LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
School of Engineering Science
Industrial Engineering and Management
Global Management of Innovation and Technology

Master's Thesis

Techno-Economic Assessment of Protein Produced from Electrical Energy

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ABSTRACT

Author: Amila Pramianshar **Title: Techno-Economic Assessment of Protein Produced from Electrical Energy** **Year:** 2018 **Place:** Lappeenranta	
Type: Master's Thesis. Lappeenranta University of Technology **Specifications:** 94 pages, 35 figures, and 15 tables	
First supervisor: Ville Ojanen, Associate Professor, Docent **Second supervisor:** Jero Ahola, Professor	
Keywords: Food from electricity; Power-to-X technologies; Techno-economic; sensitivity analysis; food innovation; food development	

Food is primary need for everyone and in the near future this need will increase since the growth of people and the resources will be changing. These days a lot of food development projects to tackle huge food demand in the future and supporting the sustainability perspectives. Developing protein production from various resources is one example of that which is in this case, single cell protein development. Single cell protein development is implementing power-to-X technologies approaches. The implementation of power-to-X technologies in the scope of food development could be beneficial part in the future since the used of energy could support sustainability focused. However, for applying this approach, techno-economic analysis should be utilized before applying this innovation into big market. The production cost is determined by calculating mass and energy balance, LCOE formula and the costs of other parameters such as material and electricity among others, before conducting the techno-economic assessments by utilizing widely accepted calculation model. The assessment shows three important parameters which are affecting the production cost such as electricity price, CO_2 price, and efficiency of electricity to biomass. By utilizing some scenarios for the analysis, the result shows there is some difference in production cost. This research could be the base model for future research of developing power-to-X technologies in the scope of food innovation project especially for protein production in the near future.

Acknowledgements

First, I am obliged to Ville Ojanen for giving his permission to me for working in the collaboration thesis project between my master program which is Global Management of Innovation and Technology and LUT Energy System School since my big interest in energy sector. Also, I am feeling really grateful because of his support and guidance for this thesis work and whole my master studies in Finland.

This master thesis is part of MOPED project which is collaboration between Lappeenranta University of Technology (LUT) and Technical Research Centre of Finland VTT Ltd. Also, this master's thesis project is conducted at the Laboratory of Digital Systems and Control Engineering in LUT. I would like to say big thanks for Professor Jero Ahola and Pasi Vainikka for allowing me to join his research project and finishing my final studies under his research groups. Even, the process is so tough, but I was really enjoying the moment of working in this topic. Also, I want to thank to Vesa, Georgy, and Mahdi for their support on my thesis project. In addition, I would like to thank to Professor Olli Pyrhönen who gives me this opportunity to doing my thesis with LUT Energy System School.

Almost 2 years, I am studying in LUT, I found some friends who always cheer and support me until I finish my studies. Thanks to all of my classmates and friends such as Abhishek, Saeid, Sohail, Soumyajit, Alejandro, Olga, Kees, Laura, Lies, Aleksandra, Grace, Cristina, Joonas, Daniel, Rafael, and other who I could not write all of the name here. I will always remember our moments together in Lappeenranta, Finland.

Special thanks to my parents and my sister for their support, pray, and motivation. Without their love and hope, I would not able to finish my studies in Finland. I will always remember their love and support, also I will continue to make them proud.

Last but not least, thanks to almighty for guiding, helping, and giving me what I have today.

Lappeenranta, 25 May 2018

Amila Pramianshar

Table of Contents

List of Figures

List of Tables

Abbreviations

ABPDU – Advanced Biofuels and Bioproducts Process Development Unit

CAPEX – Capital Expenditures

$C_{4,09}H_{7,13}O_{1,89}N_{0,79}$ – Protein Component

CH_4 – Methane

$CH_{1,77}O_{0,49}N_{0,24}$ – Protein Component

CO_2 – Carbon Dioxide

Crf - Annuity Factor

CxHyOz – Hydrocarbon Component

DAC – Direct Air Capture

EU – European Union

FAO – Food and Agriculture Organization

FET - Future and Emerging Technologies

FLH – Full Load Hours

G-t-L – Gas to Liquids

H_2 – Hydrogen

H_2O – Water

IEA – International Energy Agency

kg – kilogram

kJ – kilo Joule

kW – kilo Watt

LCOE – Levelised Cost of Electricity

LCOP – Levelised Cost of Protein

m^3 – Cubic meter (Volume)

MWh – Mega Watt hour

N – Lifetime

NH_4-N – Ammonia

NH_3 – Ammonia

NREL – National Renewable Energy Laboratory

O_2 – Oxygen

OM cost - Operational and Maintenance cost

OPEX – Operating Expenditures

P-t-G – Power to Gas

P-t-L – Power to Liquids

PEM - Polymer Electrolyte Membrane

PMT – Payment (PMT Function in Microsoft Excel)

PV – Photovoltaic

PR – Progress Ratio

SCP – Single Cell Protein

USDA – United States Department of Agriculture

WACC – Weighted Average Cost of Capital

€ - Euro

η_{el} – Effieciency of Electricity

ΔG – Gibbs Energy

1. Introduction

Food is a primary need for everyone in the world. The demand for food always has always increased every time since the growth of population also increased. Refers to FAO (2009), the growth of world population will be increased more less 2.3 billion around 2009 until 2050. In 2009, the demand for food such as cereals for human and animal already around 2.1 billion tones, this will make sense, if the demand will be reached around 3 million tons in 2050. Based on those analysis, today a lot of people concern how to fulfil the future demand for food. The reason is if the food production cannot catch the demand, the food problem will be increased quickly. Many research projects are being coduncted across the world to to boost food production in the future. However, the limitation of resources and land should be a concern because the environment and the climate will chnage in the future. To tackle this situation, there are several developments of technologies already progressed such as use power to specific matter, sustainable food innovation, and more project related to food technology.

1.1 Background

In 2006, FAO (2009) already reviewed about innovation of food production, especially in product and technology development. The background of the discussion is the probability of economic returns from food sector which is more concerned in agricultural production. The agricultural sector needs to follow the recent trends from food demand until the production efficiency. On the other hand, this situation also makes some possibilities of problems to pursue all the trends from current condition and future prediction. FAO (2006) took this point to discussed how to tackle the issue of recent and future food production by adopting innovation process. Moreover, in the case of food industry development, the concept of development would be related to any other industrial development which is employing product and process development as a main core tool to prosecute innovation into food production. The need of food industry innovation is also related to the consumer demand hence their value of food is changing over time. FAO (2006) mentioned the actual product development is emerging other sector to step up their position in the cycle of food industry such as food producer and food researcher.

The product development based on FAO (2006) consideration is researching product and process in systematic and commercialized based which is having aim to developing product and process itself for specific customer need. Furthermore, Booz, Allen and Hamilton Inc. (1982) and Cooper and Kleinschmidt (1986) gave the essential stages of product development such as,

- product strategy development
- product design and development
- product commercialization
- product launch and post-launch

On the other hand, the final product of the development process still needs assessment. The assessment is to determine if the outcome is an innovative product or new product. The perspective of assessment will be different from actors' point of view, actors here are consumer, distributors, and producers. However, FAO (2006) stated seven categories to simplify the level of newness product such as,

- creative products;
- innovative products;
- new packaging of existing products;
- reformulation of existing products;
- new forms of existing products;
- repositioned existing products;
- line extensions.

Moreover, Figure 1 shows the stage of product development process. As mentioned from Booz, Allen and Hamilton Inc. (1982) and Cooper and Kleinschmidt (1986), there are four steps of product development process, starting from strategy development to launching the product and also post production process. In figure 1 also illustrates the procedure of each specific product development stages. For instance, the stage one which is product strategy development has five steps such as screening process, initial market assessment, market research in more comprehensive way, concept advancement, and preliminary financial analysis. Furthermore, after accomplished one product development stage, there will be outcomes and giving point of view to continue the product development process or postpone the improvement approach (Siriwongwilaichat, 2001; Earle and Earle 2000).

In addition, FAO also cited from Earle and Earle (2000) about technical assessment of innovation product, start from innovation scope which is releasing something fresh or unfamiliar to the world, improving the product, and reducing the cost. After that, they also mentioned about three type of innovation such as incremental, major, and radical. Some similar products used to call by product platform. If there is some changing inside the platform, it would be derivative changes. However, there is possibility to shape new product platform which is radical changes (Earle and Earle 2000).

Then, the biggest challenge of product development is the market acceptance of new product itself. The product development should meet the customer expectations and need. For instance, when the company or project pursuing food innovation, the result is not wasting, and market would give positive reaction. This view is an essential aim to guarantee the product development matches the customer perspective, that is consumer demand. Hence without public acceptance, in this case would be market, the product would be just worthless result of innovation process, if there are no sales activities after all (FAO, 2006).

Furthermore, the trends of power conversion are getting more and more recognition especially, using renewable energy for making beneficial products. For example, renewable energy is meant to substitute diesel and fuel. The path of the technology development in power conversion is likely to give more benefits than production in the conventional way. Refers to Vainikka (2017), power-to-X technologies is using the power in this form is electricity to conversion process to produce beneficial component. The implementation of power-to-X technologies still on development, some of the project already exist but to be commercialized, it will take time. The reason is the technology will depend on the situation of the country and need some adjustments before using or choosing the technology correctly. Moreover, the trend of power-to-X technologies also give concern in feasibility side because of the concern in business perspective. Many projects show good result but hard to implement since there is no fact about the economic point of view. For instance, the production cost of the project, market reaction of the product or solution, or still no parameter to improve and adopt the project.

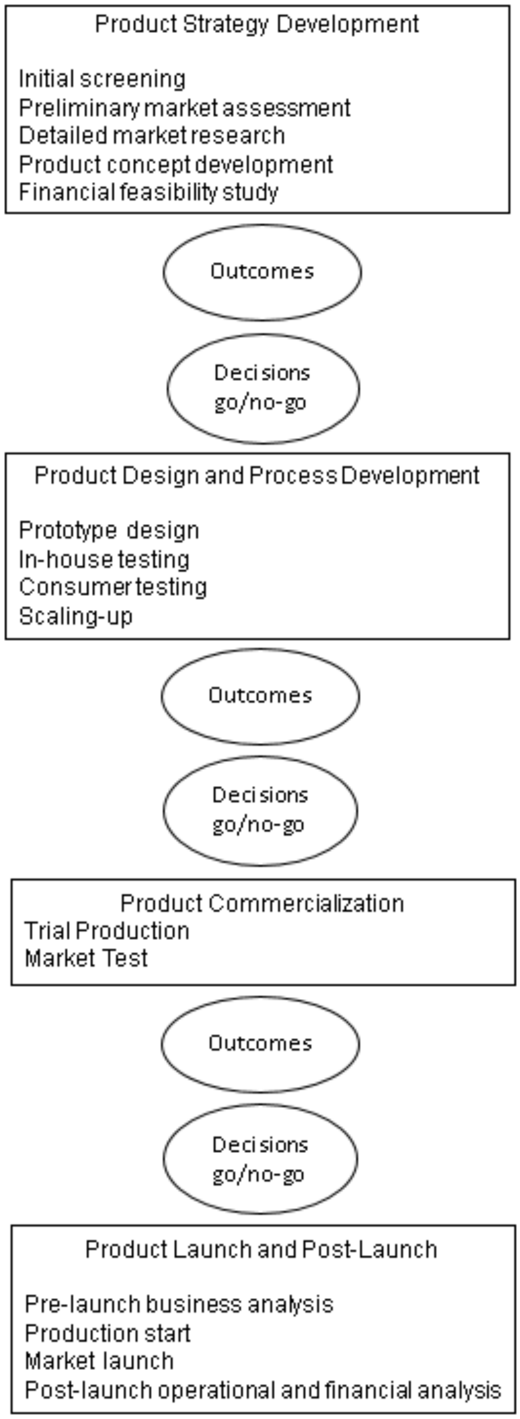

Figure 1 Flow Process of the Overall Product Development (FAO 2006, Siriwongwilaichat, 2001; Adapted from Earle and Earle 2000)

Today, the development of power-to-X technologies always be concerned in energy development. However, the reason behind power-to-X project is making something from power to be something important or beneficial. According to FAO (2006), the demand for food in the future will be increasing rapidly. People will be demanding to get more food since some people will change their life habit. Based on FAO report (2009), soon, the lack of production area and resources to produce food will face the food industry and directly give impact to the people. Related to power-to-X technologies, this situation can be one of the reason power-to-X technologies will give impact to food demand in the future. Some project of power-to-X technologies in food purpose are still under development, but the preliminary result looks promising. For instance, Sillman (2016) shows how to produce protein from electrical energy by using electrical sources from solar and wind energy. Based on that finding, this research report will be take a deep into account how to implement that solution into real life situation.

The implementation will be related in business perspective since to know how well the project or the solution, we need to take consideration the economical point of the project. The application of power-to-X technologies already in the mature step which is commercializing the project will be happened soon. Based on today's situation, the focus of techno-economic analysis will support the proof of technology development. There are many tools of techno-economic assessments, however the goal is remaining the same or almost similar.

In addition, the new technology development always been connected to disruptive technologies perspective. If we take a look to reality, the impact of technology will change the whole condition of people's life. In this case, disruptive technologies will be one factor of the consideration hence the new technology will be successful or no based on how the impact of the technology in the market is.

1.2 Research gap, objectives and questions

The purpose of this research is to know the production cost of protein production from electrical energy. This topic is continuing previous research from Sillman (2016) about the same process but in difference perspective. The perspective in this research will cover only find the production cost by using techno-economic assessment. Since the research will try discovering possible process to make pilot scale of the process, so to gain some supporting data and literature will have specific scope such as techno-economic tools and similar technology that is Power-to-X technologies. In this case, most probably some adjustment and similar approaching to gain information will be happened, basically the base of this research is taking deep into business perspective from Sillman's previous research. The goal is to make precise analysis of the process.

Based on that point of view, the main research question will cover about production cost of production process of protein from electrical energy. To make limitation of the topic and question, to get the production cost will follow previous research about techno-economic assessment from Fasihi et. al. (2016), the research was focusing to find production cost in different scenario including electrical resources. In this research only conduct one energy source which is solar energy but in different ownership from company and own solar panel. To make it clear, this research will propose one main research question:

How to evaluate production cost of protein produced from electrical energy?

The main research question will get support from two more sub questions to get more precise finding about the main question such as:
RQ1: How much does it cost to produce protein from electrical energy?
RQ2: *What is the most impactful parameter in the calculation of production cost?*
RQ3: *Which kind of sources are more beneficial for this production process?*

The research is also referring to previous discussion from FAO about food innovation industry. Since the focus of this research is calculating the production cost of the production process and analyzing the value to finding some useful information for future development of the production process. The approach of this research is similar like first stage of product development process, that is product strategy development. Based on product strategy development stage, the procedure to execute this stage has five points such as initial screening, initial market analysis, designing concept process and financial analysis (FAO 2006, Siriwongwilaichat, 2001; Adapted from Earle and Earle 2000). On the other hand, the goal of techno-economic assessment also related to second stage of product development process which is product design and process development. The reason is giving extra finding to future development of the production process. Based on figure 1, every stage will provide outcomes after finishing one stage of the product development process and also from the outcomes, the decision to continue the process or halt the development will appear too. These points of view will support the objectives and process to answer the research questions of this research.

Moreover, the objective of this research is also practicing the approach of product development stage components which is financial analysis and designing concept process. Start from designing the production process, making production cost calculation, and analyzing production cost by utilizing financial analysis approach. As mentioned before, the intention will provide beneficial finding to improve the concept and also figure some important things which is still hiding behind the concept. These two purposes are referring to the outcomes and decision after doing the product development stage.

1.3 Exclusion and Limitation

The thesis will focus on escalating the production process concept to calculation model to finding production cost of food from electricity. The scope of the research will start from building the concept of production process based on previous research and some literature review. Then, making calculation model as a tool for calculating the production cost. The calculation model based on mass and energy balance equation from Sinnott and Towler (2009). The calculation model will focus on main reaction of the process such as input to the reaction, reaction condition, and output of reaction. On the other hand, the preparation of material, capturing and pre-process for some resources are not part of this studies. The input data will be variation of data from literature which is related and also supporting this research.

The concept of the process is referring some previous research and similar project like this research since the reaction process to produced food from electricity still quite unfamiliar in the level of commercialization. Because of that, the research will be involving some assumption to support the cost estimation and analysis process. Moreover, the mass and energy balance equation are the main resources to find solution for designing the calculation model. The approach of the mass and energy balance will follow reaction process from Liu, Year. In this case, the concept will combine electrolysis unit and reactor in one place to produce biomass by utilizing electricity as main resources with some additional chemical compounds.

Based on some limitation and exclusion, the flow process of this research will be explained in the next sub-chapter and chapter. To make it clear, the analysis will consider only for in-situ electrolysis process and using sensitivity analysis approach. The assumption and adjustment are needed to support this research. The reason is limited resources which are concerning in the similar topic. Furthermore, the topic of this research is practicing the product development process of food industry innovation. However, the focus just to know the effect of the parameter of the production cost which is related to feasibility studies with economic analysis procedure. It will give barrier this research will be not discussing about market reaction of the final product. Additional point, the research is still in early stage process to build the pilot plant, in this point of view, the project is in between of strategy and design stage.

1.4 Structure of the study

The outline of this studies is started from literature review of the topic which is related to food-from-electricity. The literature review covered about the development of single cell protein, that is the main product of this research, then discussed the technology development of the production process, also the techno-economic assessment of power-to-X technologies project, and the relation of the development of production process with innovation management. To summarize all of the sub section of literature review, sub section of literature review summary included to this research to giving view of research gap from literature point of view.

After summarizing literature review, to covering central concept of the research, theoretical framework part is added. In theoretical framework would give direct explanation about what production process is applied in this research and some equations are used to find the production cost. In addition, the theoretical framework also defined the central concept of this research which is techno-economic assessment for power-to-X technologies. The central concept has aim to adding more information about techno-economic assessment in general perspective. Since if look through literature review, the point is giving example of techno-economic analysis practice in power-to-x technologies.

The theoretical framework is contributing the structure of research methodology in this research. The involvement of theoretical framework is supported the explanation of analysis method which is utilized for analyzing the production cost. The reason is referring the disclosure of techno-economic assessment as an approach to solve the research question of this research. In methodology part clarified research strategy of this research, what type of research is conducted for this research, data collection process, defining analysis method, and describing hypothesis. The methodology part is following Sanders et. al. (2009) concept of research method for business student.

The result would be interpreted with graph and table to give better illustration of the project. The result is including the result of techno-economic analysis and variation of production cost based on certain scenario. The result is based on certain equation and formula which are discussed on methodology part. The discussion part would be reviewing the result with previous research which is covered on literature review part. The discussion part also covered the bridge between techno-economic assessment, power-to-x technologies development and innovation management. The last part of this thesis report would be conclusion part. The conclusion part would be wrapping the contribution of this research, the implication of the research finding, and the limitation of the research. Also, the recommendation for future studies based on the verdict of this research. Figure 2 shows the structure of the report which is followed for finding the answer of research questions.

