (the waste case) shows a more preferable business case, compared to the route of biomass to methanol (the biomass case). From the investigation, the waste case shows lower capital cost than the biomass case. For instance, with the same material (waste or biomass) input quantity of 40 kton/year, the waste case only need 20 M€, which is half amount of what the biomass case needs for its capital cost. The difference capital cost between both two cases is growing with an increase in the input quantity. Besides, IRR of the waste case is comparatively higher. When the feedrate is 30 kton/year, the biomass case could only provide IRR of -4.8%. On the other hand, the waste case shows IRR of 7,5% higher than the waste case and this difference remains the same regardless the feedrate.

A profitable business cases are noted for the waste case. From the investigation, it is revealed that the waste case could provide a positive IRR at the input quantity above 22 kton/year. This is different from the biomass case, where the IRR remains negative until the biomass input quantity reaches 50 kton/year

Increasing the input quantity can improve the NPV and IRR of business case. This is clearly seen for the waste case. The NPV and IRR are continuously growing with an increase in the waste feedrate, making it possible to move toward the requirement (NPV>0, IRR>9.5%). However, the quantity of waste is limited at maximum 57.76 kton/year. At this input quantity, the NPV and IRR are respectively -3.1 M€ and 7.7%. Following this result, the sensitivity analysis is done to investigate which factor could significantly affect the value of NPV and IRR.

NPV and IRR are sensitive to the investment cost of gasifier. Based on the sensitivity analysis, a 20% reduction of the investment cost of gasifier cost has resulted to the inclining of the NPV to positive 6 M€ and IRR to positive 12%.

Intermittent operation (winter summer cycle) has negative impact on NPV. Running the system only within 20% time of the year (methanol production at low E price and electricity production at high E price) does not show any improvements. To maintain the yearly production, the capacity must be enlarged, resulting to higher capital cost. Furthermore, the system has low sensitivity to E price. As a result, the growth of cash flow by intermittent operation does not compensate the larger capital cost.

CHAPTER 9: OVERALL CONCLUSION AND RECOMMENDATION

To summarize all the previous chapters, this chapter provides overall conclusion, and recommendation. The conclusion includes the summary of important points or messages from the study as well as the answers of research questions. Meanwhile, the recommendation describes the possibility of further studies.

9.1. Conclusion

The research questions have been determined in Chapter 1: Introduction. These research questions are:

1. *Which P2G route is likely feasible to be in integration with the existing Twence Plant?*
2. *What operation scenario has the most benefits for Twence?*
3. *How much the Interest rate of Return (IRR) of the selected P2G business case?*

In order to answer above research questions, literature reviews, flowsheeting simulation, and financial investigation have been performed. Finally, the following conclusions can be made as the answers.

The route of waste to methanol is the most feasible business case of P2G. Compared to the process of methanation, methanol synthesis has a higher product yield and needs less amount of hydrogen. Furthermore, the comparison between different feedstock (CO_2, biomass, waste) is performed and the use of waste (the waste case) turns out to be the most preferable case. The waste case has comparatively higher profit. It has IRR of 9% at maximum waste feedrate of 57.8 kton/year and this is around 7.5% higher than the case of using biomass (the biomass case).

A continuously operation is the preferable scenario for the route of methanol synthesis. Based on the sensitivity analysis of the waste case, the intermittent operation (CF=0.2) failed to provide more profitable business case. This result contradicts with the common perception that P2G business is more attractive for fast intermittent operation. It appears that running the system only at low and high electricity and The lower NPV and IRR occurs because the capacity of equipment such as electrolyzer and CHP must be enlarged to maintain the yearly production.

The power to gas technology in this study is more likely to act as a chemical converter instead of energy storage. From literature reviews, it is mainly highlighted that power to gas plays a role in the decarbonization scenario. As a chemical converter, the route of the methanation and methanol synthesis from CO_2 or biomass can be very attractive. Through these routes, the business cases of replacing fossil based chemicals/fuels for mobility sector or industry will be more feasible. In addition, technical investigation is performed and it is revealed that the role of P2G as a converter of biomass to methanol is more efficient.

High wind penetration on electricity supply contributes in making a feasible market for P2G. This known by comparing Denmark, which is having the highest share of wind based electricity, with other countries such as Norway, Sweden, and Netherlands. Based on analysis of spot electricity price in 2014 using frequency graph, it is known that Denmark (DK1) has comparatively low mean value but high standard deviation. This condition led to a suitable environment for P2G technology. In contrary, the Netherlands spot price APX-NL 2014 shows the least feasible market for P2G. However, it can be argued that Dutch market will evolve toward a condition similar with DK1, because Netherlands as well as other European countries has set a higher target of RE production.

Knowing the history data of APX-NL 2014, Twence shall avoid a P2G system that is vulnerable to electricity price. For this, the route of waste to methanol has a business case in which the NPV and IRR are not sensitive to electricity price. Through this route, it is possible to minimize the risk if the electricity price unexpectedly changes.

The major challenge for biomass/waste to methanol conversion is the gasifier. From the example financial study, it is known that the gasifier with biomass input quantity of 30 kton/year has capital cost of 12.6 M€. This already accounts 50% of total capital cost. Hence, the reduction in its investment cost is expected.

9.2. Recommendation

The accomplishment of this study has opened various possibilities for further investigations. The next phase of P2G researches at Twence may include investigations on:

1. **The prediction of energy market and other supporting policies**: This study only presents historical data of energy market price and a simple conclusion was made based on the data. However, the P2G business case shall be able to predict the upcoming market price for instance methanol, methane, electricity price, etc. By doing so, the level of risk can be assessed thoroughly and finally it will lead to a reasonable and reliable business life span. In addition, the further study about the possibilities to have allowance from local, national, or European institution shall be performed. Based on the sensitivity analysis, the investment subsidy also takes a significant effect on NPV and IRR.

2. **The improvement on the accuracy of model:** There are many ideal assumptions and simplification in the model. Therefore, the model needs further modification to increase the accuracy. For example, methanation and methanol synthesis reaction shall apply the kinetic model. This way, the model becomes accurate to predict the impact of low kinetic rates of certain elementary reaction and the effect of catalyst, operation temperature and pressure can be identified. Besides, the composition of feedstock (waste, biomass, etc) shall be determined based on the actual condition. For instance, the waste actually consists of complex mixtures and it will involve various reactions producing emission and by products. In this case, ideal assumption may provide a large error.

3. **The use of syngas to back up the steam production:** Twence needs a back up system in case that an unexpected problem or shutdown occurs in the waste incineration plant. For this, the P2G system, that produces syngas, could become a solution. The syngas is stored in a high-pressure storage tank and it is burned at CHP during the emergency situation. To provide such a system, it is important to identify design parameters for example the required volume of syngas, additional amount of feedstock, etc. Moreover, investigation on the storage tank and the operation of CHP are also important.

4. **The use of heat residue:** It is known that the gasification releases sensible heat and the methanation and methanol synthesis are exothermic. These processes provide heat residues that shall be utilized to increase the overall plant efficiency. To do this, further investigations are needed such as pinch analysis, energy and exergy analysis. It is also important to identify the heat consuming process in the P2G system. For instance, the heat residues can be used for auxiliary process such as the drying before gasification.

5. **The technology development of gasifier**: From this study, it is concluded that the main technical and economical challenge is the gasification technology, especially plasma based gasification. Nevertheless, this report only provides a short literature review of plasma gasification. Therefore it is highly suggested to investigate in more detail about the state of the art, and its next development stage. Moreover, the companies involved in this technology shall be investigated as well.

6. **The process of making other chemicals from waste**: The waste processing plant shall be shifted from energy recovery to material recovery. The final products should not be limited to methane or methanol. It is also recommended to do further investigations about the possibility of making other chemicals such as ethanol, propanol, etc. After all, the new business of converting waste into chemicals may help Twence to survive in the future energy market.

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APPENDIX

Appendix A: Data of energy market price: electricity, methanol, methane, CO_2

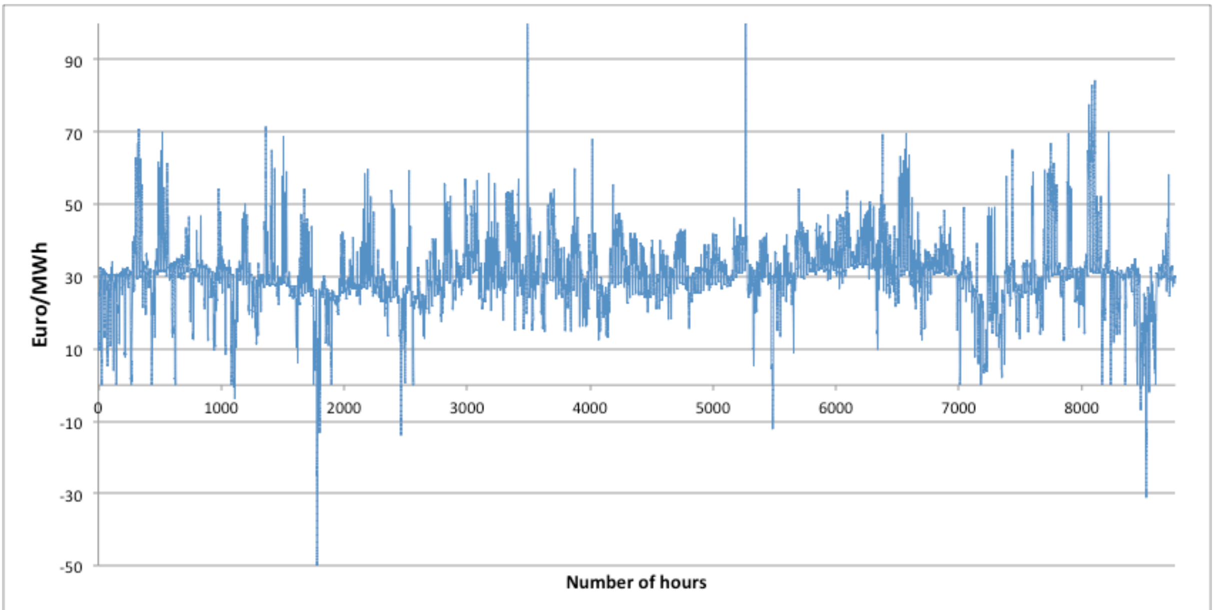


Figure 20 Day-Ahead Electricity for Denmark (DK1)– History data of 2014 [41].

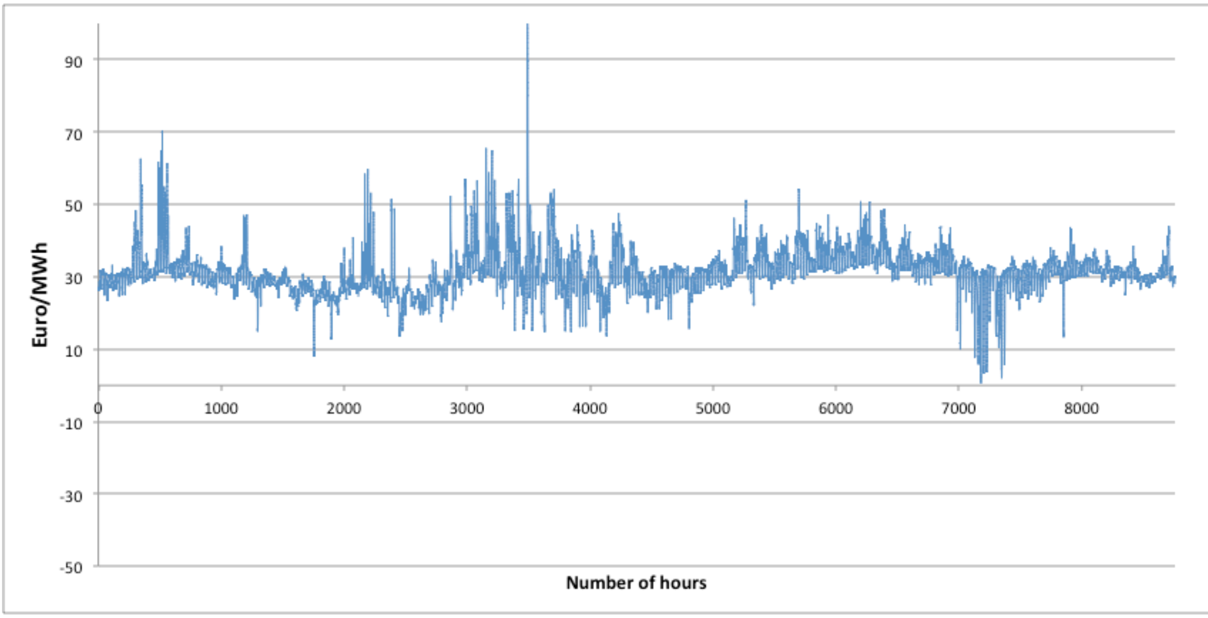


Figure 21. Day-Ahead Electricity for Sweden (SE1)– History data of 2014 [41].