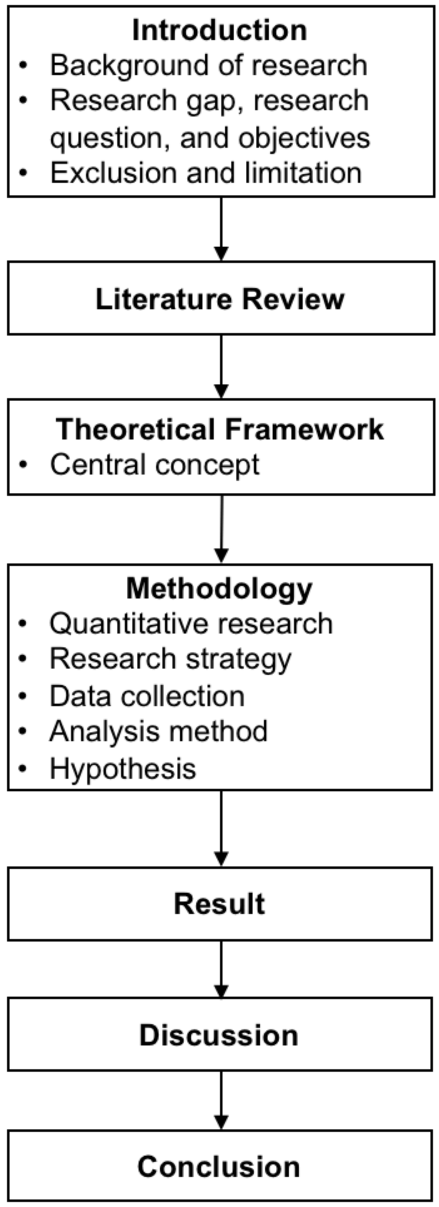

Figure 2 Structure of thesis report/studies

2. Literature Review

Main Theories

In this section, discover the relevant theories to answer the research question, which is slightly mentioned in previous part. The approach of this research is continuing the previous research from Sillman (2016) about protein production from electrical energy. However, the research will take a deep overview in techno-economic assessment of the process in different scenario. The process of production will be adopting from Sillman (2016) and for selection of CO_2 sources will follow Reiter and Lindorfer (2015) evaluation. To find out possible electrical sources in this case will adapt from Sillman (2016), however, in this research only conduct one energy source which is solar energy. For techno-economic assessment will follow the similar guidelines based on Fasihi (2016), Breyer (2017), and Tredici et. al. (2015) approaches. Some formula and steps also citing from those authors since the techno-economic assessment is quite new in the research environment. The figure 3 will cover the summary of the main theories and the main scholar to support answering the research question.

Literature Review

This literature review will be divided into three subthemes such as protein production with electrical energy and techno-economic analysis/assessments. The literature review is supporting the research to establish the goal itself and giving deep analysis from the similar topic related to this research topic (Saunders et. al., 2009). The purpose is to make more precise review from similar research topic, it might be showing new insights if the analysis is effective (Strauss and Corbin, 1998; Saunders et. al., 2009).

Figure 3 The Main Theories and The Authors

Protein production is related to food demand issue in 2050 based on analysis from FAO (2009). In this case, finding possible options to produce protein with current or predictive situation would be the good overview. After discovering protein production, the techno-economic analysis review will be covered similar case to find possible guidelines to conduct the assessment. Hence the approach is quite new tools in research environment, but many researchers already conducted the research and gained valuable result. On the other hand, the literature review can affect development of the research, in this case, the research question could be changed or developed after the literature review would be happened.

2.1 Technology Behind Protein Production

Protein can be produced from animal, plant, and biomass with some specific method to convert from big substance to beneficial substance or we can say edible form. Sillman (2016) gave overview how the impact of producing protein from animal and plant in current situation and it will be related to FAO (2009) review about food demand in 2050. The relation is concerning in natural resources and land availability since in the near future, the mass production would be increase according to demand from the people.

There are many options to produce protein from different sector. However, produce protein from biomass will be better options since it boosts sustainability point of view such as environmental issues and opportunity to implement new valuable solution (Sillman, 2016). Based on Sillman (2016), there are two options to produce protein from biomass which is using bioreactor. Two options such as photo-bioreactor and syngas-based bacterial growth (Sillman, 2016). But the current situation of the options is different, the photo-bioreactor process already well-known in the research and public environment. However, the syngas-based bacterial growth is potentially good option, but the research development is stuck on lab-scale condition (Sillman, 2016). The reason is still finding the possible conditions to run the process (Sillman, 2016; Yu, 2014; Munasinghe and Khanal, 2010). The process of two options is quite similar but the different of technologies should be determined since the different needs of post-processing the biomass.

The photo-bioreactor process is more possibility adopting from algae production (Tredici, 2016; Sillman, 2016) since many researchers already accomplished the research into mass production in some part of the world, this process could make standardisation of this research. Especially, In EU, many research already adapted photo-bioreactor patent from Green Wall Panels. However, the previous focus of using photo-bioreactor is nothing related with protein production. On the other hand, Sillman (2016), explained in deep overview the process to achieve protein from photo-bioreactor process. The needs of nutrient input are mandatory to conduct this process which is standard for the biomass production (Sillman, 2016).

Furthermore, the syngas process for bacterial growth is still in grey research area since many researchers still developing the possible condition to commercialize this solution. (Yu, 2014; Sillman, 2016). In addition, Sillman (2016) shows the research development of this solution based on Elsevier (ScienceDirect database platform) is growing significantly almost 300 publications about syngas-based bacterial growth. Sillman (2016) focused to developing the second option because the output of production will give more protein content around 60-70% for feed and it can be suitable for food too since for animal feed purpose already possible (Sillman, 2016; Volova and Barashkov, 2010). The process still need the nutrient to growth the biomass (Sillman, 2016; Akiyama et al. 2003) since it similar process like bioprocess development. However, the concern of mass transfer in the process is also big problem (Sillman, 2016). In addition, many options already determined to avoid and prevent the problem such as selecting possible utilization of the instrument, making larger contact area and put the drying parameter (Sillman, 2016; Daniell et al. 2012; Munasinghe and Khanal, 2010).

The production process is always required energy however implementing the sustainable solution to the process would be one important point to develop new solution (Sillman, 2016). From Sillman (2016), using renewable energy as an option is totally possible since the growth of wind and solar energy is increasing every year. However, to implement the use of renewable energy need more attention since the availability, the area, and the energy resources should be considered before developing the process. The needs of electricity are regarding water electrolysis as input of the process (Sillman, 2016). Moreover, the purpose to utilize solar energy more in the future have been discussed from Emard (2015) which is focusing in solar energy as solution for agriculture scope in the US. Emard (2015) mentioned solar energy market is escalating every single day, that is related from Sillman (2016) studies and IEA point of view for renewable energy sector especially wind and solar energy. In the US, solar energy is growing rapidly fast behind Germany, China, Italy, and Japan, the implementation solar energy makes solar energy itself as second energy option after natural gas for electricity generation. Based on Emard (2015), solar energy is beneficial resources not only for residential and commercial used but also in industrial perspective especially agriculture.

On the other hand, Emard (2015) only discussed about energy substitution from conventional energy to solar energy utilization in agriculture industry. The reason is the big potential of solar energy in the US market. According to The USDA (United States Department of Agriculture), they reported in 2011, solar energy is offering a lot of positive impact similar like other renewable energies such as the cost is more stable, decreasing the pollution and greenhouse gas problem, and could be the alternative options, to avoid building new electricity grid. Also, the maintenance cost and fuel cost are relative cheaper compare to conventional energy, but in this case is depending on the energy subsidies and energy savings (Emard 2015, USDA 2011). The potential of solar energy is very future-proof not only for substituting renewable energy but also used for some technical need inside the farm or agriculture process such as pumping, lighting, refrigeration, heating, and could be for more operational need (Emard 2015). Based on Emard (2015) research about solar energy as substitution of conventional energy for agriculture industry, the point of view is supporting follow-up research from Sillman (2016), that is using renewable energy for producing food.

The important input for the process is CO_2, that is also supporting carbon emissions issue (Sillman, 2016; Choi et al., 2011). The sources of CO_2 can be from direct air as mentioned from Sillman (2016) thesis. The direct air capture is based on variation of technologies which is using chemicals to capture and intensify carbon dioxide (CO_2) with ambient air as the resource (Carbon Removal). DAC also one solution to tackle carbon emission issues since it could be stored geologically or used as commercial non-degradable product (Carbon Removal). Figure 1 illustrates direct air capture schemes based on carbon removal studies.

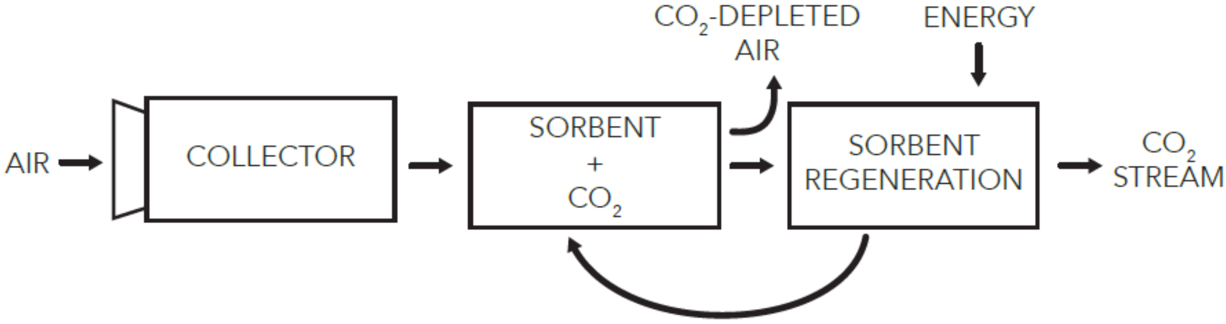

Figure 4 Direct Air Capture Technology Process (Carbon Removal)

Based on Carbon Removal, Direct air capture is adopting the photosynthesis process which is extracting CO_2 from air. DAC is utilizing chemicals adequate to capturing CO_2 from other chemicals in the air. After other chemicals get saturated with CO_2, energy is joined to the DAC process, the energy is in the form of heat, humidity, pressure, etc. Then, purify CO_2 will be the final form and the chemical excess will be used for regeneration process to repeat process (Carbon Removal).

The development of DAC technology is becoming trend these days since the systems of DAC have similarities with submarines and in space applications. However, until now, still no commercial-scale of DAC implementation for carbon emission solution. On the other hand, Carbon Removal also mentioned about the large-scale DAC process could be the important tools for tackling climate change. But, the development of the large is still in the early stage. In addition, there are five research organizations which concerned about DAC research such as Carbon Engineering, Climeworks, Global Thermostat, Infinitree, and Center for Negative Emissions at ASU. Carbon Engineering is already having pilot plant in Squamish, BC place in October 2015. Then, Climeworks has guaranteed a commercial relationship for CO_2 recycling with Audi. Similar path like Carbon Engineering, Global Thermostat is working their pilot plant in Menlo Park, CA. Infinitree is developing the DAC technology which is targeting the greenhouse market for introductory customers. In academic area, Center for Negative Emissions at ASU is developing DAC with the leader group, professor Klaus Lackner. 4 of the DAC development are utilizing swing process to capture CO_2. Only Carbon Engineering is implementing a liquid potassium hydroxide approach. Figure 5 shows the location of DAC technology development leader.

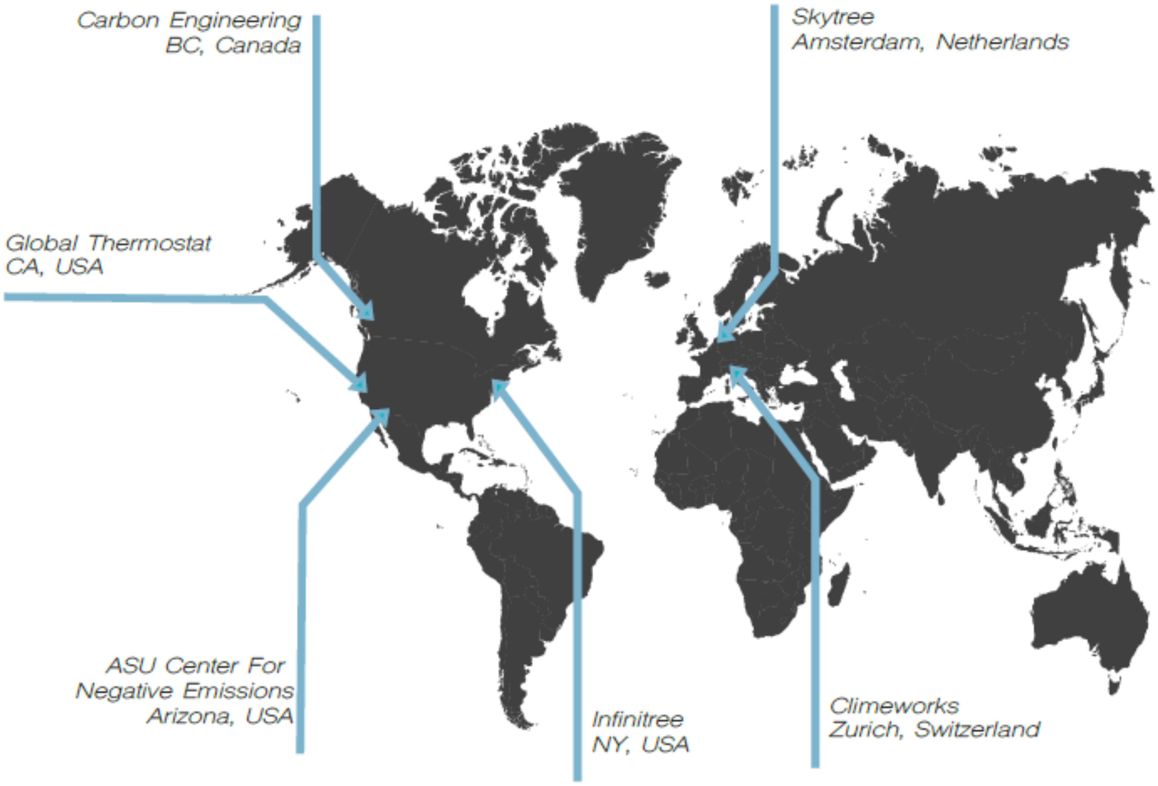

Figure 5 The Leaders of DAC technology development (Carbon Removal)

However, there are more option to gain CO_2 based on where the CO_2 from such post-combustion process and by-product industrial process. For instance, exhaust gas and CO_2 from biotechnological process (Reiter and Lindofer, 2015; Choi et al., 2011). Reiter and Lindofer (2015) also determined quite precise about CO_2 source for power-to-gas application which is similar like Sillman (2016) solution. The similarity is using renewable based purpose for taking care sustainability approach.

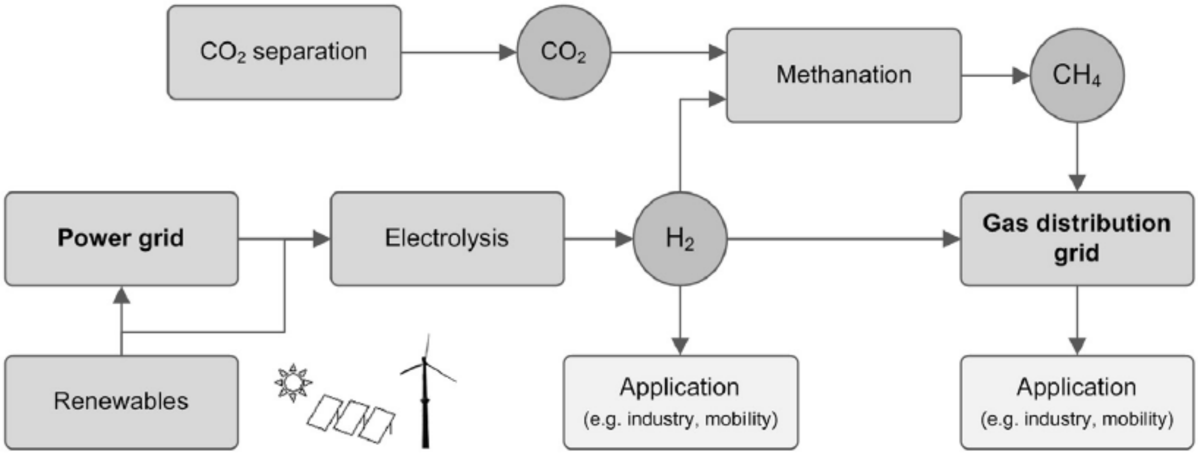

Figure 6 Power-to-gas technology utilizing carbon dioxide (Reiter and Lindofer, 2015)

Figure 3 represents the flow process of producing CH_4 by utilizing carbon dioxide from separation process and electrolysis process which is using renewable energy as electricity power sources. In addition, Reiter and Lindofer (2015) explained about CO_2 sources for input for power-to-gas application based on case study in Austria. There are three type of CO_2 sources such as CO_2 from combustion process, CO_2 as by-product from previous process in this case is in industrial sector, and CO_2 from the atmosphere. Figure 4 shows the CO_2 potential sources and concentration level of the CO_2 itself.

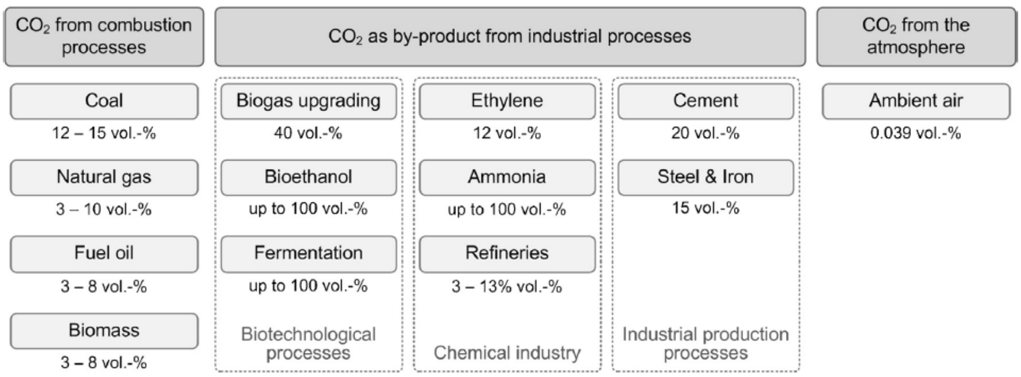

Figure 7 CO_2 potential sources and CO_2 concentration level (Reiter and Lindofer 2015; Metz et. al. 2005)

In addition, the technology of capturing and separating CO_2 also has been overviewed by Reiter and Lindofer (2015), chemical and physical absorption are well-known method for CO_2 separation in industrial sector and power plants. On the other hand, using chemical absorption is good for selectivity but it costs more for regeneration since the need of high thermal energy input. Moreover, adsorption processes are studied to have high selectivity but still under developing to be more commercialized. Cryogenics methods are already developed and supporting process in breweries and bioethanol production. The same situation for membrane technology which is relatively good for post combustion process but the implementation still far from established for commercial market. Figure 5 breakdown the list of technology of CO_2 separation.