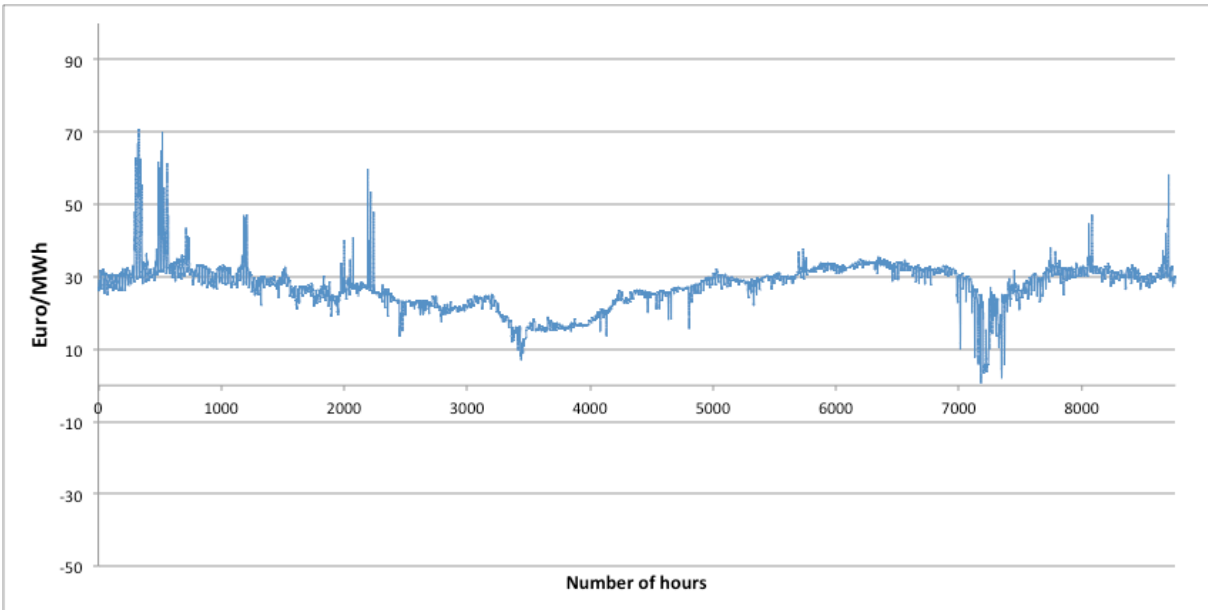


Figure 22. Day-Ahead Electricity for Norwegia (Oslo)– History data of 2014 [41].

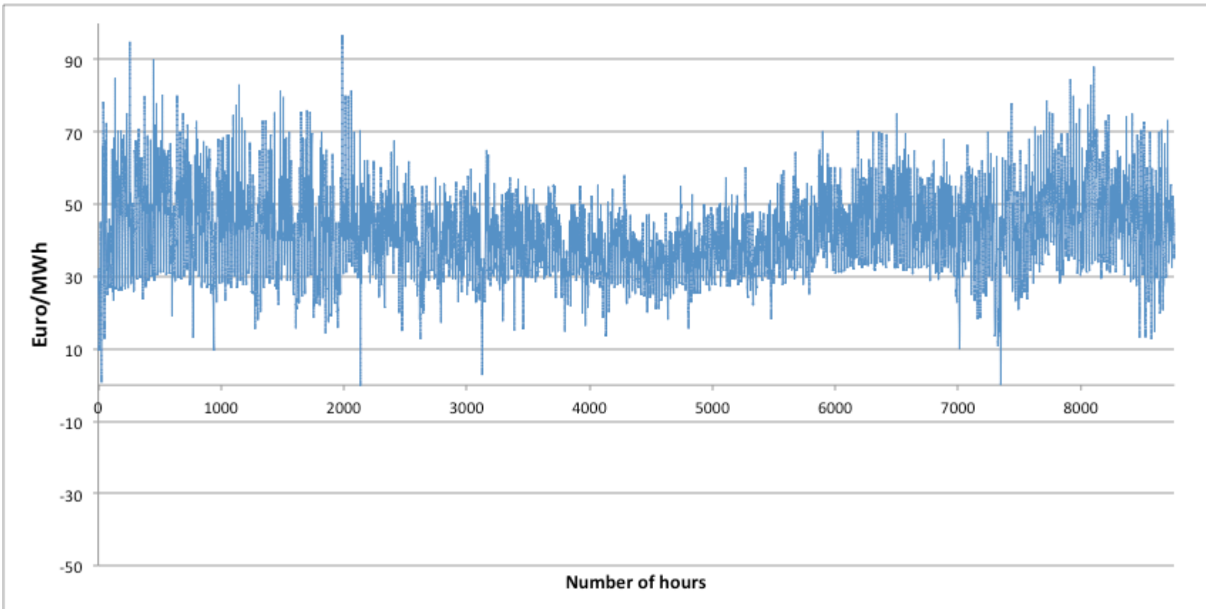


Figure 23. Day-Ahead Electricity for Netherlands (APX-NL)– History data of 2014.

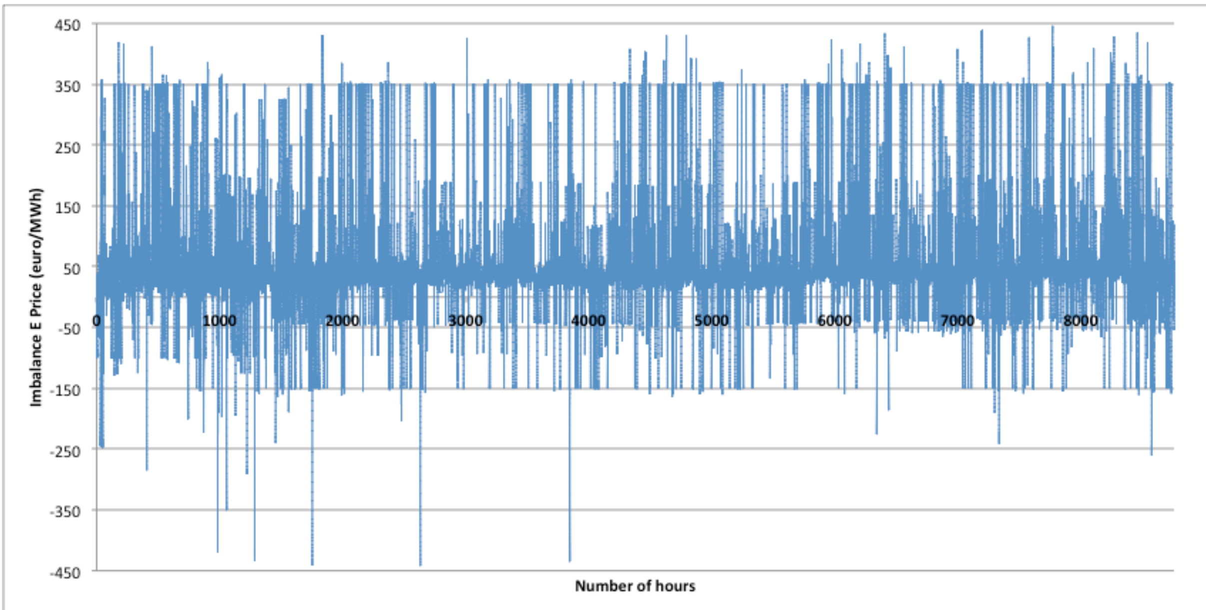


Figure 24. Imbalance Market 2014 by Tennet.

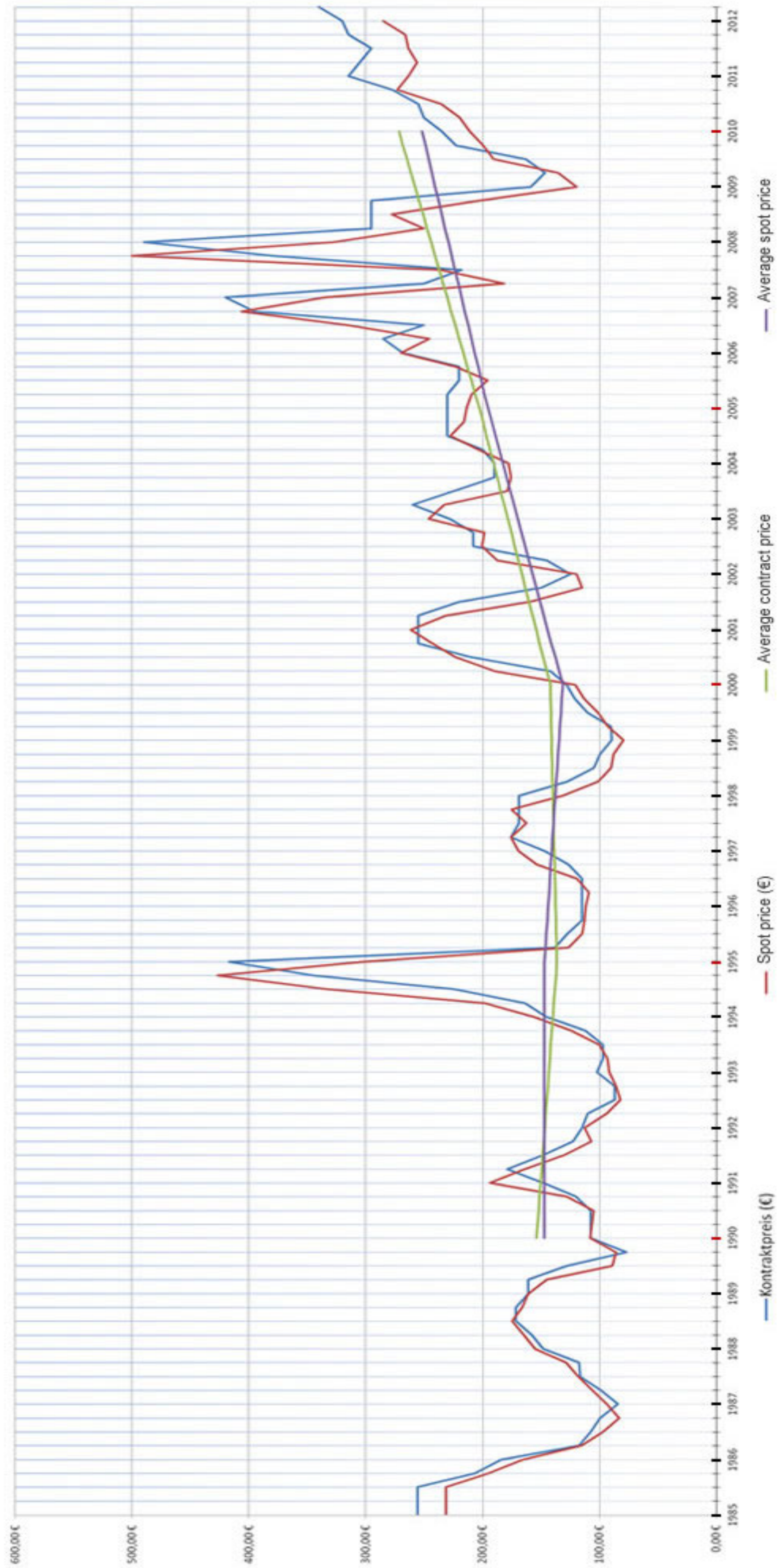


Figure 25. European Methanol Price History 1985-2012 [32].

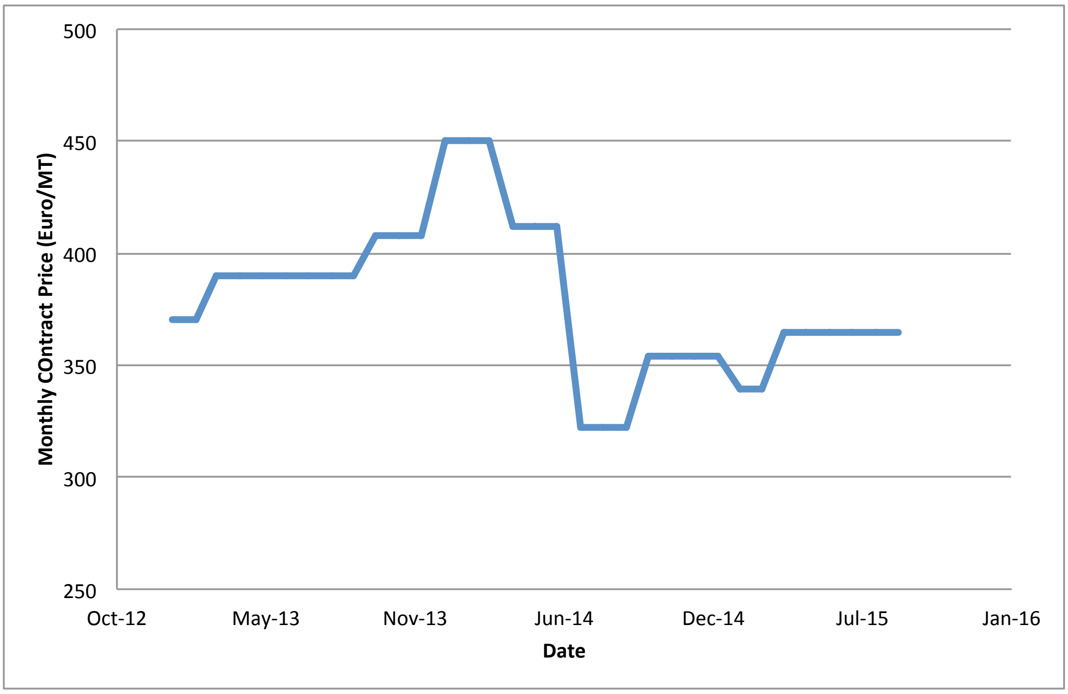


Figure 26. European Monthly Methanol Price 2013-2015 [33].