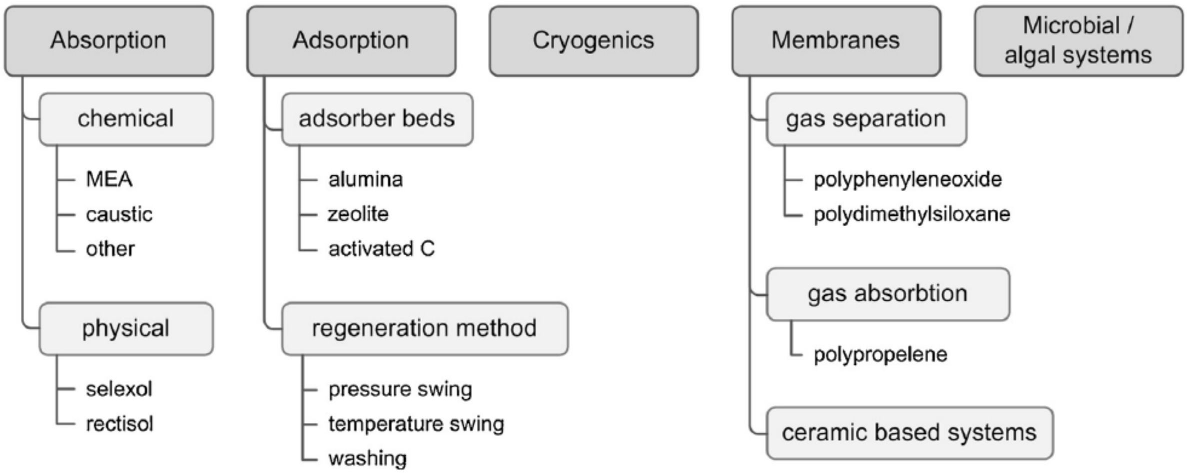

Figure 8 Variation of CO_2 Separation Technologies (Reiter and Lindofer 2015; Rubin et. al)

2.2 Single Cell Protein (SCP) Development

The development of producing protein based on power-to-X technologies is already in bright way. There are two similar research about producing biomass with the purpose of replacing the conventional protein needs. InnovatieNetwork (2015) has been published open proposal about producing protein based on power to gas to protein purpose. The raw materials are gas CO_2, gas Hydrogen, and Ammonia with additional nutrients. The CO_2 sources of their process could be from output of fermentation gas or exhaust gas. InnovatieNetwork (2015) will be using hydrogen-oxidizing reactor for main reaction of the process. The reaction based on Tanaka et. al. (2001) which is:

$$21{,}36\ H_2 + 6{,}21\ O_2 + 4{,}09\ CO_2 + 0{,}75\ NH_3 \rightarrow C_{4,09}H_{7,13}O_{1,89}N_{0,79} + 18{,}70\ H_2O$$

According to InnovatieNetwork (2015), The total cost of the production process is 1.464.590 €/year for 500 tonnes/year production capacity. The focus of total cost is CAPEX, raw material cost such as H_2, CO_2, and Ammonia, and OPEX for reactor. CAPEX and OPEX are 232.900 EUR and 50.000 €/year based on 500 tonnes/year of production capacity (InnovatieNetwork 2015). In addition, they explained three different scenario of production capacity such as 500 tonnes/year, 250 tonnes/year, and 25 tonnes/year. They also mentioned reactor production cost based on the volume of the reactor from 5-50 m^3 reactors volume until 100-150 m^3 reactors volume. They predicted the reactor cost based on their experience and market condition.

Table 1 Reactor Production Cost

Reactor Size (m^3)	Price (EUR/m^3)
5-50	2300
50-100	2000
100-150	1700

(InnovatieNetwork, 2015)

Table 2 CAPEX and OPEX based on plant capacity

Plant Capacity (tonnes/year)	Reactor Size (m^3)	CAPEX (EUR)	OPEX (EUR)
500	137	232900	50000
250	68	137000	25000
50	7	16100	2500

(InnovatieNetwork, 2015)

In addition, InnovatieNetwork (2015) also gave detail about production cost regarding the variation of production capacity. The calculation of production is summary all of the cost to produce the protein such as raw material cost, CAPEX, and OPEX. In this case, InnovatieNetwork (2015) made assumption CAPEX with 10 years for Amortization for all of the CAPEX. Based on their prediction of production cost, the H_2 cost looks higher compare to other raw material such as CO_2 and Ammonia. Table 3 shows total cost of the protein production based on InnovatieNetwork (2015) calculation.

Table 3 Total Cost of Protein Production based on InnovatieNetwork

Production Capacity (ton/year)	H_2 Cost (EUR/ year)	CO_2 Cost (EUR/year	Ammonia (EUR/year)	CAPEX	OPEX	Total Cost
500	1257000	124500	9800	23290	50000	1464590
250	628500	62250	4900	12350	25000	733000
25	62850	6225	490	1610	2500	73675

(InnovatieNetwork, 2015)

Furthermore, Oesterholt et. al (2017) and Matassa et. al. (2014) are still developing the single cell protein production with different point of view. They more focus in water used for the production process. However, the basic process and raw materials are similar like Sillman (2016) and InnovatieNetwork (2015). The reaction is:

$$5{,}2\ H_2 + 1{,}5\ O_2 + 1{,}0\ CO_2 + O{,}2\ NH_3 \rightarrow CH_{1,77}O_{0,5}N_{0,2} + 4{,}6\ H_2O$$

In addition, this research is trying to upscaling their project from 5 liters to 400 liters for volume of the reactor in the production process (Oesterholt et. al 2017). Based on their project presentation, Oesterholt et. al. (2017) implementing InnovatieNetwork (2015) research to pursue commercialize size of the production. On the other hand, the focus of the production also including for animal feed purpose and human food which is improvement from InnovatieNetwork (2015) project. Oesterholt et. al. (2017) gives evidence of production SCP is high potential in the point of view of waste water chain and economical potential.

However, the research is still developing method of extracting ammonia. Moreover, public acceptance or market acceptance, specification of protein figure, and novel food implementation are other relevant aspects which are under consideration of this research (Oesterholt et. al 2017). Figure 1 illustrate the cost and revenues of Oesterholt et. al. (2017) research which is combining the minimum and maximum condition of specific cost component.

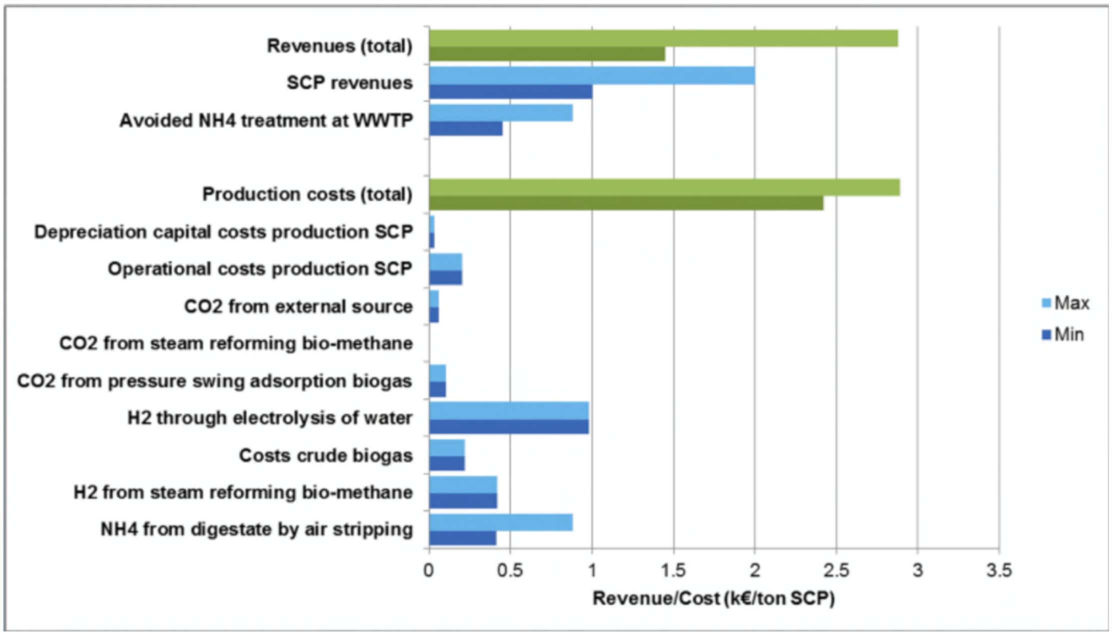

Figure 9 Cost and Revenues of Power to Protein (Oesterholt et. al. 2017)

Oesterholt et. al. (2017) also show their preliminary production cost which is around 2400-2800 €/ton SCP. The production cost consists of depreciation capital cost, operational cost, CO_2 cost, H_2 cost, and ammonia cost. Production cost components in this research is closed to production cost calculation from InnovatieNetwork (2015).

On the other hand, two of similar research are using ex-situ process which is utilizing H_2 as resources from outside the reactor. In addition, Liu et. al. (2016) has been finding the in-situ process of hydrogen oxidizing reactor. Their research is focusing on electricity-to-product efficiencies of the process. Also, Liu et. al. (2016) mentioned about reaction to produce biomass which is having high protein content. The reaction is:

$$CO_2\ (g) + 0{,}24\ NH_3\ (aq) + 0{,}525\ H_2O\ (l) \rightarrow CH_{1{,}77}O_{0{,}49}N_{0{,}24} + 1{,}02\ O_2\ (g)$$

The energy gibbs of the reaction is 479 kJ/mol (Liu et. al. 2016). The electricity-to-product efficiency as mentioned in their research is around 54% (Liu et. al. 2016). Moreover, refers on Liu et. al. (2016), their research is trying to make the H_2 synthesis more sustainable by supported from solar energy to gain more efficiencies of the product.

2.3 Techno-Economic Assessments in the scope of Power-to-X Technologies

The basic understanding of techno-economic analysis is to find production cost of the process (Tredici, 2015; Fasihi, 2016). The method of two authors is quite similar but different approaches. However, from Tredici (2015), the research shows some basic theory about CAPEX, OPEX, and some other components which is needed in the calculation process. However, the research of Fasihi (2016) is quite suitable with the trends of using power-to-X technologies since the purpose of the Fasihi's research is finding production cost of process for P-t-L, G-t-L, and P-t-G.

Start from determining, CAPEX and OPEX. CAPEX is abbreviation from capital expenditure which is all the cost to build or develop the process, including instruments and every part of the process. It can be related the cost to build the factory which is initial cost to construct the process (Tredici et al., 2015; Peters et. al., 1991). OPEX is operating cost which is cost to operate the process, including labor, electrical use, nutrient, administration, and maintenance (Tredici, et. al., 2015). In OPEX and CAPEX there are two different cost such as direct and indirect cost. Those of cost are different since different perspective, to make it clear direct cost is more like planning approaching and indirect cost is the cost depending on the exact situation (Tredici et. al., 2015; Peters et. al., 1991). More specifically, in OPEX, direct cost is labor, fertilizer and chemical cost, and electrical energy cost (Tredici, et. al., 2015). On the other hand, OPEX indirect cost consists of maintenance cost, overhead, and administration (Tredici, et. al., 2015).

In addition, there are a lot of research about techno-economic assessments in the scope of power to x technologies. For instance, Liu et al. (2017) used techno-economic assessment to measure the reliability of biojet fuel production from camelina in Canada. The approach of finding the production cost looks similar like Tredici et. al. (2015) approaches which is interesting. Li et al. (2017) focused on economic analysis by breaking down the total capital cost, operating cost, calculating marginal cost, average cost, and economic operating scale, and also, finding NPV and break-even point of the project. In addition, Li et al. (2017) mentioned about sensitivity analysis, that is beneficial tools to compare different parameter within some base scenarios to evaluate the impact from each parameter. The sensitive analysis could be conducted by comparing different parameter such as camelina oil prices (as a resources), co-product credits, hydrogen cost, plant capacity, discount rate and capital cost (Li et. al. 2017). The illustration of the result shown as impact figure between parameters and table with different NPV result based on the plant capacity of producing camelina oil in Canada (Li et. al. 2017). Figure 10 and Table 4 will show the result of techno-economic analysis from Li et. al. (2017) project.

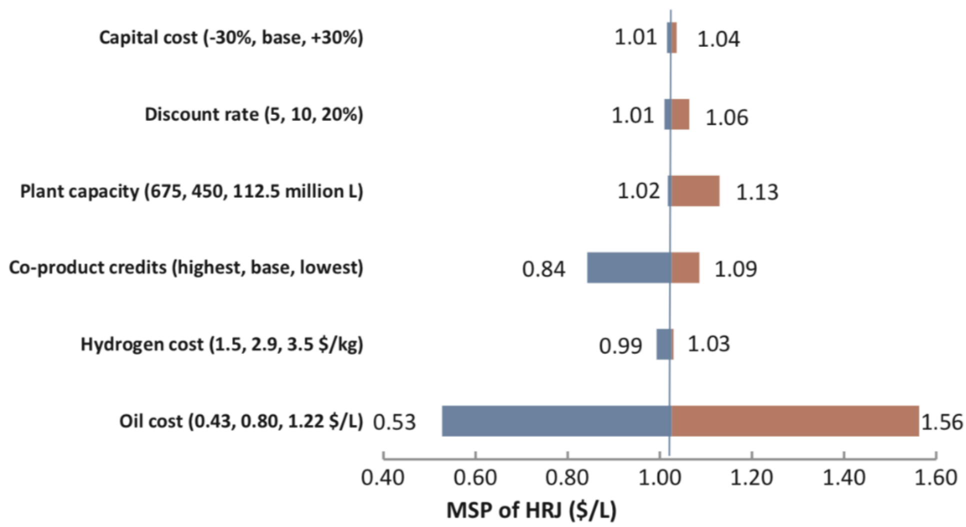

Figure 10 Impact of Economic Factor of Producing bio jet fuel in Canada (Li et al. 2017)

Table 4 Sensitivity Result of Producing bio jet fuel in Canada

Capacity-HRJ	NPV	NPV ($'000) 5% Discount Rate Camelina oil purchase cost $ L^{-1}		
		0.43	0.80	1.22
225 million	NPV_HRJ Price $0.60L−1	11,044	−1,121,641	−2,460,660
	NPV_HRJ Price $0.80L−1	326,501	−618,549	−1,957,568
	NPV_HRJ Price $1.00L−1	638,418	−115,457	−1,454,476
	NPV_HRJ Price $1.20L−1	950,335	218,059	−951,384

(Li et. al. 2017)

Another example about techno-economic assessment, research from Swanson et. al. (2010) did the same approaches as Li et al. (2017) which is using sensitivity analysis for biomass-to-liquids production from gasification process. The method is quite similar like Li et. al. (2017) have been doing. Start from designing the production process and figuring out the economic analysis. Moreover, Swanson et. al. (2010) used software to conduct economic calculation, Aspen Icarus Process Evaluator, and also literature resources to calculate some components of total cost. Figure 11, 12, and 13 illustrated the sensitivity analysis of biomass-to-liquids production from gasification process which is using different scenario for low temperature and hot temperature.

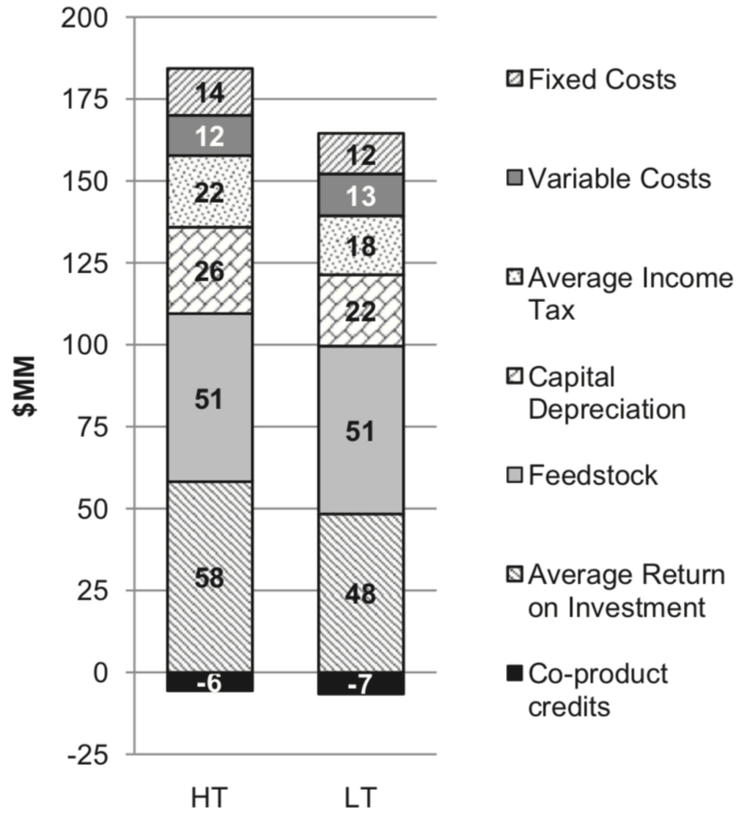

Figure 11 Annual Operating Costs for biomass-to-liquids (Swanson et. al. 2010)

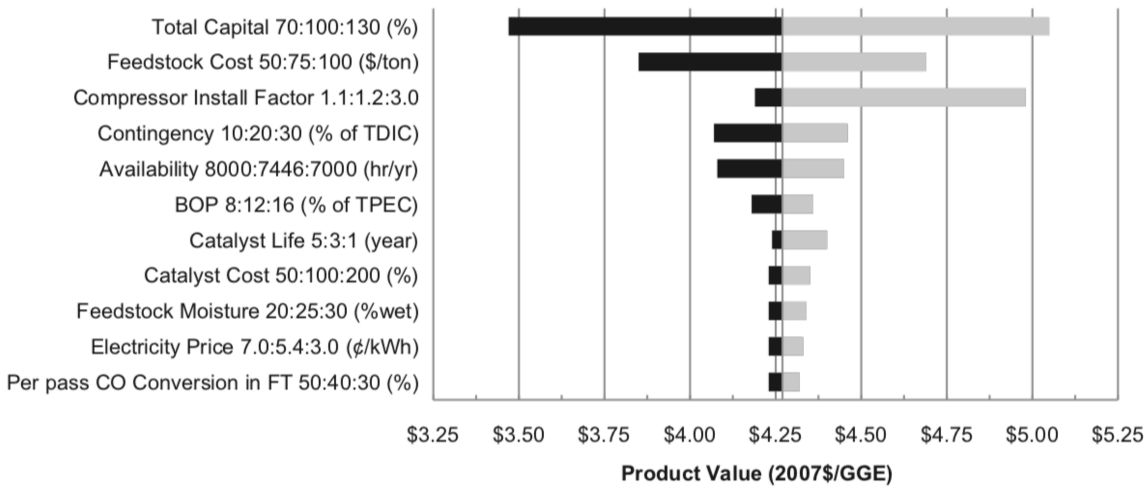

Figure 12 sensitivity results in HT scenario (Swanson et. al. 2010)