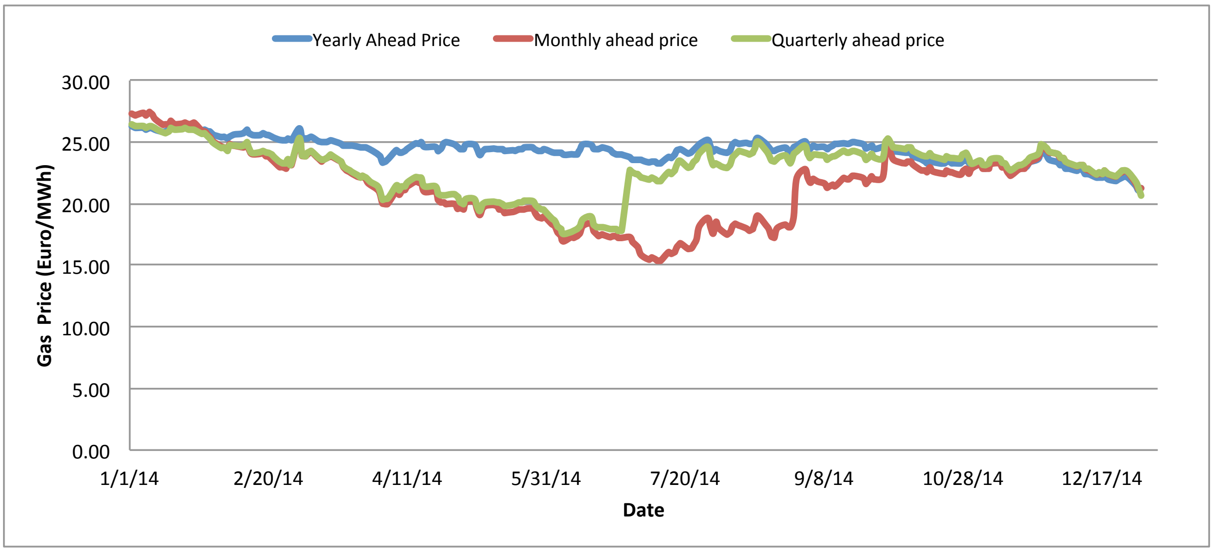


Figure 27. Yearly, Quarterly, ad Monthly Ahead Gas Price [42].

Appendix B: The combined flowsheet

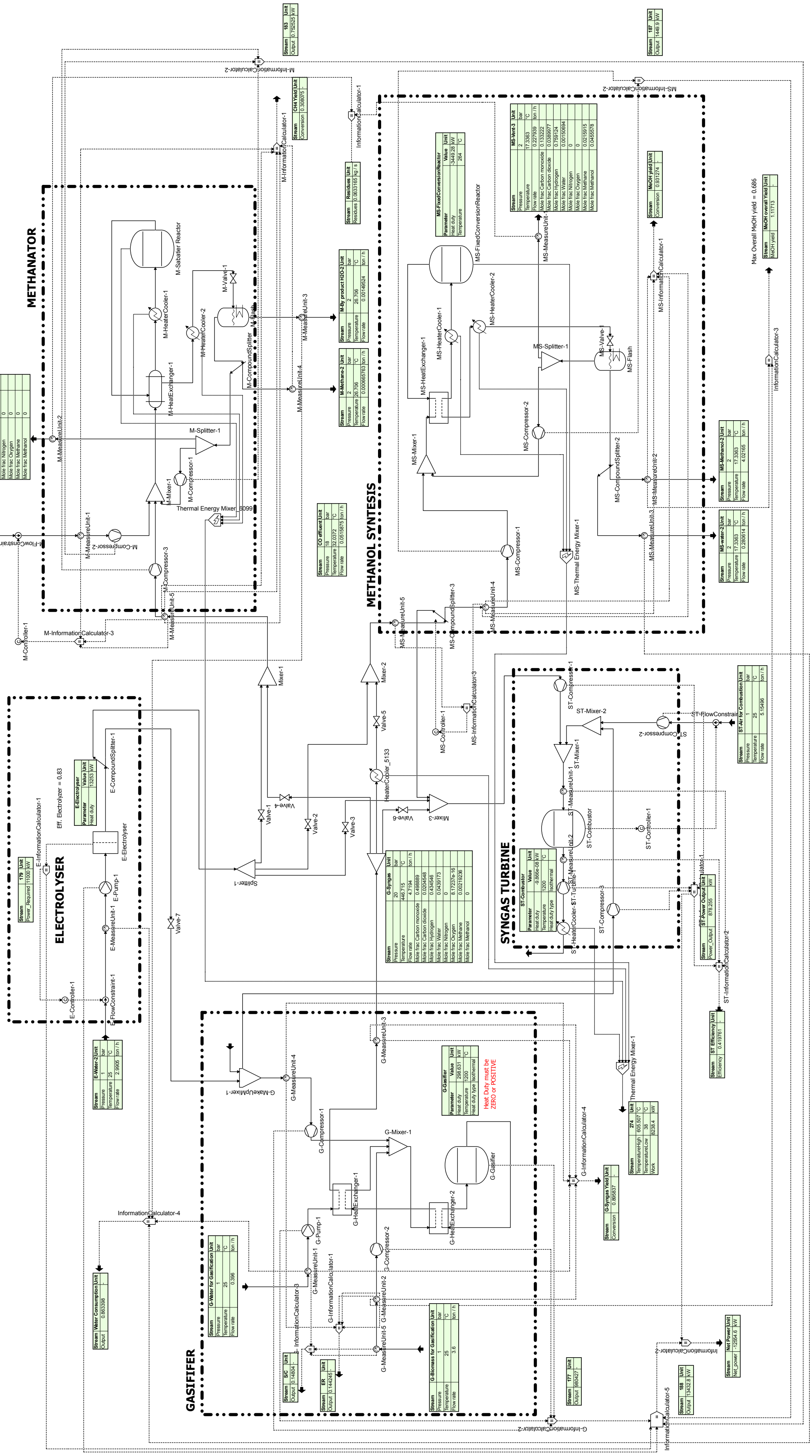


Figure 28. The combined flowsheet.

Appendix C : Financial calculation spreahsheet

WASTE/BIOMASS TO METHANOL v3 27Oct15

Factor bij inflatie 0%: 8.8124 € 3,090,060

Investment principles			
Lifespan / Amortization		20	year (max 20)
Investment per kW electrolyzer+Methanol Syn Plant		**1,221**	Eur/kW
Investment per kW Combined Heat Power (CHP)		**2,000**	Eur/kW
Investment per Ton per Day (TPD) Gasifier		**229,750**	Eur/TPD
Electrolyzer power installed		**2,178.01**	kW
CHP power Installed		**1,124.31**	kW
Gasifier Installed		**63.30**	TPD
Project costs %		10%	
Unforeseen costs (uncertainty) %		30%	
Investment subsidy		0%	
Energy inflation	MJB 2016-2020	0.0%	
Cost inflation	SBL,7jun12	2.0%	

Assumptions Benefits / In- and output			
Input		***Organic Waste***	
Input quantity		57,760	
Input price biomass	MJB 2016-2020	€ 22.00-	€/ton
Input price OF	MJB 2016-2020	€ 43.00	€/ton
Input price		€ 43.00	
Water quantity		2,604	ton/year
Price of water		€ 2-	€/ton
Methanol Price ex. Transport		€ 400.00	€/ton
Transport costs		€ 20	€/ton
Methanol Price		€ 380	€/ton
Average E-Price (selling)		€ 38	€/MWh
High E-price		€ 54	€/MWh

Operational assumptions		
Full load hours	**8,760**	hours
Electrolyzer Capacity Factor	0.9	
CHP Capacity Factor	0.9	
Methanol prod.rate	8,267	ton/year
E-production rate	8,963	MWh/year
Total E-consumption	17,362	MWh/year
Organic waste consumption	57,760	ton/year
Organic waste output inert material	22%	of input
Price for bottom ash organic waste	€ -18	
Operational production loss*	1%	
*Each year the plant will lose some efficiency in the methanol producti[...]		
Capacity factor	***Yearly production***	

Leonie Broeze:
For biomass based on the current price (2015: € 25,-) of bottom ash for the biomass power plant. For organic waste the price is lowered with € 7,- because of the non-ferro material (1%) which it contains.

Assumptions operational costs			
Maintenance	literature	5.0%	/investment
Maintenance costs		€ 1,239,001	/year
Reinvestment electrolyzer*		***5-yearly***	
Reinvestment costs electrolyzer		10.0%	/original invest
*In this business case included in the yearly maintenance costs			
Staff		€ 300,000	/year
E-consumption (buying)		€ 60	€/MWh
		€ 43	€/MWh
[...]n system)		8,400	MWh/year
[...]sts*		5.0%	/above costs
[...]d costs are included in unforeseen			

Assumptions Financial expenses		
VV initially	bron,datum	70.0%
	bron,datum	0.0%
Redemption	bron,datum	€ 953,078-
Interest rate %	bron,datum	5%
VPB%	bron,datum	25.0%
For the sensitivity analysis		
Input quantity		100%
E-price (selling and buying)		100%
Methanol price		100%

PROJECT TOTAL			**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Year			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Net investments																			
Investment per kW electrolyzer+Methanol Syn Plant	100%		2,659,093																
Investment per kW Combined Heat Power (CHP)	100%		2,248,627																
Investment per Ton per Day (TPD) Gasifier	100%		14,542,845																
Project costs %			1,945,056																
Unforeseen costs (uncertainty) %			5,835,169																
Investment subsidy			-																
Net investment			27,230,791	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Benefits / In- and output																			
Input quantity	Organic Waste	ton		57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760	57,760
Input	Benefits	€		€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680	€ 2,483,680
Water quantity		ton		2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604	2,604
Water	Cost inflation	€		€ 5,209-	€ 5,313-	€ 5,419-	€ 5,528-	€ 5,638-	€ 5,751-	€ 5,866-	€ 5,983-	€ 6,103-	€ 6,225-	€ 6,350-	€ 6,477-	€ 6,606-	€ 6,738-	€ 6,873-	€ 7,011-
Methanol production		ton		8,267	8,184	8,101	8,019	7,936	7,853	7,771	7,688	7,605	7,523	7,440	7,357	7,275	7,192	7,109	7,027
Methanol sales		€		€ 3,141,303	€ 3,109,890	€ 3,078,477	€ 3,047,064	€ 3,015,651	€ 2,984,238	€ 2,952,825	€ 2,921,412	€ 2,889,999	€ 2,858,586	€ 2,827,173	€ 2,795,760	€ 2,764,347	€ 2,732,934	€ 2,701,521	€ 2,670,107
E production		MWh		8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963	8,963
E sales	Energy inflation	€		€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097	€ 336,097
Inert material	Cost inflation	€		€ 228,730-	€ 233,304-	€ 237,970-	€ 242,730-	€ 247,584-	€ 252,536-	€ 257,587-	€ 262,738-	€ 267,993-	€ 273,353-	€ 278,820-	€ 284,397-	€ 290,084-	€ 295,886-	€ 301,804-	€ 307,840-
Total In- and output				**€ 5,727,141**	**€ 5,691,049**	**€ 5,654,864**	**€ 5,618,583**	**€ 5,582,205**	**€ 5,545,727**	**€ 5,509,149**	**€ 5,472,467**	**€ 5,435,679**	**€ 5,398,784**	**€ 5,361,779**	**€ 5,324,663**	**€ 5,287,433**	**€ 5,250,086**	**€ 5,212,620**	**€ 5,175,034**
Operational costs																			
Maintenance	Cost inflation	€		€ 1,239,001	€ 1,263,781	€ 1,289,057	€ 1,314,838	€ 1,341,135	€ 1,367,957	€ 1,395,316	€ 1,423,223	€ 1,451,687	€ 1,480,721	€ 1,510,335	€ 1,540,542	€ 1,571,353	€ 1,602,780	€ 1,634,835	€ 1,667,532
Staff	Cost inflation	€		€ 300,000	€ 306,000	€ 312,120	€ 318,362	€ 324,730	€ 331,224	€ 337,849	€ 344,606	€ 351,498	€ 358,528	€ 365,698	€ 373,012	€ 380,473	€ 388,082	€ 395,844	€ 403,761
E-consumption (buying)	Energy inflation	€		€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259	€ 848,259
Unforeseen operational costs*		€		€ 119,363	€ 120,902	€ 122,472	€ 124,073	€ 125,706	€ 127,372	€ 129,071	€ 130,804	€ 132,572	€ 134,375	€ 136,215	€ 138,091	€ 140,004	€ 141,956	€ 143,947	€ 145,978
Total operational costs				**€ 2,506,623**	**€ 2,538,942**	**€ 2,571,908**	**€ 2,605,533**	**€ 2,639,830**	**€ 2,674,813**	**€ 2,710,496**	**€ 2,746,892**	**€ 2,784,017**	**€ 2,821,883**	**€ 2,860,508**	**€ 2,899,904**	**€ 2,940,089**	**€ 2,981,077**	**€ 3,022,885**	**€ 3,065,530**
Depreciation	geen inflatie	€		€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-	€ 1,361,540-
EBIT - Earnings Before Interest and Tax				**€ 1,858,978**	**€ 1,790,567**	**€ 1,721,416**	**€ 1,651,511**	**€ 1,580,836**	**€ 1,509,375**	**€ 1,437,113**	**€ 1,364,035**	**€ 1,290,123**	**€ 1,215,361**	**€ 1,139,732**	**€ 1,063,219**	**€ 985,804**	**€ 907,469**	**€ 828,195**	**€ 747,964**
Investment Material Assets			(27,230,791)				-												
Investment in Working Capital	2%		544,616	(609,026)	1,368	1,383	1,398	1,414	1,429	1,445	1,462	1,478	1,495	1,513	1,530	1,548	1,567	1,585	1,605
Depreciation	correctie			1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540	1,361,540
Cash flow	voor belasting		(26,686,175)	2,611,491	3,153,475	3,084,339	3,014,449	2,943,789	2,872,344	2,800,098	2,727,036	2,653,141	2,578,396	2,502,784	2,426,289	2,348,892	2,270,575	2,191,320	2,111,109
Cash flow cumulative	voor belasting		(26,686,175)	(24,074,684)	(20,921,209)	(17,836,870)	(14,822,421)	(11,878,632)	(9,006,289)	(6,206,191)	(3,479,155)	(826,014)	1,752,382	4,255,166	6,681,455	9,030,347	11,300,922	13,492,242	15,603,351