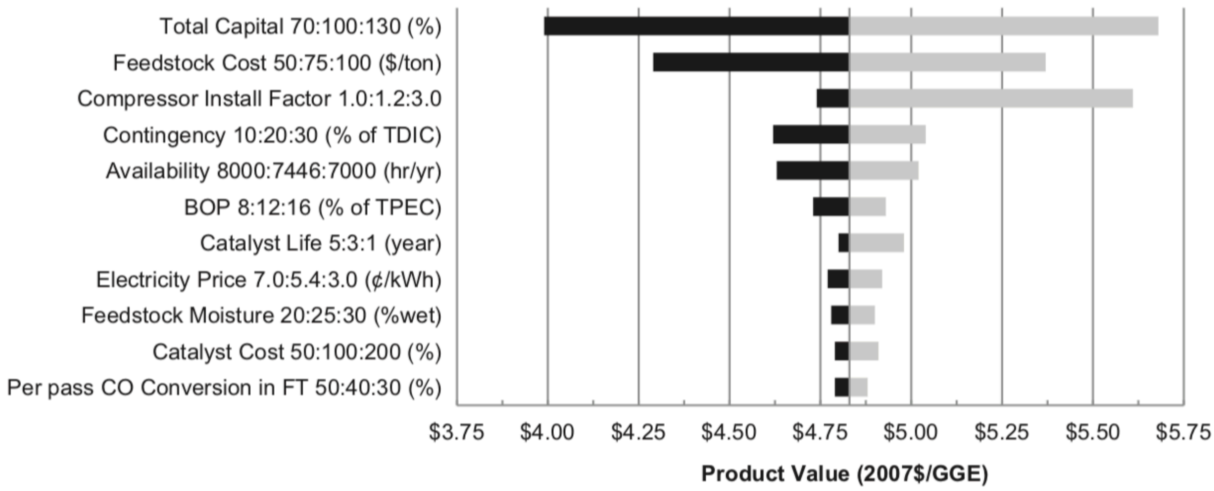

Figure 13 sensitivity results in LT scenario (Swanson et. al. 2010)

Different approach is showing from Fasihi (2016) research, the approach of techno economic assessments is showing the impact of the solution from power-to-X technologies. Refers to Fasihi (2016), the methodology of techno-economic assessments is based on annual basis model and hourly basis model. Figure 14 will show formula from Fasihi (2016), where the content of the calculation method is showing the production cost in the current trend because of using renewable energy technologies.

$$LCOE_i = \frac{Capex_i \cdot \mathrm{crf} + Opex_{i,fix}}{FLh_i} + Opex_{i,var} + \frac{\mathrm{fuel}}{\eta_i}$$

$$\mathrm{crf} = \frac{\mathrm{WACC} \cdot (1+\mathrm{WACC})^{\mathrm{N}}}{(1+\mathrm{WACC})^{\mathrm{N}} - 1}$$

$$FLh_{PV,el} = PV_{irradiation} \cdot PR$$

$$LCOE_{gross} = \frac{Wind_{FLh} \times Wind_{LCOE} + PV_{FLh} \times PV_{LCOE}}{(Wind_{FLh} + PV_{FLh})}$$

$$LCOE_{net} = \frac{LCOE_{gross}}{1 - \mathrm{overlap}}$$

Figure 14 Techno-Economic Analysis Formula (Fasihi, 2016)

Figure 14 shows list of LCOE formula which is including CAPEX, OPEX, crf, and FLH (Fasihi 2016). Moreover, Breyer (2017) mentioned about LCOE, mainly for whole power generation technologies, in this case the result of LCOE would be in €/kwh. Then, to construct value of LCOE, LCOE formula consists of CAPEX, crf, OPEX, FLH, fuel cost, efficiency, carbon cost and greenhouse gas emissions (Breyer 2017). The result of LCOE formula should be transformed from €/kw to €/kwh by calculating CAPEX, OPEX, WACC, lifetime and energy output from technologies which is referred to FLH (Breyer 2017). For figure 14 all formula is focusing for power-to-X applications and there is some modification of the formula compare to LCOE formula from Breyer (2017) because of the focus in LCOE for hydropower technologies.

$$LCOE = \frac{CAPEX\,.\,crf + OPEX_{fixed}}{FLH_{el}} + Opex_{var} + \frac{fuel}{\eta_{el}} + \frac{carbon\,.\,GHG}{\eta_{el}}$$

(Breyer 2017)

The techno-economic assessments from those two authors would have similarity but different method, Fasihi (2016) is using the formula to find LCOE and Tredici et. al. (2015) is calculating the cost to build factories more similar like economical calculation for building chemical industry. However, from Tredici et. al. (2015) is approaching build well-known factories compare to Fasihi (2016) research is more like showing the potential solution to the global environment. The approach of Fasihi (2016) is suitable with the purpose of the research topic of this research. Then, to determine missing component to calculate using the formula, the cost calculation method of Tredici et. al. (2015) could be supporting the research.

2.4 Implementation power-to-X technologies from Innovation Management point of view

The development of technology by associating with innovation studies would be called as emerging technologies (Rotolo et. al. 2015). The research of emerging technologies is growing quite fast now which is showing from increasing some literatures mentioned about emerging technologies from showing the impact of the technology for economy and society, constructing the policy of new technologies, also grouping the typical feature of novelty and growth (Rotolo et. al. 2015, Porter et al. 2002, Martin 1995, Boon and Moors 2008, and Small et. al. 2014). In addition, Rotolo et. al. (2015) show some definition of emerging technologies from 12 different authors and find 5 attributes of emerging technologies such as radical novelty, relatively fast growth, coherence, prominent impact, also uncertainty and ambiguity (Rotoloet. al. 2015).

Related to emerging technologies, Horizon 2020 (2018) (European Commission Project) also focused on future and emerging technologies which is focused to explore potential technology. The aim of this project is to push radically some new findings about technology via cooperation between progressive various science and innovative engineering. This movement helps Europe become center of future technology research in the future and that is giving possibility to provide some benefit to the society. The project of Horizon 2020 is related to biotechnologies, arts and science, data analysis and FET promotion, global system science, green technologies, medical and neuro technologies, nano technologies, quantum technologies, robotics, and technologies with new material (Horizon 2020 2018). All of focused project of Horizon 2020 are related to explanation from Rotolet et. al. (2015) about some example about emerging technologies which is included nano technologies and some biology research.

Discussed about emerging technologies which is combining innovation approach and science to make new solution for society (Horizon 2020, Martin 1995, Day and Shoemaker 2000, Stahl 2011). The focused in energy and technology are also favorable, this is showed in the related project of Horizon 2020 with the goal is researching of technologies for future to reach more sustainability perspective (Horizon 2020 2018). Also, Hussain et. al. (2017) also gave pictures about emerging technologies in renewable and sustainable energy point of view, they are mentioned five sector of renewable emerging technologies such as marine energy, concentrated solar photovoltaics (CSP), enhanced geothermal energy (EGE), cellulosic ethanol, and artificial photosynthesis. They discussed about potential and the development of the mainstream energy resources from advanced or special structure. According to Hussain et. al. (2017), they analyzed the utilization of the energy technology from some energy resources to produce something new or something more beneficial which is similar like explanation of power-to-X technologies from Vainikka (2017). Since

Vainikka (2017) explained power-to-X technologies is about utilizing energy resources to make something more beneficial. It can be seen some of power-to-X technologies are having characteristics like emerging technologies since some of the development of power-to-X technologies are still in early stage but developing rapidly and to apply the technology still uncertain and but some of them could give more benefit to the society (Rotolet et. al. 2015, Vainikka 2017).

As one of emerging technologies, Power-to-X technologies is one of initial effort to tackle climate change issues these days (Vainikka, 2017). The goal is utilizing energy to produce new or common form which is beneficial for daily human need. The development of power-to-X technologies are already well-developed, but it still has place to grow more in the near future. For example, implementing power-to-technologies applications to utilizing carbon which is also supporting the activities to reduce carbon emission issues such as power-to-liquids and power-to-gas. For those approaches, it would be related with electrolysis process since the need of H_2 as one of important input to produce some beneficial product. In addition, utilizing CO_2 would be better options to cover the climate change issues in the sense to reduce carbon emission. There are a lot of process to producing beneficial product in the case implementation power-to-liquids and power-to-gas technologies which is referring to syngas conversion process. In syngas conversion process, including fischer-tropsch process and methanation procee. On the other hand, the principle of power-to-X technologies would be using electricity or excess electricity from renewable energy resources to the unit process for producing beneficial form (Vainikka, 2017). Based on Vainikka (2017) the concept process of power-to-X technologies is utilizing electricity to electrolysis unit to produce H_2 and continuing with CO_2 reduction process to get final result which is CxHyOz form (Hydrocarbon component). Figure 15 shows the flow process of power-to-X technologies focused on producing some beneficial hydrocarbon component.

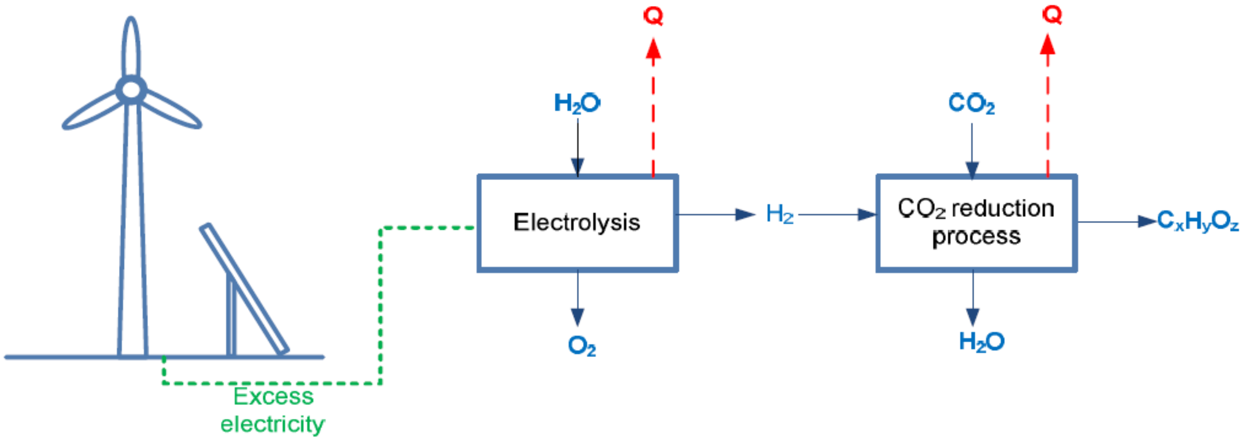

Figure 15 The Principle of Power-to-X application (Vainikka, 2017; Courtesy of Cyril Bajamundi, VTT)

The syngas conversion which is the core process of power-to-liquids and power-to-gas applications. The focus is utilizing carbon and H_2 to produce some hydrocarbon product. There is some product which is beneficial and important such as olefin, gasoline, ethanol, etc. Figure 16 represents the syngas conversion scheme with the final product per each synthesis process.

Moreover, Vainikka (2017) also explained some additional process of utilizing $CO_2 + H_2$ which is applying first law of energy efficiency. Referring from Hannula (2015) about process of producing synthetic fuel from biomass slag, carbon dioxide, and electricity, figure 17 illustrates the flow process of synthetic fuel and light production. From those process have some result such as methane, direct fuel use, fuel additives, plastics, and drop in.

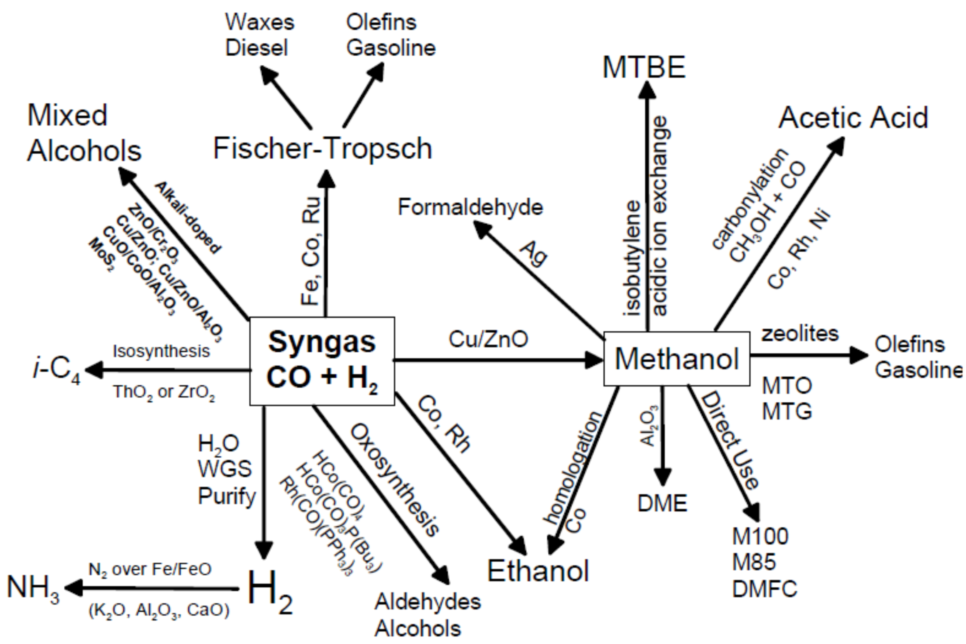

Figure 16 Syngas Conversion Processes (Vainikka, 2017; Spath and Dayton, 2003)

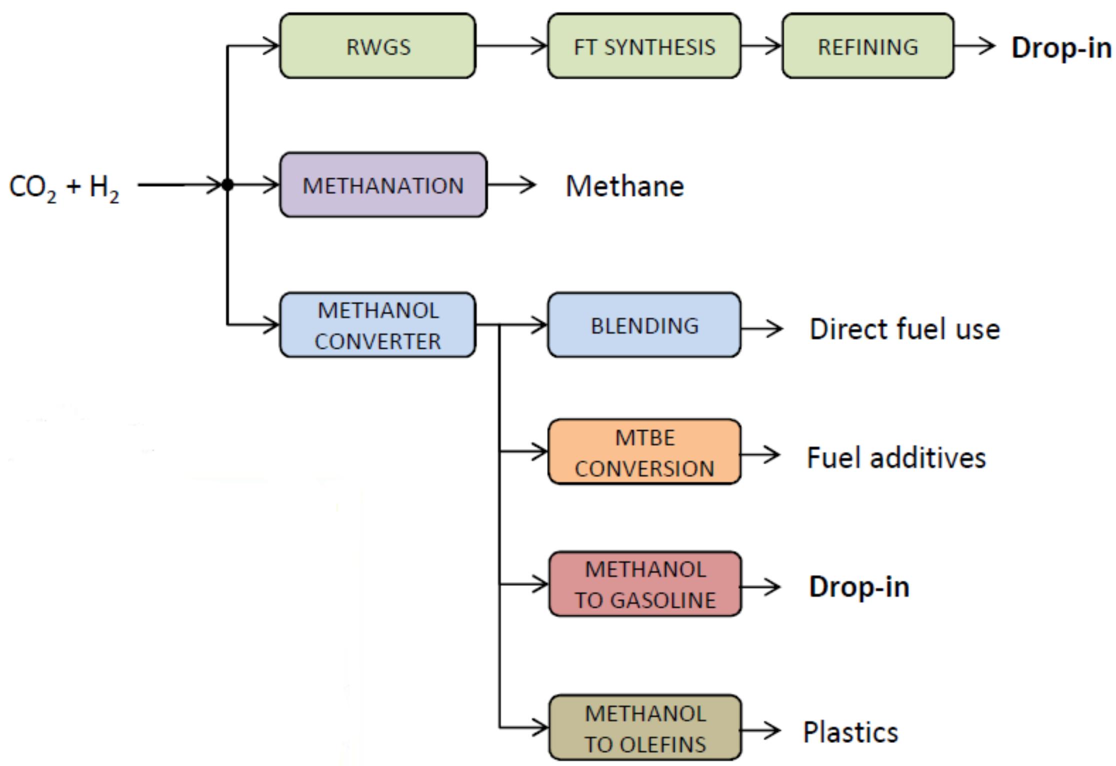

Figure 17 The synthesis process for produced synthetic fuels and light (Vainikka 2017; Hanulla 2015)

Furthermore, the concept and principal of power-to-X technologies is having relation with energy scenario development. The relation in the sense of tackling climate change issues. Kramer (2017) reviewed about relation between energy scenario and innovation management. Start from focus of energy scenario itself, scenario in here is not only give prediction about the future case but also determined the future development by answering what if question to provide the answer for facing the unpredictable future. Before going through to the exploration of connection between energy scenarios and innovation management, reviewing the meaning of innovation should be covered first. Kramer (2017) referred to oxford dictionary about meaning of innovation and disruptive. Innovation has meaning based on oxford dictionary as 'the change of something established by the introduction of new methods, ideas or products'. In this case, the innovation will always be growing depends on the environment reaction of the innovation. Then, disruption is 'serious alteration or destruction of structure', the definition is based on oxford dictionary. In the real life, disruption as something which is people avoid being happened. On the other hand, 'disruptive innovation' will be unusual combination of word, that is going and already developing in real life situation.

The disruptive innovation in energy sector is happened since the development of technologies and business innovation inside its sector. Kramer (2017) refers to IEA research about renewable energy development, the disruptive technologies started to appear after 1970 but the growth of renewable energy becomes more various after 2000. The disruptive technologies have definition as 'technologies breaking through' which is in energy sector disruptive technologies is appeared after oil crisis in 1970. It can be seen; renewable energy appear these days is not breakthrough technologies (Kramer 2017). On the other, disruptive innovation also proof the reason of the energy and policy are appeared these days (Kramer 2017). Figure 18 represents the growth of renewable energy development.

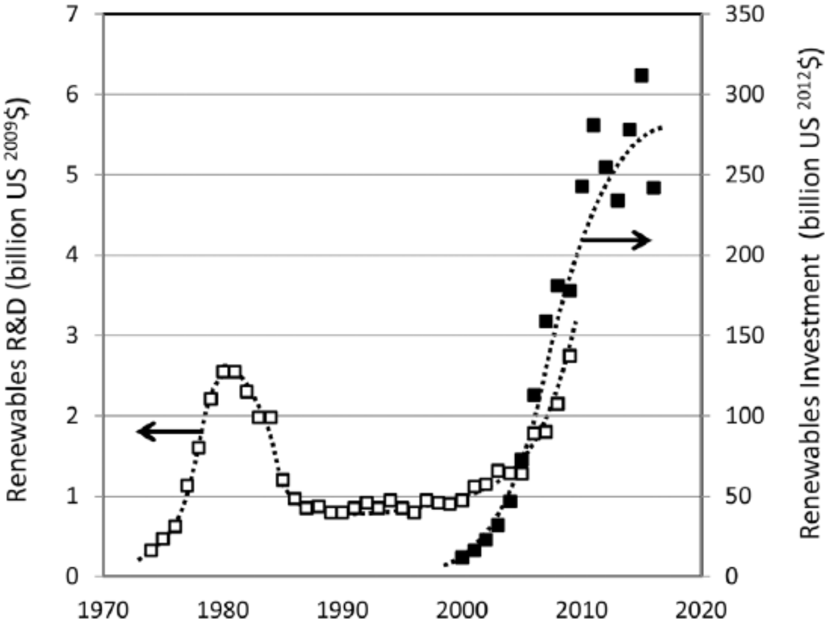

Figure 18 Renewable Energy Development (Kramer 2017; IEA 2010; FS-UNEP/BNEF 2017)

Moreover, Kramer (2018) also defined the link between the scenario and the approach of innovation. There are three levels of disruption such as environmental disruption, economic disruption, and little disruption. The little disruption or light disruption is low level to put the effort for tackle climate change issue, Kramer (2018) described this level is connected to Schumpeterian disruptive innovation which is the effort would be worked just the matter of time. Then, economic disruption is the condition when the effort to tackle climate change issues in the level of prevention. That is situation if the effort from some organization don't work out, they already prepare the alternative to overcome from that circumstances (Kramer 2018). The last one is environmental disruption as the end of the range is defined as 'positive checks' which is if some climate focus organization fail to tackle the issues, it will be the limit of the effort to overcome from climate change issues (Kramer 2018; Malthus 2006). To illustrate the level of disruptive innovation and type of population in the sense of innovation and disruption for energy scenario, Figure 19 would be visualized the connection between those point.