PROJECT TOTAAL, INCREMENTEEL	
Disconteringsvoet voor belasting	9.50%
NPV (Net Present Value)	(3,083,014)
IRR (Internal Rate of Return)	7.7%
Payback period	10 jaar

9

8.6 jaar

Invultabel tbv autom.grafiek	basis IRR	7.7%		
Lifespan / Amortization		15	20	25
	7.7%	5.9%	7.7%	8.3%
	(3,083,014)	(5,013,708)	(3,083,014)	(2,122,730)
Investment Electrolyzer		120%	100%	80%
	7.7%	7.0%	7.7%	8.3%
	(3,083,014)	(4,185,017)	(3,083,014)	(1,981,012)
Investment Gasifier		120%	100%	80%
	7.7%	4.5%	7.7%	11.5%
	(3,083,014)	(9,109,974)	(3,083,014)	2,943,945
Investment Subsidy		0%	0%	20%
	7.7%	7.7%	7.7%	10.0%
	(3,083,014)	(3,083,014)	(3,083,014)	800,349
Input quantity		80%	100%	120%
	7.7%	6.2%	7.7%	8.7%
	(3,083,014)	(4,415,639)	(3,083,014)	(1,528,669)
Methanol Price		80%	100%	120%
	7.7%	4.3%	7.7%	10.7%
	(3,083,014)	(8,241,577)	(3,083,014)	2,075,548
E-price (change in selling and buying prices)		120%	100%	80%
	7.7%	7.0%	7.7%	8.3%
	(3,083,014)	(4,058,415)	(3,083,014)	(2,107,614)
Maintenance costs (% of investment)		7%	5%	3%
	7.7%	4.0%	7.7%	10.7%
	(3,083,014)	(8,331,310)	(3,083,014)	2,165,281
Capacity factor			Yearly production	Winter/Summer cycle
	7.7%	8.0%	7.7%	8.0%
	(3,083,014)	(3,876,460)	(3,083,014)	(3,876,460)

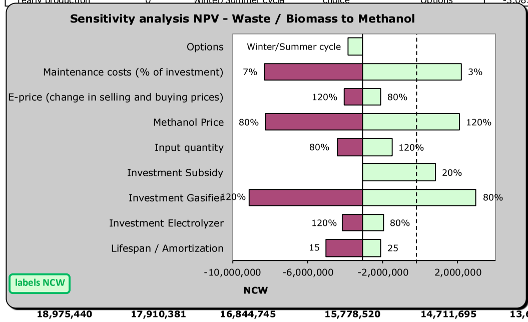
sensitivity

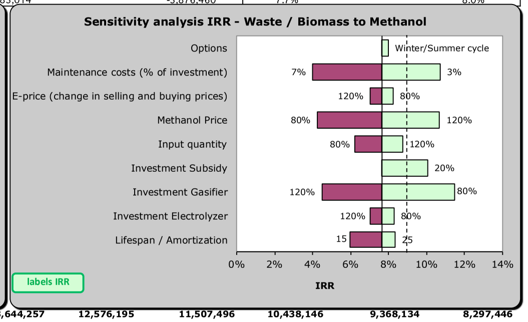
financiering

Grafiek-as schuiven

Gevoeligheid WASTE/BIOMASS TO METHANOL

input variables					NCW			IRR		
basis	minimaal	maximaal	eenheid	variabele	basis	minimaal	maximaal	basis	minimaal	maximaal
20	15	25	year	Lifespan / Amortization	-3,083,014	-5,013,708	-2,122,730	7.7%	5.9%	8.3%
100%	120%	80%	%	Investment Electrolyzer	-3,083,014	-4,185,017	-1,981,012	7.7%	7.0%	8.3%
100%	120%	80%	%	Investment Gasifier	-3,083,014	-9,109,974	2,943,945	7.7%	4.5%	11.5%
100%	0%	20%	%	Investment Subsidy	-3,083,014		800,349	7.7%		10.0%
100%	80%	120%	%	Input quantity	-3,083,014	-4,415,639	-1,528,669	7.7%	6.2%	8.7%
100%	80%	120%	%	Methanol Price	-3,083,014	-8,241,577	2,075,548	7.7%	4.3%	10.7%
100%	120%	80%	%	[...]ange in selling and buy[...]	-3,083,014	-4,058,415	-2,107,614	7.7%	7.0%	8.3%
5%	7%	3%	%	[...]ance costs (% of inve[...]	-3,083,014	-8,331,310	2,165,281	7.7%	4.0%	10.7%
Yearly production	0	Winter/Summer cycle	choice	Options	-3,083,014		-3,876,460	7.7%		8.0%