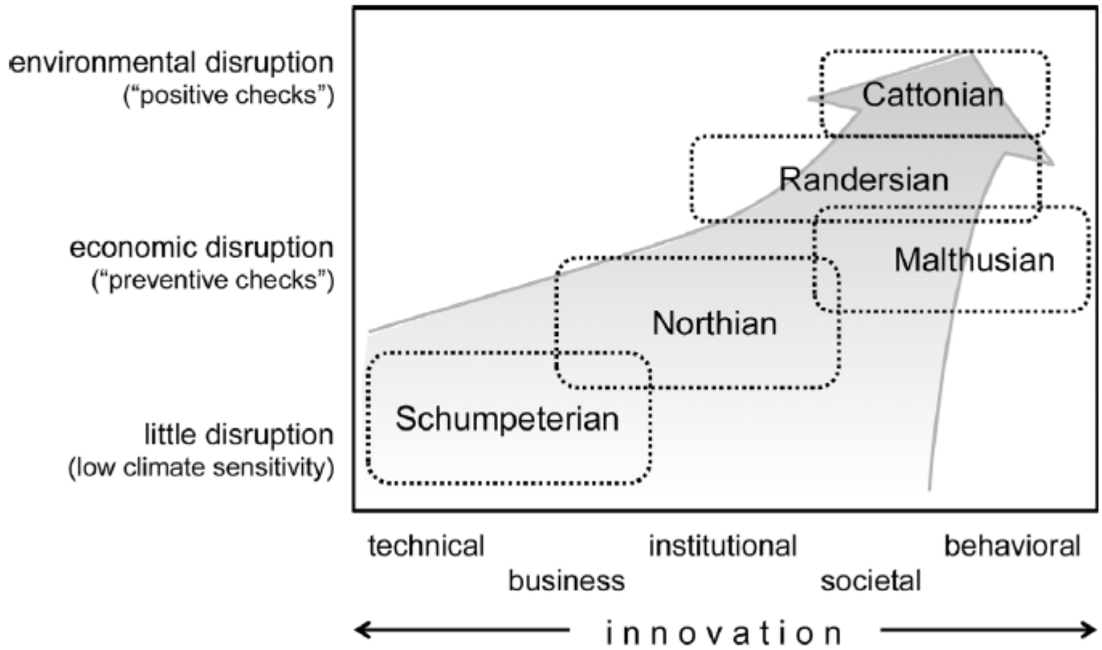

Figure 19 The link between innovation and disruption in energy scenario case (Kramer 2018)

According to Figure 19, there are five different populations such as Schumpeterian, Northian, Malthusian, Randersian, and Cattonian. Also, the range of innovation is from technical innovation to behavioral change. The innovation level start from technical innovation and business innovation since to change or improve something could be happened by proposing new methods and some 'fresh' ideas. Then, institutional innovation as core point for organization or community with focus in climate change trends since need a roof to pursue some ways for preventing and overcoming from the problem. This innovation level leads to make new systems which is acceptable and could be applicable in the social level, called societal innovation. The final of the range is behavioral changes, that is all of the effort or new things reinstate the current one. According to Kramer (2018), Schumpeterian is starting point of the effort, then, Northian phase, that is when the institution starts to pursue the innovation to tackle climate change issue. Malthusian is the situation when the prevention starts to appear. Continue with Randersian which is the innovation trying to implement in the radical way. Moreover, Cattonian is the disruptive innovation would be implementing precisely for energy scenario purpose.

Furthermore, Reardon et. al. (2017) discussed about the relation between innovation and technology for food purpose. They mentioned about food transformation stages of food systems from Reardon et al. (2012) such as traditional system, transitional stage, and modern system. But all of the stages are focused in farming sector not in big scale production or food factories. On the other hand, they find major implications of pursuing innovation in food sector, start from the possibilities of changing in agrifood in the level of institution and also technology. Then, supply chain from agriculture sector will give effect to financial sector since transformation of technology and institution. The economic infrastructure and policy environment are beneficial for accepting and developing the transformation of supply chain. Next, farmers are supporting the adoption of new innovations which is important for implicating the policies since the possibilities of cost reduction and more efficient and effective the flow of the production process. Last major implications, the farmer which is not recognizing the relation between innovation and technology, this situation needs to observe more since it related to evolution of food chain.

Based on the Reardon et. al. (2017) and Kramer (2017) about relation between innovation, technology, and food, Vainikka (2017) shows the new process to pursue food innovation by applying power-to-X technologies. Figure 20 shows the food production process by transforming energy which is renewable energy to produces single-cell protein in the structure of biomass. In addition, the process is applying new technologies such as direct air capture to get CO_2 from atmospheric air which is quite new in the market. The concept of the process is similar like Liu et. al. (2016) approaches by combining reactor and electrolysis unit process in one unit.

Based on Figure 20, the food innovation project is starting to combine with energy development sector which is quite future proof and support FAO intention to developing food innovation product to avoid food demand issues in the future. The process on figure 17 is in the level little disruption which is still in early stage but also could be bigger since the approach already widely-known. There are 2 similar research of protein production by utilizing renewable energy as the main sources, first from InnovatieNetwork (2015) and the improvement comes up from Oosterholt et. al. (2017). Moreover, the disruptive technologies could be happened but depends on the implications policies of the relation between innovation and technology for food purposes would be approved or still under development especially for policy environment.

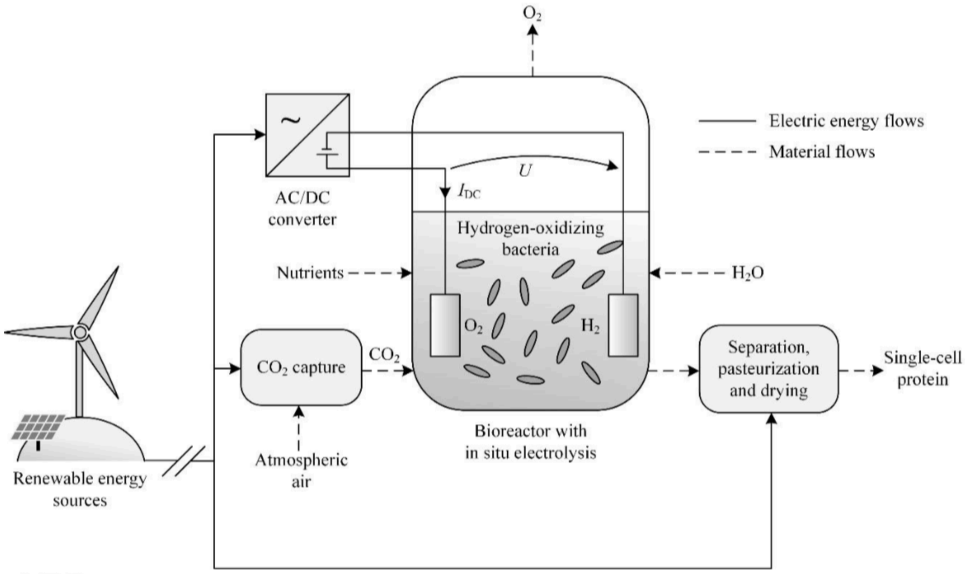

Figure 20 Power-to-Food Process (Vainikka, 2017)

2.5 Summary of the literature review

To give overview of the literature review from two subthemes, this section will show summarization of the literature review. In the end of the summary, will propose table of literature review to give simple understanding to the reader.

The process of making protein from electrical energy could be described as bioprocess since the purpose of concerning environmental impacts (Sillman, 2016). There are two processes such as photo-bioreactor and syngas process (Sillman, 2016). Photo-bioreactor is already in the mass scale production and can be called well-known process than syngas process. Syngas process is still under development by many researcher, Sillman (2016) explained almost 300 publications focus on developing the syngas process in the scope of producing biomass. The biomass production can be related to produce protein since many researchers already found the inside component of biomass has protein structure. However, it is still on animal feed purpose, and need to determine more for normal food (Sillman, 2016; Volova and Barashkov, 2010). The production process also need CO_2, to gain CO_2 could be from direct air, post-combustion process, and by-product of industrial process (Reiter and Lindofer, 2015; Choi et al., 2011). The concern of energy uses also give beneficial impact to implement new solution, in this case using renewable energy is also future-proof (Sillman, 2016).

InnovatieNetwork (2015) and Oesterholt et. al (2017) are developing similar topic like this research with different process point of view which is utilizing H_2 from separate process. In addition, Liu et. al. (2016) are trying to figure out the efficiencies of the utilizing H_2 directly inside the reactor. The reason is pursuing sustainable focus (Liu et. al. 2016) which is relating with Sillman (2016) research focus.

Furthermore, the need of techno-economic assessment is to figure out the production cost. Fasihi (2016) shows some formula to calculate the production cost regarding the current trend of power-to-x technologies and renewable energy technology. However, to gain more specific data, if some date cannot be approachable, the calculation method in Tredici et. al. (2015) can be attached since the cost calculation is more precise and similar like economic calculation to make chemical factory (Peters et. al., 1991).

Emerging technologies is the source of motivation to explore new technologies in the future (Horizon 2020 2018). The focused is giving more sustainable solution for society. Moreover, the development of emerging technologies is rapidly increased but to apply some of technologies still uncertain. However, there is a lot benefit, the society would be get, if they are ready to use or adopt the emerging technologies. There is connection between innovation management, power-to-X technologies and food development. It shows from Power-to-food process from Vainikka (2017) which is adopting power-to-X applications approach and also supporting the FAO intention. Also, the relation of innovation management and power-to-X applications could be an example of disruptive technologies. Table 5 lists all of the finding from this literature review section.

Table 5 Literature Review Summary

Subthemes	Main findings	Authors	Remaining research gaps
Protein Production to Tackle Food Demand Issue in The Future	Photo-bioreactor, CO_2 Capture, Syngas-process for biomass growth, renewable energy	Sillman, 2016 ; Reiter and Lindofer, 2015 ; Volova and Barashkov, 2010 ; Choi et al., 2011 ; Daniell et al. 2012 ; Munasinghe and Khanal, 2010 ; Yu, 2014 ; Akiyama et al. 2003	The purpose of the research of Sillman (2016) was finding the environmental impact and only for environmental issues focus. The purpose of Reiter and Lindofer (2015) was only giving overview of CO_2 capture not really related to cost calculation.
Single Cell Protein (SCP) Development	Production cost, Reaction of the process	InnovatieNetwork 2015 ; Oesterholt et. al (2017) ; Matassa et. al. (2014) ; Liu et. al. (2016)	The in-situ production process, the different CO_2 and electricity sources.
Techno-Economic Assessments in the scope of Power-to-X Technologies	LCOE, cost calculation method, CAPEX, OPEX	Fasihi (2016) ; Tredici et. al. (2015) ; Peters et. al., (1991); Swanson et. al. (2010); Breyer (2017)	Slightly different approach but can be combined to give better calculation result. Fasihi (2016) method more suitable to the research question since similar subject power-to-X technologies and the result interpretation could be refers from Swanson et. al. (2010)
Implementation power-to-X technologies	Relation between power-to-x technologies,	Vainikka (2017); Reardon et. al.	The concept of the innovation level of disruptive technologies

from Innovation Management point of view	innovation management, and food development	(2017); Kramer (2017)	in energy technologies still not widely approve.

3. Theoretical framework

The framework of the research is based on the production process with in-situ electrolysis of H_2-oxidizing reaction to make protein from Liu et al. (2016). In addition, the production process looks similar with InnovatieNetwork (2015) and Oosterholt (2017). The difference is only in the part of utilizing the H_2 and O_2 since they try to utilize H_2 and O_2 outside from the reaction process. Figure 21 will be adopted in this research with some modification. The modification is changing the flow of resources for input of reactor since it utilizes a different method.

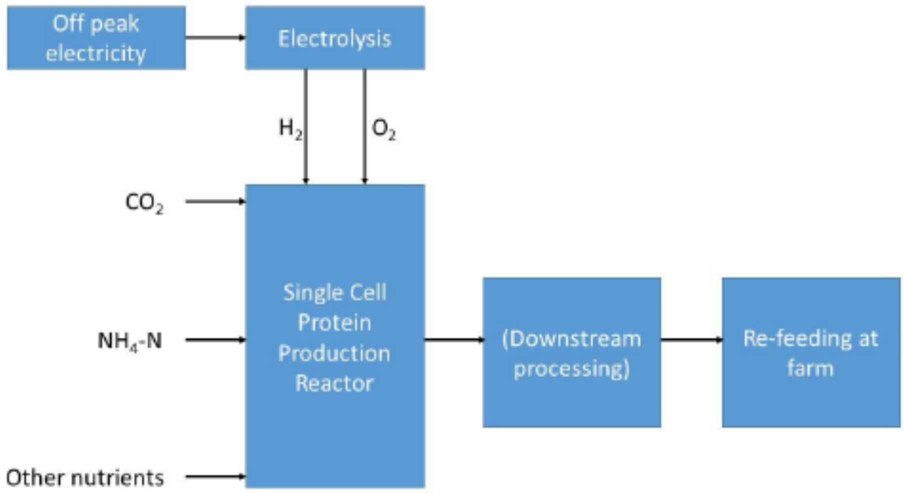

Figure 21 Protein Production Process (*InnovatieNetwork 2015)*

According to InnovatieNetwork (2015), the reaction process needs H_2, O_2, CO_2, NH_4-N (Ammonia), and other nutrients as input to produce the biomass included the single cell protein. This process is modified and is clearly explained in the Oosterholt et. al. (2017) project in Netherlands. The focus of their research is utilizing waste product to produce raw material such as CO_2 and NH_3, and also to use the gas reforming from biogas plant (to supply CO_2) for input material of electrolysis process. The goal of the project is managing and adopting the waste water chain in Netherlands, due to environmental concerns and climate change. Otherwise, the focus is clearly stated to producing ammonia from waste water. The figure 22 shows the mechanism process of Oosterholt et. al. (2017) project.

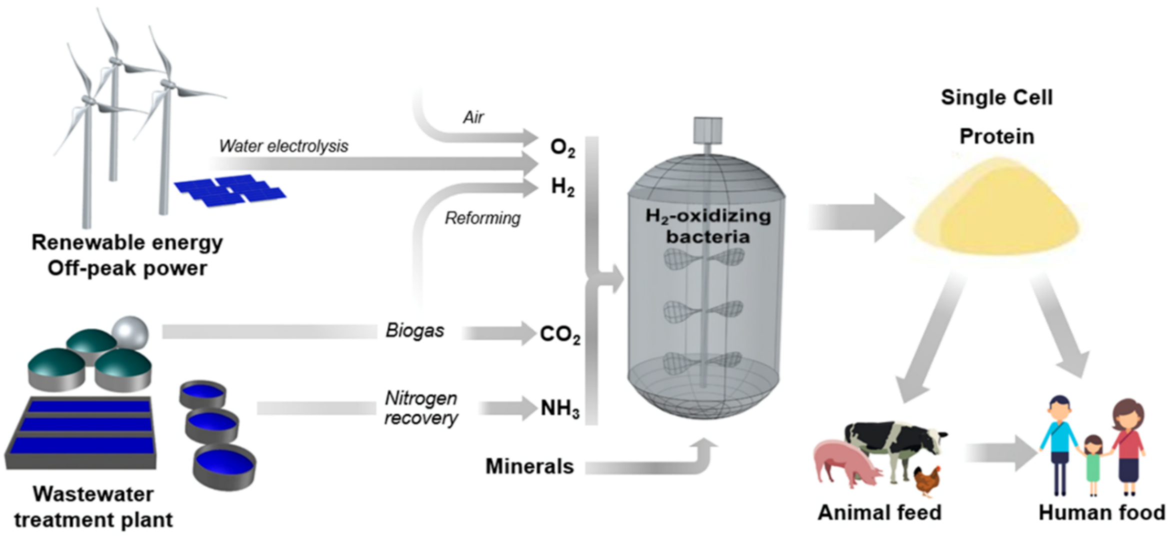

Figure 22 The mechanism process of power-to-protein project (*Oosterholt et. al., 2017)*

The input of the process from Oosterholt et. al. (2017) is similar to the InnovatieNetwork (2015) approach. However, Oosterholt et. al. (2017) gives more detail such as, the raw material source and the target market of the product. The raw material source of power-to-protein project Oosterholt et. al. (2017) utilizes wastewater to supply NH_3 and CO_2. Then, reforming product from CO_2 becomes input to electrolysis process for supplying H_2 and O_2 to the production process. Renewable Energy resources also take part to support the production process. The target of the product is fulfilling the need of animal feed and also human food which is an improvement from the InnovatieNetwork (2015) project since their goal is only for animal feed purposes. In addition, the process is using H_2-Oxidizing bacteria reactor and also this process shows insight from the previous work (in this case InnovatieNetwork, 2015) in the choice of reactor which is suitable for the production process.

Liu et. al. (2016) uses the same approach for producing protein by utilizing electricity. To estimate the quantity of raw material required for the process, this research will be referring to Liu et. al. (2016) since there is reaction to produce biomass with in-situ electrolysis. The reaction is

$$CO_2\ (g) + 0{,}24\ NH_3\ (aq) + 0{,}525\ H_2O\ (l) \rightarrow CH_{1,77}O_{0,49}N_{0,24} + 1{,}02\ O_2\ (g)$$

From that reaction will get ΔG / Gibbs energy, to know how much electricity is needed for the process. Gibbs energy for the process is 497 kJ/mol. Mass and Energy balance is needed to figure out the quantity of raw material needed as the input of the process and, the cost of the raw material will be an important aspect for obtaining the production cost. Moreover, the investment focus on the cost of instrument will be used in the system such as reactor, pre-production, and post-post processing unit.

3.1 Central Concept

According to Literature review, there are some concepts of economical calculation for the implementation of new technology. The research could be focused on levelised cost of electricity or product (Fasihi et. al. 2016), normal investment calculation (Tredici et. al. 2015) or simplified production cost calculation from the InnovatieNetwork (2015). In addition, Swanson et. al. (2010) and Li et al. (2017) give an overview on how to do analysis after we have the production cost. The studies utilize a sensitivity analysis to know which parameters are important for constructing the production cost. Figure 23 will shows the theoretical model of this research.

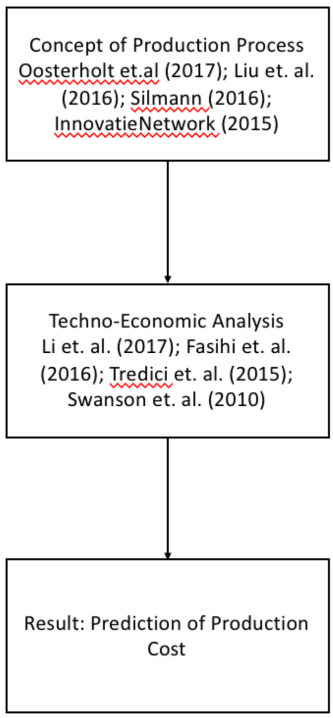

Figure 23 Theoretical Model of the Research

3.2 LCOE based calculation

The main point of this calculation is composing cost from capital expenditures and operational expenses, divided with the capacity of the production or full load hours (how long the process will run every year) (Breyer, 2017). Figure 14 shows the formula and some supporting formula to get the production cost. In addition, there is capacity recovery factor which is a function of lifetime and weighted average cost of capital (Breyer, 2017). In this research, this approach will be hard to pursue since not many studies are focusing on the economical aspect of protein production from electricty. Some assumptions will be determined to support this calculation and achieve the production cost based on LCOE formula.