18,975,440	**17,910,381**	**16,844,745**	**15,778,520**	**14,711,695**	**13,644,257**	**12,576,195**	**11,507,496**	**10,438,146**	**9,368,134**	**8,297,446**	**7,226,068**

FORMULA TO CALCULATE ELECTROLYZER COST

Electrolyzer Capacity (KW)	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000	16000	17000
Hydrogen production rate (kg/h)	30.14286	60.57143	91	121.4286	151.8571	182.2857	212.7143	243.1429	273.5714	304	334.4286	364.8571	395.2857	425.7143	456.1429	486.5714	517
Hydrogen production rate (kg/day)	723.4286	1453.714	2184	2914.286	3644.571	4374.857	5105.143	5835.429	6565.714	7296	8026.286	8756.571	9486.857	10217.14	10947.43	11677.71	12408
Capital cost ($)	1827187	2807767	3607305	4308290	4944115	5532435	6083992	6605921	7103261	7579734	8038188	8480859	8909544	9325716	9730597	10125220	10510461
Capital cost ($/kW)	1827.187	1403.884	1202.435	1077.073	988.8229	922.0725	869.1417	825.7401	789.2512	757.9734	730.7444	706.7382	685.3496	666.1226	648.7065	632.8262	618.2624
Capital cost (euro/kW)	1644.468	1263.495	1082.192	969.3653	889.9406	829.8653	782.2275	743.1661	710.3261	682.1761	657.6699	636.0644	616.8146	599.5103	583.8358	569.5436	556.4362

Reference

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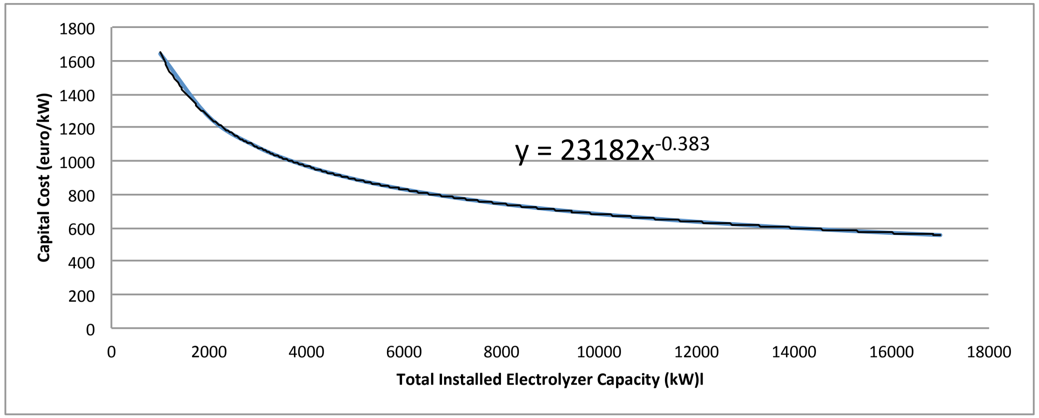
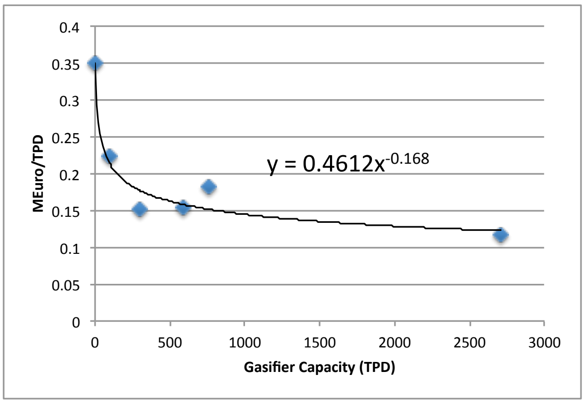


FORMULA TO CALCULATE GASIFIER COST

Gasifier Capacity (TPD)	Capital Cost (M$/TPD)	Capital Cost (MEuro/TPD)
5.253322426	0.38795987	0.34916388
97.96844798	0.24849498	0.223645485
297.3941917	0.16923077	0.152307692
591.1391288	0.17023411	0.153210702
764.3784638	0.20133779	0.181204013
2708.248117	0.13010033	0.117090301



Refererence

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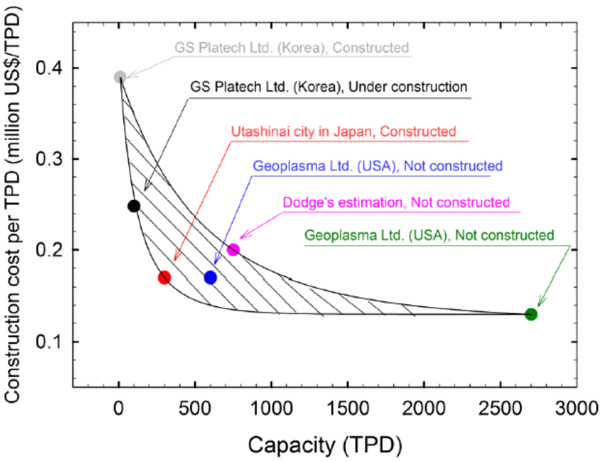

SUMMARY

BIOMASS TO METHANOL

Methanol Production (ton/year)	=	0.449126	x	Input Quantity +	24.72222
E Production (MWh/year)	=	0.48945	x	Input Quantity +	35.51
Total E Consumption (MWh/year)	=	0.947332	x	Input Quantity +	-14.1889
Total Water Consumption	=	0.173606	x	Input Quantity +	143.8333

WASTE TO METHANOL

Methanol Production (ton/year)	=	0.14269	x	Input Quantity +	24.81222
E Production (MWh/year)	=	0.155415	x	Input Quantity +	35.49778
Total E Consumption (MWh/year)	=	0.298102	x	Input Quantity +	-14.1922
Total Water Consumption	=	0.044477	x	Input Quantity +	143.8333

ELECTROLYZER CAPITAL COST

Capital cost (Euro/kW)	=	23182	x	capacity (kW) ^	-0.383

CHP CAPITAL COST

capital cost (Euro/kW) >5MW	=	1300
capital cost (Euro/kW) <5MW	=	2000

GASIFIER CAPITAL COST FOR BIOMASS

Capital cost (MEuro/TPD)	=	0.4612	x	0.65	x	Input Quantity	^	-0.168

GASIFIER CAPITAL COST FOR WASTE

Capital cost (MEuro/TPD)	=	0.4612	x	0.4	x	Input Quantity	^	-0.168