3.3 Cost Estimation

In this concept, the calculation is based on simple numerical calculation which is the sum of all of the expenses for protein production including Capex, Opex, and raw material cost. Tredici et al. (2015) already determined the calculations in a chemical plant design. On the other hand, Innovatiework (2015) from The Netherlands showed a simplified approach for calculating the total cost required to produce protein from power-to-X technologies.

3.4 Techno-economic Assessments: Sensitivity Analysis

Today, the development of new technologies in the energy sector are very impressive along with the development of power-to-x technologies. The development has been precipitated by climate change issues with recourses becoming more and more limited. NREL, is an organization that concerns itself with Energy Analysis Research to analyze the development of new technologies in the energy area. The goal of Energy Analysis Research is to establish a platform for the development project and understand the impact of the innovation processes. The platform has a purpose to transform the innovation into real life practice to give an illustration to investors and policy makers alike. The analysis from NREL has five different contents such as complex system analysis, impact analysis, sustainability analysis, techno-economic analysis, and geospatial data sciences. The techno-economic analysis is the only one component which is similar to this research. With reference to NREL, techno-economic analysis is the conduction of life cycle analysis and sustainability analysis of energy projects in the scope of technology development, to determine the impact for R&D guidelines and the opportunities among the competitors. Moreover, ABPDU also mentions about techno-economic analysis, as a bridging tool between research project and commercial project plan. The approach of techno-economic analysis based on ABPDU starts with process design, mass balance and energy balance analysis, estimating cost of the process, profitability analysis, and finally sensitivity analysis. On the other hand, NREL and ABPDU has similarities in techno-economic assessment in the scope of financial matter since, they are doing cost estimation and prediction of cost scenario from different aspects. Both of them are using sensitivity analysis as one of the main tools for doing techno-economic assessment.

Based on the topic search options on Sciencedirect there are a lot of different explanations about sensitivity analysis but, most of them are from pharmaceutical applications According to O'Connor et al. (2017), sensitivity analysis is an instrument to form quantitative risk evaluation that assesses the connection among parameters, material, and the quality of final product. Moreover, Grudzinskas and Gombar (2012) also mention sensitivity analysis as a portfolio optimization method, where the focus is identifying and quantifying features of the project which is related to commercialization purpose. Sensitivity analysis delivers two objectives such as determining the project drivers and identifying the distinction of the project which gives an added value to the final product (Grudzinskas and Gombar 2012). Furthermore, MacKerron (2007) provided insights on sensitivity analysis that is an essential procedure in the evaluation of any mathematical model, which in this case refers to crop growth stimulation. In addition, MacKerron (2007) also discussed in another research about two types of sensitivity analysis, 'internal' analysis and 'external' analysis (MacKerron and Waister 1985; MacKerron 1985). 'Internal' Analysis is an examination by changing the function inside the model from unfounded understanding of the proceeding or it could be from performance variation (MacKerron and Waister 1985). On the other hand, 'external' analysis is an examination of sensitivity from the output of the model, to trigger the input value of the model (MacKerron 1985). In addition, Fishman et. al. (1995) also provided explanation about the purpose of sensitivity analysis in assessing a model by functioning the variation control of parameter values. A summary of all these explanations were provided by MacKerron (2007) for testing the sensitivity analysis, by running four parameters which have the most impact on production.

Techno-economic assessment has become a popular tool for analyzing recent projects in energy technology and power-to-X technologies. As mentioned ealrlier, Li et. al. (2017) and Swanson et. al. (2010) conducted techno-economic assessments for energy technology projects. Also, both of them are using sensitivity analysis as a main instrument for assessing their innovation process by functioning the greatest parameters for conducting the analysis. Li et. al. (2017), conducted a sensitivity analysis to determine the need for evaluating the effect of parameter variation from the basic model of scenario. The parameters assessed for the sensitivity analysis include material cost, co-product cost that produced from the process, plant capacity, discount rate, and capital cost (Li et. al. 2017). Moreover, Swanson et. al. (2010) utilized sensitivity analysis under economic analysis of producing biomass-to-liquid by conducting gasification process. Their aim was to find out the most dominant parameters on product value by determining sensitivity analysis with parameters such as capital cost, material cost, electricity price, and technical parameters (Swanson et. al. 2010).

After obtaining insights on techno-economic assessment and sensitivity analysis from Sciencedirect and previous research about techno-economic assessment for power-to-X technologies and energy technologies, explanation from Investopedia and Corporate Finance Institute could be the central concept of focus for sensitivity analysis. Corporate Finance Institute explained sensitivity analysis as an instrument used in financial modelling to assess how the variation of values from independent variable impact dependent variables under certain precise conditions. Using sensitivity analysis in engineering development is a popular concept these days since this analysis is commonly used from biology to economic purposes. In addition, corporate Finance institute also mentioned that sensitivity analysis is useful for assessing ‘Black Box Process’ by utilizing several inputs with opaque function. Opaque processes are still difficult to understand as basic studies. For instance, in geography, analyzing variations in climate models and determining the relationship between parameters are very complex. Furthermore, Investopedia explain that sensitivity analysis requires certain assumptions to resolve how the different values of an independent variable affect dependent variables. Both of them also mentioned Excel as a main instrument to conduct sensitivity analysis by using What-if analysis function.

What-if analysis is constructed by a set of variables to figure out how it impacts the outcome by changing one variable. Refering to Corporate Finance Institute, the benefit of influencing sensitivity analysis is

- It gives credibility to the financial model by measuring with different options
- It provides flexibility with the changing circumstances
- It supports decision makers by providing possible choices before making the final decision

Figure 24 is a summary of Techno-economic process as the main concept of this research and also gives a clearer picture of the theoretical framework based on an explanation of the central concept adopted from various resources such as NREL; APBDU; O'Connor et al. (2017); Li et. al. (2017); Grudzinskas and Gombar (2012); Swanson et. al. (2010); MacKerron (2007); Fishman et. al. 1995; MacKerron and Waister 1985; MacKerron 1985; Investopedia; and Corporate Finance Institute.

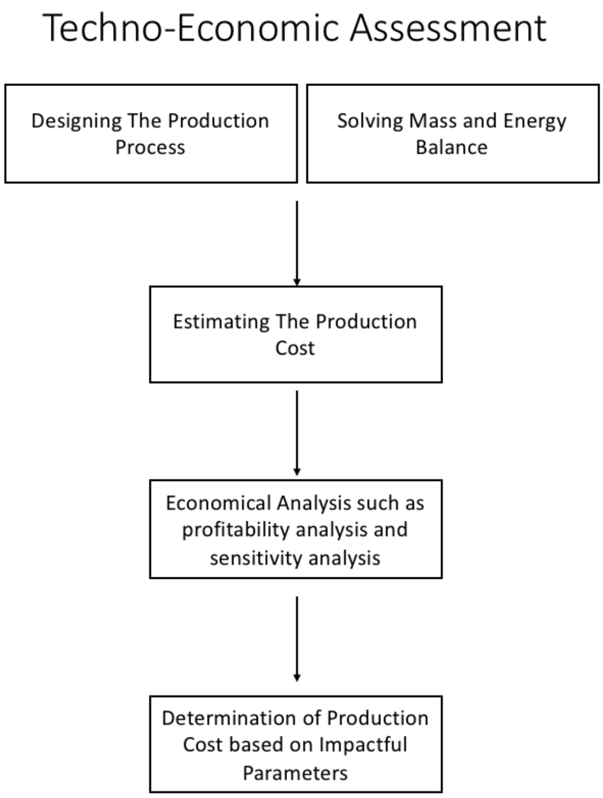

Figure 24 Central Concept Summary

4. Methodology

In this chapter, will give thorough steps how the research it will be going to be. From what kind of research strategy will be used, what kind type of research and data collection. Also, how the research finding will be analyzed. The methodology and the base of analysis are from theoretical model and central concept. Also, get additional determination by referring Research Methods for Business student book written by Sanders et. al. (2009). In addition, Figure will give introduction how the methodology will be conducted for this research.

Figure 25 Methodology of The Research

4.1 Research Strategy

To get outcome from this research, the need of research strategy should be beneficial. In this research, will be using "Case Study" for research strategy. The reason is investigating specific particular picture with using some data from various resources. This strategy will be involving different scenarios to figure out how the research problem could be solved (Sanders et. al. 2009).

Starting by making calculation model based on previous research about single cell protein development which is conducted by Sillman (2016). Additional concept input from Liu et al. (2016) for justifying the reaction process in the calculation model. From Liu et al. (2016), the idea of using renewable energy as a main energy resources for the production process is influencing this research to utilize the renewable energy into consideration. Oosterholt (2017) and InnovatieNetwork (2015) also give illustration how to design the model should be, since the similar concept of production process. The model will need to solve to figure out cost estimation by conducting mass and energy balance measurement. The measurement will follow Chemical Engineering Design book from Sinnot and Towler (2009), to get insight how to solve the mass and energy balance of the process.

The cost estimation will be the next step after figuring out the mass and energy balance since from the previous step will support the data finding for all prices of the parameters which are used for the calculation model. All data which are used for calculation will be explained from data collection section. The purpose of cost estimation is giving the base case before developing the analysis method and to get some pictures of the parameters which are having strong relation with final production cost. The production cost formula, cost estimation, and also, mass and energy balance formula will be getting more explanation from Quantitative Research section.

Furthermore, this research will adopt "Case Study" as research strategy, which is in this case using data from various resources to find out how does affected to calculation of production cost. Then, to support the calculation, there some of possible scenario to assess the production process. The reason is finding the possible option to make decision for the future development of this research which is food-from-electricity project. Also, giving some basis of the beneficial parameters that is having more impact for the production cost. Then, the base scenario will be following previous research from Sillman (2016) and combining with research from Liu et al. (2016) about in-situ electrolysis to give differentiation from similar project. The additional scenario will be adopted to give precise result of analysis.

4.2 Quantitative Research

Quantitative research is using numerical data for finding outcomes of the research problems. So, it means this research will be a quantitative research since using some data from various resources and focused on electricity price, raw material cost, and total unit cost to figure out the production cost of food from electricity. Raw material cost in this research will be covering from CO_2, Ammonia (NH_3) and Nutrient. Also, total unit cost of main instrument which is reactor and in-situ electrolysis unit will support the calculation of production cost. Moreover, it sounds more like qualitative studies rather than the quantitative studies, but the data will be input and parameter of calculation model for doing further analysis to gain some result.

The formula of the calculation will be determined in this section based on the previous research and some literature. There are two main focus in the calculation approach, mass and energy balance and cost estimation. In this research, the mass and energy balance calculation refer from Sinnot and Towler (2009) which is calculation for chemical engineering design, the purpose is knowing the flow process of the production. According to Sinnot and Towler (2009), the equivalence of mass and energy balance is based on Einstein's equation which is mass and energy can be converted since they are equivalent. The equation is:

$$E = mc^2$$

E = energy, J

m = mass, kg

c = the speed of light in vacuo, 3×10^8 m/s

(Sinnot and Towler 2009)

Then, there are two conservation equation, general conservation equation and steady state equation. General conservation equation is equation for any type of chemical process, can be explained as:

$$Material\ Out = Material\ in + Generation - Consumption - Accumulation$$

On the other hand, steady-state equation is when the process has zero of the accumulation term. The equation would be simplified as:

$$Material\ out = Material\ in$$

(Sinnot and Towler 2009)

In this research would be utilizing the steady-state equation since the purpose of calculating production cost of new process and technology development. Moreover, there is still next calculation need to be solved, that is energy balance. Refers from Sinnot and Towler (2009), general equation of energy balance would be similar like the equation of mass balance, so the conservation of energy is:

$$Energy\ out = Energy\ in + generation - consumption - accumulation$$

As well as for the steady-state process, the equation would be reduced as:

$$Energy\ out = Energy\ in$$

(Sinnot and Towler 2009)

The first equation of energy conservation is the first law of thermodynamics statement. Energy balance could be for any kind of process, specifically for chemical engineering process would be involving exothermic energy and endothermic energy. Energy balance could be more complicated than solving mass balance since energy has many forms from potential energy, kinetic energy, internal energy, work, heat, and electrical energy. For this research, the energy balance would be determined and needed to know the energy need for the process. The reason is the need of energy will be input for the calculation model to finding the production cost.

The calculation model constructed from mass and energy balance, parameter which is some prices, and the efficiency of the process or unit which is involved in the production. The input will be the protein production in kilogram based. It can be called, the first assumption. From that, the calculation is going backward to figure out how many raw materials we need. The raw materials such as Ammonia (NH_3), Carbon dioxide (CO_2), Water (H_2O), and Nutrient which is various chemistry compounds. The efficiency of the unit would be the parameter of how many kilograms of the component need on the process and how much electricity consumption for the production.

After understanding the concept of production process by making calculation model, the second step of the quantitative research is cost estimation. The production cost would be discovered from the investment cost of the unit and operation cost; however, it can be simplified by how much electricity consumption and how much cost to spend for produce 1 kg protein from this process. To calculate total unit cost is using and referring from various research which is focusing in similar focus of research, utilizing electricity or energy to produce food. The concept of total unit cost is calculating the cost of the unit with the unit size or capacity based on investment formula in Microsoft Excel. For the material cost which is CO_2 cost, Ammonia Cost, and H_2O cost will have different calculation method. CO_2 cost and Ammonia Cost are having the same concept of calculation to get the cost estimation for finding production cost, after getting the need of CO_2 and NH_3 multiply with the cost from literature and resources of the material. In addition, for this research is using various resources of CO_2 to get more alternatives of cost estimation. For H_2O cost would be assuming as estimating total unit cost of electrolysis unit since the production process will be utilizing electrolysis with in-situ approach. The next calculation is energy cost calculation which is electricity cost and heat cost, related to the aim of this research which is involving energy to make food from electricity, this step would be necessary to constructing production cost. The electricity price is based on Nordpool price and IEA prediction price of renewable energy price. For heat energy will assume to using electrical energy to substitute the heat need, so the heat energy price will be the same as electricity price. The last step of cost estimation is finding the operational and maintenance cost (OM cost) by using OM cost from literature and adjusting to the capacity process of this research. Those are the cost estimation flow process before getting the production cost. The calculation of production cost will be applying LCOE formula as based calculation formula. LCOE formula will be referring from Mahdi et. al. (2016) and Breyer (2017) research which is having similar purpose, power-to-x technologies development. Also, the LCOE formula will help to utilizing the analysis method to finding the possible production cost this research. In addition, figure 26 shows the calculation method flow of this research.

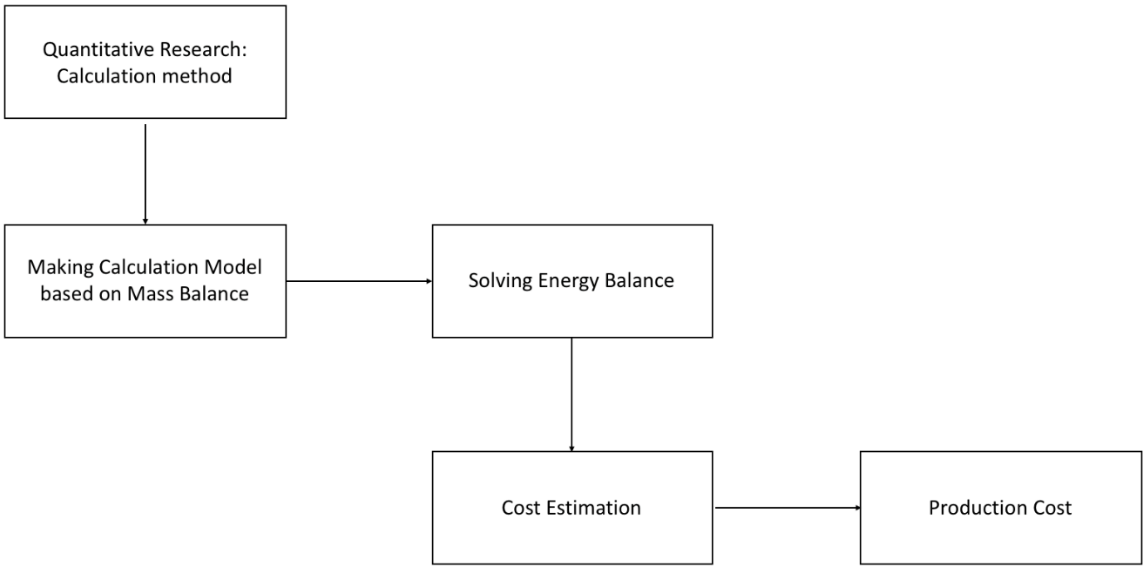

Figure 26 Flow Process of Quantitative Research

4.3 Data Collection

Data collection in this research could be the input and parameter. But most likely all of the data will be collected as parameter such as price, efficiency of the unit, and energy of the reaction and flow. All data are collected from various resources such as scientific paper, public research proposal, presentation and book. All of them are used in calculation model. All the tables below will show all data which are used for this research.

Table 6 List of Molar Mass for The Production Process

Chemical Compound	Molar Mass (gram/mol)
C	12,01
H	1,01
O	16
N	14
CO_2	44,01
H_2O	18,02
O_2	32
NH_3	17,03
H_2	2,02

(Green and Perry, 2008)

Table 6 shows the molar mass of chemical compounds which are used for making the calculation model and finding the molar mass of the biomass compound. The concept of using the molar mass is multiplying the value of molar mass with the chemical compound.

Table 7 List of CO_2 Prices Used for the Calculation Model

CO_2 Source	CO_2 Price	Literature Source
Direct Air Capture	0,17 €/kg	APS (2011)
Residual gas Fermentation	0,006 €/kg	Reiter and Lindofer (2015)
Flue Gas from Pulp and Paper	0,15 €/kg	Onarheim et al. (2017)

Table 7 presents the CO_2 prices from various sources which are utilized into the calculation model. The CO_2 price need to multiply with CO_2 need from mass balance calculation to get the CO_2 cost for generating production cost.

Table 8 Electricity Price

Electricity Type	Electricity Price (€/MWh)
1	30
2	40
3	100

(Nordpool, IEA)

The electricity price will be assumed based on Nordpool and IEA data. As mentioned before, the purpose of this research is utilizing electricity to producing food, it also assumed some of electricity type are used for this research based on renewable energy resources such as solar energy. The reason is finding the average price of electricity from nordpool to know market price of electricity and adopting IEA prediction price of utilizing renewable energy resource to get all of the electricity price. The electricity price is needed to figure out the electricity cost by multiplying with energy need from energy balance calculation. The electricity cost will be the one parameter which is involving the calculation of production cost

Table 9 Reactor Price

Reactor Capacity (ton/year)	Reactor Price (EUR)
50	2300
250	2100
500	1700

(InnovatieNetwork 2015)

The reactor price is adopting from previous research of InnovatieNetwork (2015) since the organization who collaborated in their project is having experience of utilizing and constructing the reactor which is used for this research. InnovatieNetwork (2015) stated they will be using reactor for producing single cell protein but it was not giving exact type of reactor. On the other hand, the follow up research from Oosterhoolt et al. (2017) are mentioned to utilizing H2-oxidizing reactor for the production process. For this research, the production process will be using H_2-oxidizing reactor with the price from InnovatieNetwork

(2015) as an assumption price. The reactor price is needed to fill the total unit cost of the production process which is also used for finding the CAPEX.

Furthermore, Table 10 shows the electrolysis unit price which is used in the production process. The prices of electrolysis unit are referred to hydrogen.gov.us and some literatures. To calculate H_2O cost in this research use assumption by using the price of producing H_2 and multiply with the need of H_2O for the process hence the central concept of utilizing in-situ electrolysis process.

Table 10 Electrolysis Unit Price

Electrolysis unit type	Price (€/kg)	Reference
PEM	5	US gov (2009)
PEM	7 - 9	NelHydrogen (2017)

The focus of this research is utilizing more efficient process, to make comparison the electrolysis unit type will have two different calculations from PEM electrolyser and SEC electrolyser. SEC electrolyser is more commercialized compare to PEM electrolyser but less efficient. It might be useful for further analysis, that is the next explanation, Analysis method. In addition, for the calculation model will just using directly the price of H_2 production and the efficiency will follow the process efficiency based on Liu et. al. (2016). Other parameter used for this research are listed on table 11.

Table 11 Other Prices for the Calculation Model

Parameter/Unit	Value	Reference
Efficiency of the process	54%	Liu et. al. (2016)
NH_3 (Ammonia)	0,07 €/kg	Alibaba.com
Nutrient	0,08 €/kg	Alibaba.com
Post Processing Unit	365958 €	Matche.com

Those are the prices which used for the calculation model. All the prices in the calculation model will be used for parameters. The parameters are beneficial for analysis process in this research since it will show which parameter is having more impact to production cost. Some of the prices will get adjustment for currency conversion and unit conversion. However, some of the prices also get a little modification regarding inflation or higher or lower prices based on year changes.

As mention in the beginning, all data collection of this research is based on the primary and secondary resources. The goal of this research is figuring out the production cost of food-from-electricity by utilizing this data collection for the parameter and input of calculation model. The calculation model is the first step of the research process. Data collection will be the follow up process after the calculation model. The next step is analysis method, that is important to get bigger picture of production cost analysis. Moreover, the data collection could be changed depends on the need of the production process. This condition already explained in the introduction part to give overview how the research will be conducted and also the research will use a lot of assumption and adjustment since the new technology development of the production process.

4.4 Analysis Methods

The analysis will be adopting from central concept which is sensitivity analysis. As mention on central concept explanation, sensitivity analysis is having a lot of definition but basically all of the definition is going through the same approach. The approach of sensitivity analysis is using variation of variables to compare the impact from each of parameter to the final value. In this research, the goal is capturing production cost of the food-from-electricity which is the final value will be the production cost itself. The parameter will get treatment by making various variation to conduct the techno-economic assessment, in this case sensitivity analysis.

The techno-economic assessment starts from making calculation model, solving mass and energy balance, estimating some cost, figuring out preliminary production cost, and running the analysis. In the previous sub section, almost all of the techno-economic assessment flow process has been covered, this sub section will be focused on conducting analysis method for this research. The analysis method of this research is needed software which is Microsoft Excel to run the analysis process. By using Microsoft Excel as an instrument to support the analysis process is making the calculation model and analysis tool related each other. This approach is based on Corporate Finance Institute explanation. The sensitivity analysis would be conducted based on their approach (Corporate Finance Institute) as a main tool for analysis method of this research.

The calculation model will be the first resource needed for analysis methods. The calculation model will be the flow process of the production process. From the input material, the reaction process, and the output of material. Also, the heat and electricity need of the process which are solved from mass and energy balance. In addition, the variation of parameter such as CO_2 sources, Electrolysis unit type, and electricity price variation are included into the calculation model. The calculation model would be illustrated as flow process with some value which is determined from mass and energy balance calculation.

In this research is practically using a similar approach of case study in more experimental ways. Every data in here will be input data with focus on what number will put on the input section. The input section is the capacity of the production process per kg/hour from conversion of capacity in ton/year. For the base scenario, this research will be using 1000 ton/year as production capacity. Moreover, variation of value will also be adopted for CO_2 price, electricity price, and electrolysis unit price which is adjusted to H_2 production cost. The variation of value is related on the purpose of using sensitivity analysis as a main tool of techno-economic assessment in this research.

Then, by knowing the input value of the calculation model, the mass and energy balance will be automatically solved since from the input all the data will be followed based on the equation of mass and energy balance. The calculation model will be going to cost estimation, the same case as mass and balance equation, the value would be getting from calculation of the data resources and the value from mass and balance equation. One special case is CAPEX for the unit cost and also H_2 production cost, the value would be get from PMT from Microsoft Excel formula. PMT formula is financial formula or function which is on Microsoft Excel program and has purpose to computes the value for loan related on constant payments and constant interest rate (Microsoft Office,). Other cost estimation is just multiplying the value from data resources and the finding from mass and energy balance calculation.

Furthermore, the sensitivity analysis will be conducted as a main instrument of this research. Refers from Corporate Finance Institute, the analysis method would be divided as two approaches such as direct method and indirect method. The direct method would be replacing variation of numbers into something expected which is assumption of production cost. On the other hand, indirect method would be inserting different percentage changes into the calculation model, rather than directly change the assumption of production cost. Both of the methods are applying what-if analysis from Microsoft Excel to know the outcome of certain financial modelling when execute in specific condition. What-if analysis are commonly used for financial analysis. For instance, Corporate Finance Institute mentioned what-if analysis can be functioned to figure out the impact of changing the interest rates from bond prices by questioning in what-if format as wondering what would happen with the bond price if the rates interest will be changed. To answer that question, the sensitivity analysis would be taking part as main tool to solve this question.

From the analysis method, the result would be illustrating from two approaches, direct method and indirect method. The direct method will have table with some numbers which are determined the variation of production cost. However, the indirect method will employ tornado charts as the representative of the outcome. The outcome would be shown as the sort list of parameters from the most impactful to least impactful in one chart.

In this case, there will be different types of result and will be put in the table to know the differences. Because of employing different case scenario of production process. In addition, there is one more result would be illustrated in this research, for production cost with LCOE formula by finding the result from different case scenario. This result is just giving general outcome of the LCOE formula without doing some sensitivity analysis. Also, LCOE in the calculation would be called LCOP (Levelised Cost of Protein).

4.5 Hypothesis

The electricity cost would be most impactful parameter which is affecting the calculation of production cost. Also, The CO_2 sources will be the one variable which plays important rule since the relation of different unit for capturing CO_2. The hypothesis could be using CO_2 directly from Biogas plant will be cheaper than other sources and related to which electricity cost are used. The different price could be figured out from which type of electricity price is applied on the process. For example, using own solar panel could be sustainable and more renewable but if the investment cost is bigger it would be another problem.

5. Result and Discussion

5.1 The Calculation Model

The production process of Food produced from Electricity based on biomass based chemical reaction, the reaction is

$$CO_2 + 0{,}24\ NH_3 + 0{,}525\ H_2O \dashrightarrow CH_{1,77}O_{0,49}N_{0,24} + 1{,}02\ O_2$$

This reaction is having purpose to produce biomass by direct H_2 production process in the reactor. The calculation model has a goal which is finding the mass and energy balance of the process to figure out how much production cost of this process. The mass balance is giving the need of raw material to produced the final product, that is important for knowing the cost of material. As well as, the raw material cost, the mass balance and energy balance also contributed to give basic prediction of the unit process such as reactor, electrolysis unit, and post-processing unit. In addition, the calculation model is constructing the picture of electricity consumption of the process which is related to calculate production cost.

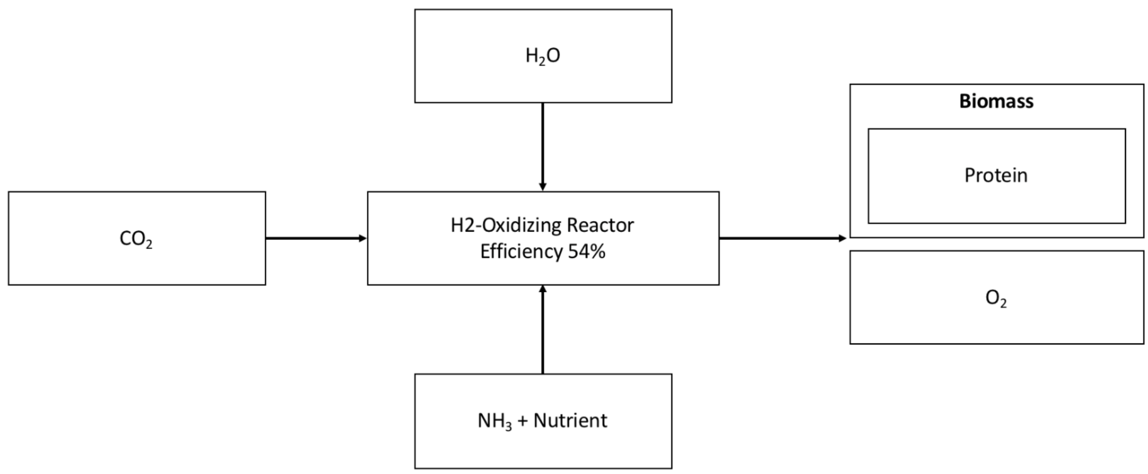

Figure 27 The Calculation Model based on Mass and Energy Balance Method

In this result section, the main focus is production of dry protein product which is 50-83% of biomass component (Anupama & Ravindra, 2000). It had impact to the calculation model for input the calculation model since the production capacity is based from dry protein product. Moreover, the sensitivity analysis compared two different scenario of production process. The Capex is more focused on reactor investment and assumed, to direct buy other component for input.

5.2 Sensitivity Analysis

The sensitivity analysis will be based on the parameter comparison of the production process which is relayed on the calculation model. Table 1 will be represented all the parameters are used in the calculation model. Based on the calculation model, there are 7 parameters used to calculate the production cost. Those paramaters related to mass balance model and energy balance model which is summarized into calculation model. According to mass balance, to produce protein, the process needs raw material such as CO_2, NH_3, and H_2. Then, energy balance gives information how much electricity need for the production process. The electricity need is important part of the process since the goal of this research is utilizing the electricity to producing food. This reason is giving connection about efficiency of electricity used to biomass which is very crucial for the whole production process. The efficiency will give different amount of electricity consumption per production, that is one of main core of this process. Moreover, electricity cost would be one of parameter since after knowing the electricity consumption, the production need to utilizing electricity by buying the resource or producing the resource itself.

Table 12 Parameter for the calculation model

No	Parameter
1	CO_2 Cost
2	Electricity Cost
3	CAPEX
4	Efficiency of Electricity used to biomass
5	Nutrient cost (NH_3 + Nutrient)
6	Operation and Management Cost

Figure 28 is illustrating in the simple way the relation between parameter, however efficiency of Electricity used to biomass is not included since the electricity cost summed up whole thing. Based on Figure 28, There are 3 dominant parameters such as Electricity cost (and also efficiency of electricity used to biomass), CO_2 Cost, and CAPEX (Reactor and Electrolysis unit). The dominant parameters as well as cost drivers of production cost.

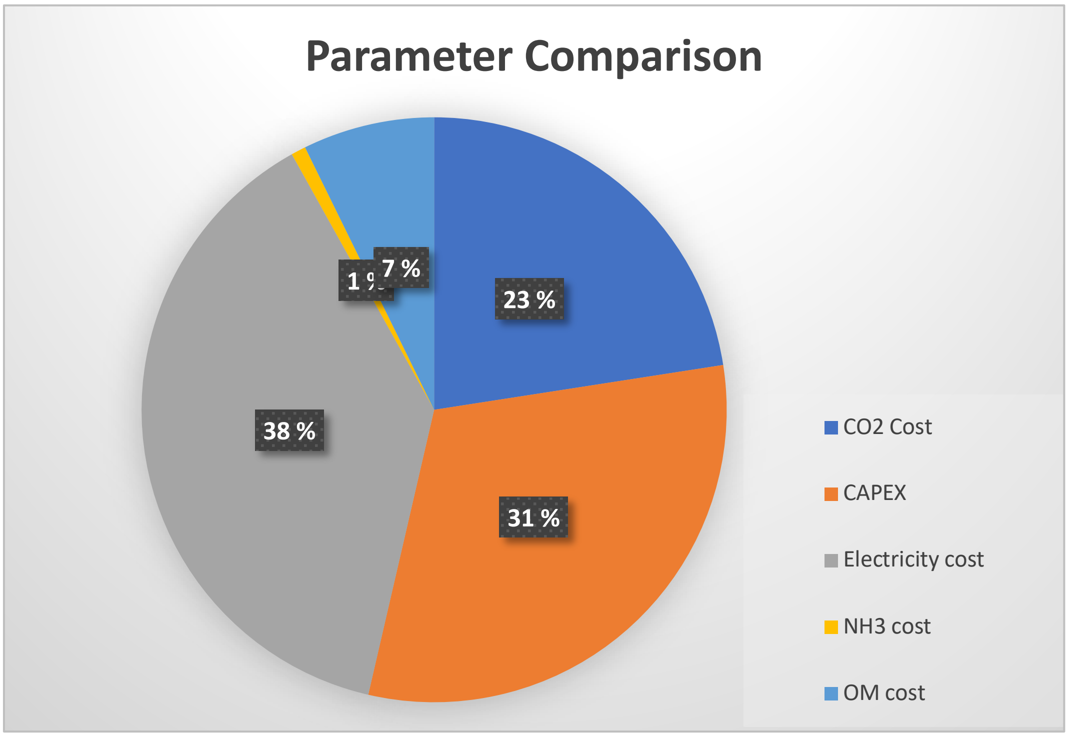

Figure 28 Parameter Comparison based on 1000 ton/year plant capacity with CO_2 Source from DAC and Electricity Price 2

In addition, Figure 28 and 29 are using same scenario, the plant capacity is 1000 ton/year, CO_2 from Direct Air Capture, and Electricity Price Number 2 (Table 8). However, Figure 3 about sensitivity analysis shows different result. Using indirect method of sensitivity analysis which is picking related parameters to get analyzed by changing the amount of parameter number within some range. For instance, Figure 29 is adopting five paurameters such as Electricity price, CO_2 Price, Efficiency of Electricity, WACC and Capex of reactor. Then, according to Indirect method, changing the amount of the parameters number which is putting different value with different range. In this case, every parameter will have different range such as for electricity price use three different input the base case, 20% from base case, and -20% from the base case. As well as, CO_2 price also utilize different input such as the base case, +20% and -20%. The same range as CO_2 price for Efficiency of Electricity to Biomass, CAPEX, and WACC.

To make it clear, the base scenario is utilizing CO_2 from DAC, using electricity price 40 €/MWh, and Efficiency of Electricity to biomass is 54%. This scenario is applied to all of base calculation and parameter comparison on figure 29 and Table 14. In addition, this research also included one scenario which is refers fortum research (Vartiainen, 2016) about electricity price in different place since the base scenario is based on finland's condition (northern countries area). Table 13 illustrates the scenario for the sensitivity analysis.

Table 13 Scenario variation for Sensitivity Analysis

Type of Scenario	CO_2 Sources	Electricity Price	Efficiency of Electricity to Biomass
1	DAC	40 €/MWh	54%
2	DAC	20 €/MWh	30%

The scenario number 2 has different in two parameters such as electricity price and efficiency of electricity to biomass. Electricity price is 20 €/MWh for scenario 2 which is referring some sunbelt countries electricity price. Moreover, efficiency of electricity to biomass is lower to assume some possible issues would happen to use this process outside Finland.

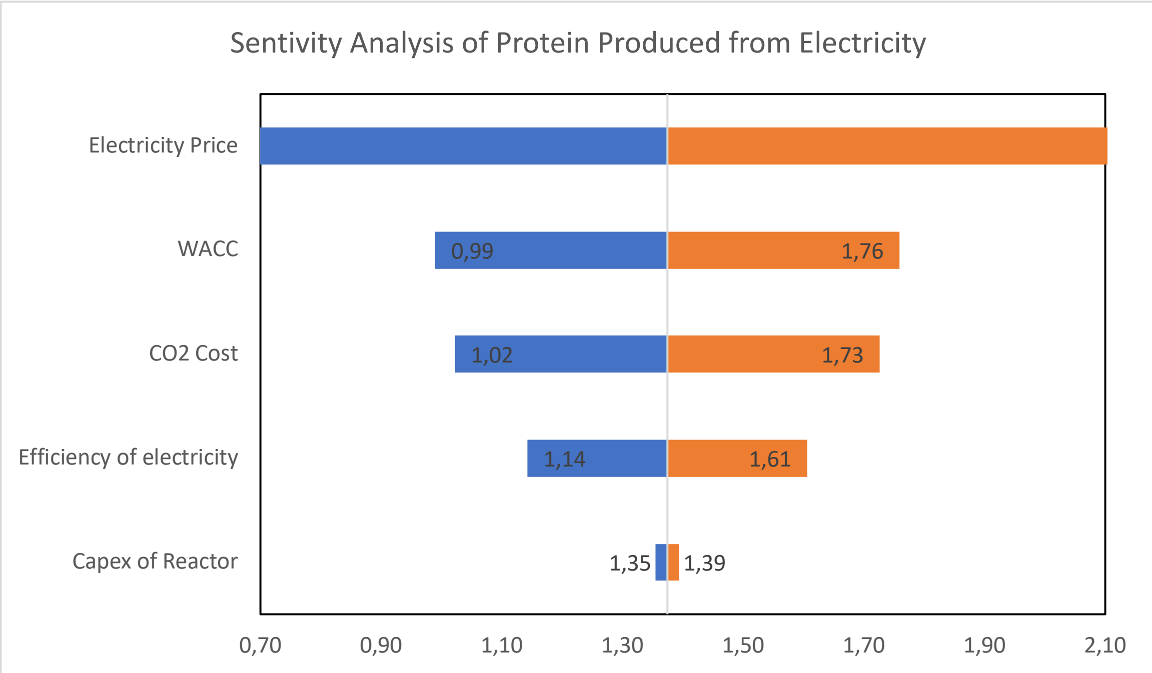

Figure 29 Tornado Chart of Sensitivity Analysis of Protein Produced from Electricity Scenario 1

The result is Electricity price having more impact regarding the calculation of production cost. It could be stated electricity price is the most sensitive parameter when calculating production cost of this process (food from electricity) with the base case (the plant capacity is 1000 ton/year, CO_2 from Direct Air Capture, and Electricity Price Number 2). Follow by WACC, CO_2 price and effiency of electricity to biomass. WACC placed number two as impactful parameter for production cost calculation. CAPEX is not really affected the construction of production cost in this case. The assumption of range is having purpose to give illustration of different case of the recent value. Since some of the value could be changed due to many factors.

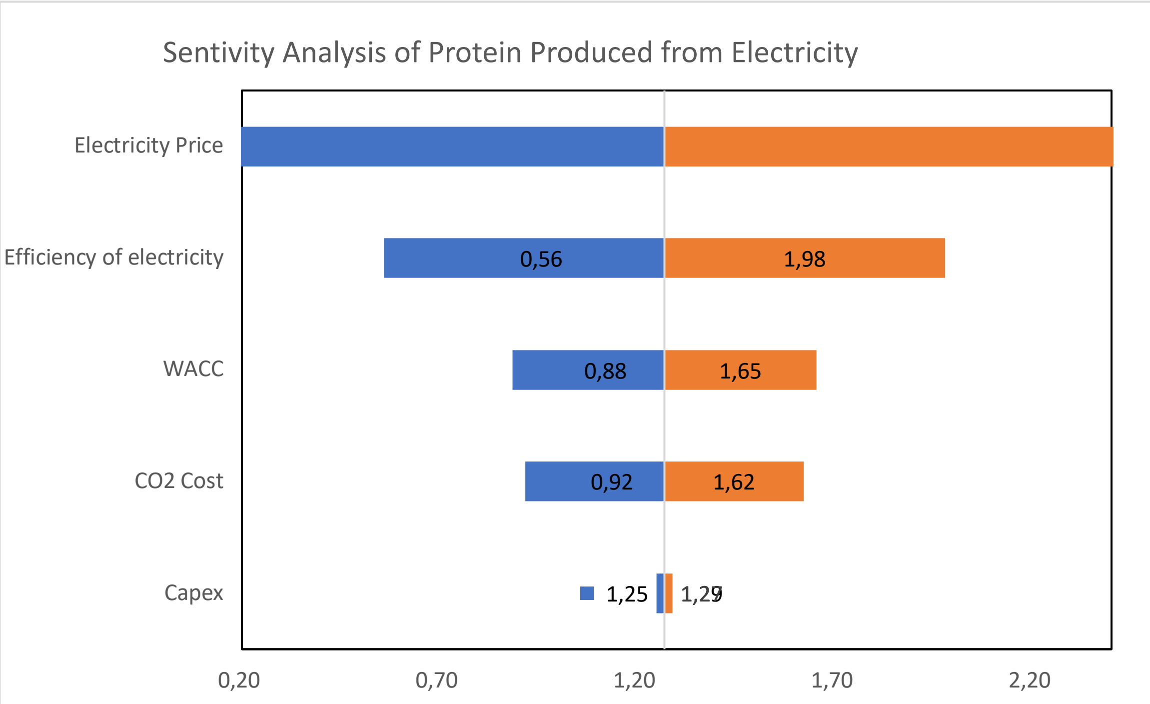

Figure 30 Tornado Chart of Sensitivity Analysis of Protein Produced from Electricity Scenario 2

On the other hand, the scenario number 2 shows different result compare to scenario number 1. In this case, totally make sense the electricity price is still the first impactful parameter among others parameter, but the product cost is looked higher in the sentivity analysis with scenario number 2. However, the efficiency of electricity is taking over second beneficial parameter and putting CO_2 in the third place. The base price of scenario 1 is 1,37 €/kg and the base price of scenario 2 is 1,14 €/kg. The different efficiency of electricity to biomass is played the big role of the calculation because the whole system is related to the electricity.

The electricity price in high sensitivity level is more than 4 €/kg for scenario 1 and more than 5 €/kg for scenario 2. This situation, it shows the price of electricity is the main important parameter of the production. However, the system builds need resources from different sector and related to the main process which is in here reactor and the reactor is having relation with efficiency of electricity to biomass. In this situation, it makes sense the CO_2 cost and efficiency of electricity to biomass are on the top lists of impactful parameters of production cost. WACC is also important hence this calculation related to the investment of the unit production which is utilizing LCOE-based formula.

Furthermore, in sensitivity Analysis has two methods, Direct and Indirect. Figure 29 and 30 is illustrating the Indirect approach of sensitivity analysis. Direct method shows in Table 14, that is analysis by comparing different electricity price and Capacity of the production plant per hour. The purpose is to be triggered the base production cost into different range of chosen parameters, in this case is electricity price and plant capacity. The base production cost is 1,37 €/kg.

Table 14 The Result of Direct Approach of Sensitivity Analysis Scenario 1

Direct Method		Electricity Cost				
LCOP (€/kg)	1,37	0,02	0,03	0,04	0,05	0,06
Capacity (kg/h)	63,13	1,15	1,29	1,42	1,55	1,68
	100,00	1,12	1,25	1,39	1,52	1,65
	126,26	1,11	1,24	1,37	1,51	1,64
	189,39	1,10	1,23	1,36	1,49	1,62
	252,52	1,09	1,22	1,35	1,48	1,62
	378,78	1,08	1,21	1,35	1,48	1,61
	505,05	1,08	1,21	1,34	1,47	1,61

Table 15 The Result of Direct Approach of Sensitivity Analysis Scenario 2

Direct Method		Electricity Cost				
LCOP (€/kg)	1,27	0,02	0,03	0,04	0,05	0,06
Capacity (kg/h)	63,13	1,31	1,52	1,73	1,94	2,15
	100,00	1,28	1,49	1,70	1,91	2,12
	126,26	1,27	1,48	1,69	1,90	2,11
	189,39	1,25	1,47	1,68	1,89	2,10
	252,52	1,25	1,46	1,67	1,88	2,09
	378,78	1,24	1,45	1,66	1,87	2,08
	505,05	1,24	1,45	1,66	1,87	2,08

Refers to Table 14, The production cost is getting lower when the capacity is becoming larger and the electricity cost also has big impact in result of production cost. The same situation applied in scenario 2 from table 15. However, the scenario 2 shows lower production cost which is 1,27 €/kg. The electricity cost is still the most influenced parameter of production cost. From direct method sensitivity analysis shows the production cost is increasing when the electricity price is getting higher. However, the production cost is getting cheaper when the capacity of the production is getting bigger. From both methods, direct and indirect, it can be seen the electricity cost has big influence for the production cost and the reason behind that is the efficiency of utilizing electricity to producing the final product.

5.3 Capital Expenditures (CAPEX) of The Production Process

CAPEX in this research is reactor cost, electrolysis unit cost, and fix-assumiption of post processing cost. The reactor cost will be based on previous research from InnovativeWorks, 2015 in The Netherland. Then, the electrolysis unit cost is based on Nelhydrogen (2017) and US hydrogen organization. The Capex is formed by assuming WACC and Lifetime of the equipment. In this research, the WACC is 8% and Lifetime of the equipment is 20 years with the based assumption for 1000 tons'/year plant capacity. The CAPEX result for capacity of 1000 tons/year is 924,23 €/kg with the electrolysis unit price based on Nelhydrogen (2017) and 880,98 €/kg with the electrolysis unit price based on US Gov (2009).

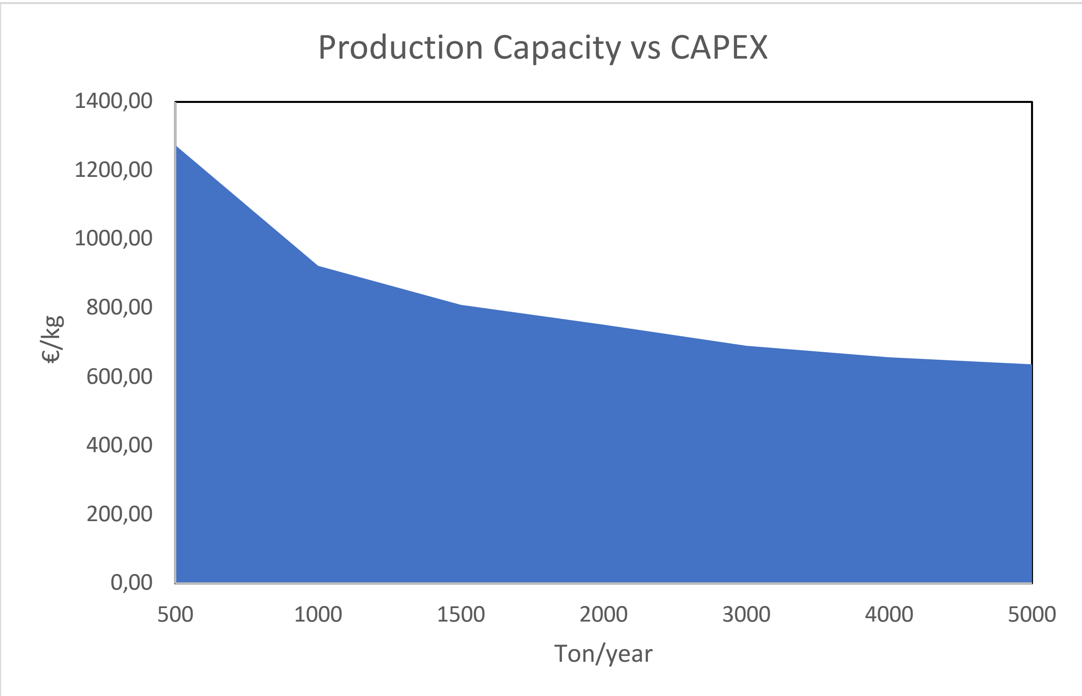

Figure 31 Capacity vs CAPEX (adopting from NelHydrogen (2017))

Figure 31 and 32 shows the relation between CAPEX and capacity of the production. Those figures use the base scenario which is scenario 1. By referring to scenario stated above, scenario 1 is utilizing CO_2 from DAC, the process efficiency of electricity to biomass is 54%, and electricity price is 40 €/MWh. The production cost in based level reaches 1,37 €/kg by adopting the electrolysis unit price from NelHydrogen (2017). Also, the price of electrolysis unit is fluctuative because of the different capacity of production process. On the other hand, by referring US gov (2009) in figure 32, it shows lower value of production cost compare to figure 31. The reason is the fix price of electrolysis production cost. The different is not so big from CAPEX calculation but when calculating the production cost, the result is 1,13 €/kg for produced dry mass protein with 1000 ton/year production capacity.

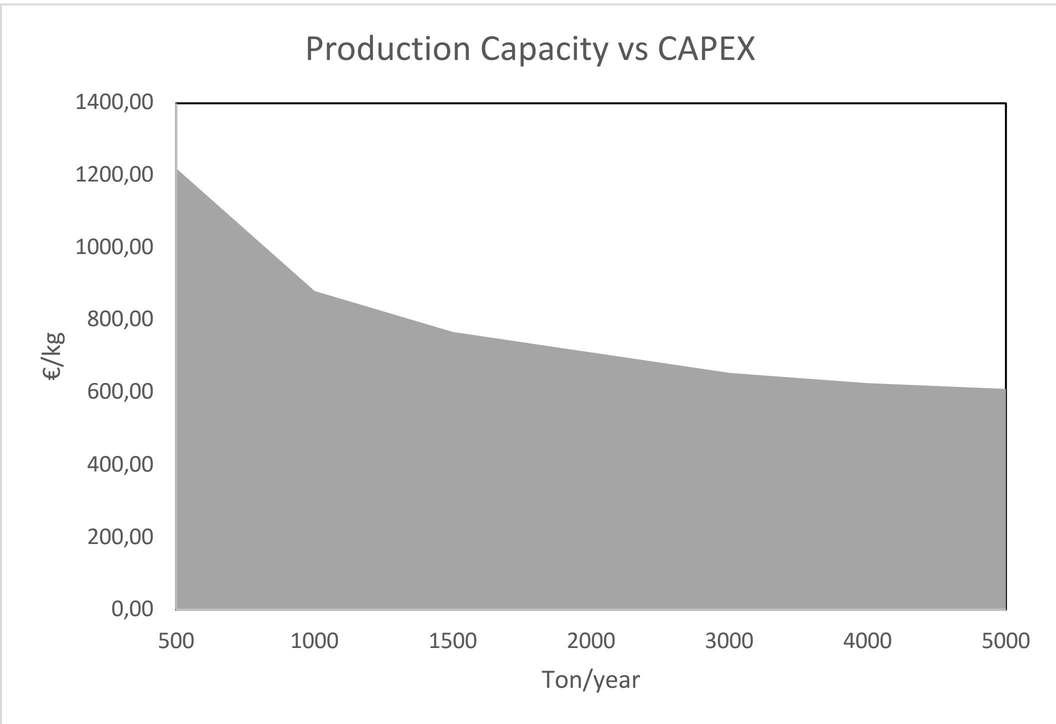

Figure 32 Production Capacity vs CAPEX with fix electrolysis unit cost (US gov, 2009)

Refers from NelHydrogen Company, who generates H_2, the CAPEX of H_2 production is getting cheaper when they increase their production capacity. The similar trend is showing in this research; The CAPEX of the production will be going down when the capacity is getting bigger.

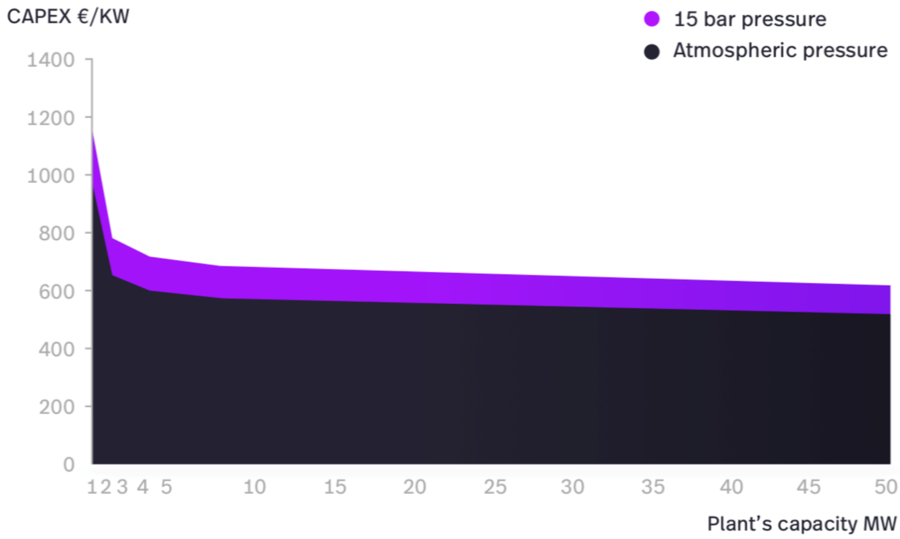

Figure 33 CAPEX of Hydrogen Production (NelHydrogen, 2017)

5.4 Levelized Cost of Protein (based on LCOE Formula)

Levelized Cost of Protein is the final protein production cost which is including CAPEX, OPEX, energy cost (in this case electricity), and raw material cost divided by the capacity. The similar trend like CAPEX vs Capacity will be illustrated in the result. The LCOP will be getting lower while the capacity of production is becoming more extensive. In figure give illustration of different the LCOP with different electricity sources and CO_2 sources versus the production capacity.

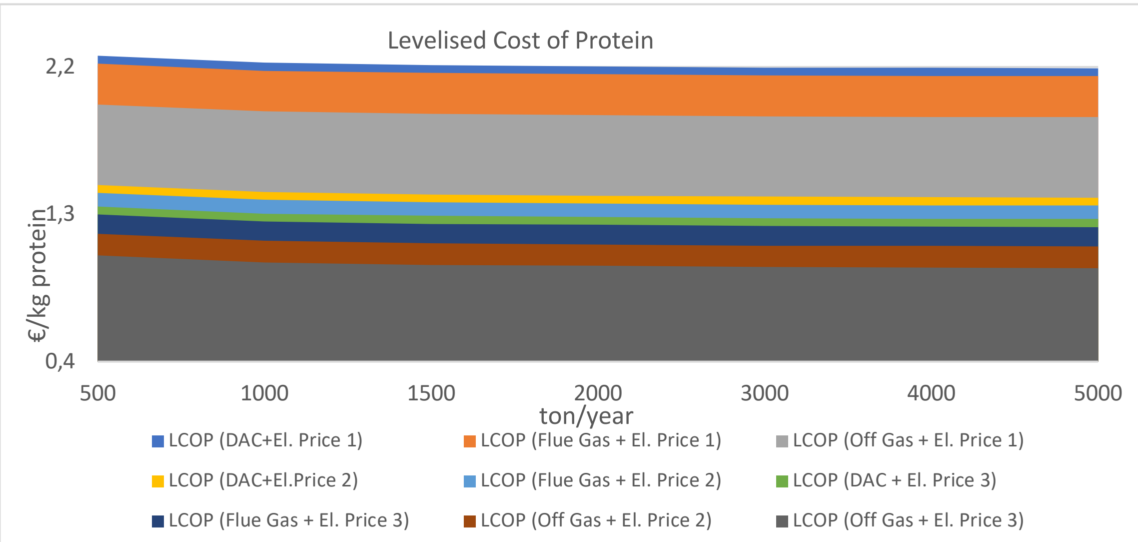

Figure 34 Levelised Cost of Protein with Different Scenario

The LCOP with CO_2 Sources from residual gas fermentation and electricity price 3 (Table 8) is the cheapest production cost among other. The highest LCOP is using electricity price 1 (Table 8) with CO_2 source from Direct Air Capture. The cost difference is related to sensitivity of the parameter since electricity price is the major cost driver and also, CO_2 cost is second cost driver of the production cost.

In addition, from the sensitivity analysis part, there are two scenarios which is using different efficiency and price of electricity with fix cost of CO_2 (utilizing DAC technology). The result is scenario 2 shows lower price than scenario 1 since the lower cost of electricity. Figure 35 illustrates the comparison between scenario 1 and scenario 2.

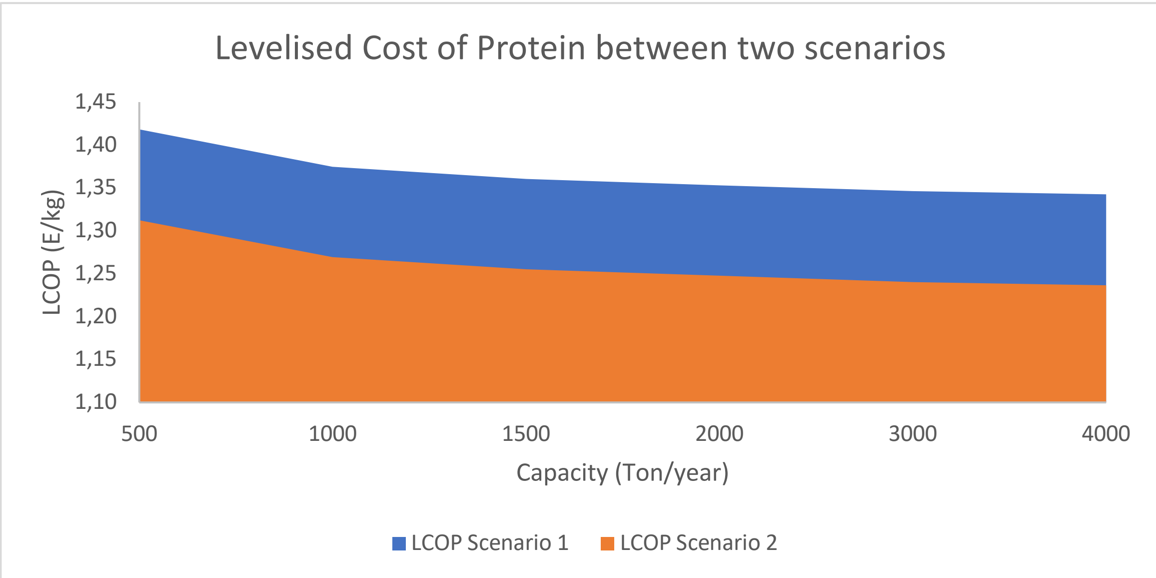

Figure 35 The comparison of LCOP between scenario 1 and scenario 2

5.5 Discussion

Based on the result of sensitivity analysis, the production cost is constructing from two different efficiency of electricity to biomass and two different electricity prices. By using different electricity prices from Fortum research are more in sustainable point of view based on previous research of Sillman (2016) and the potential of sunbelt countries from Vartiainen (2016). However, to develop own solar panel illustrate higher cost than using conventional sources by electricity provider (it could be renewable depends on the country). In this research is using Nordpool as the source of electricity price for the scenario 1. However, IEA (2017) gives prediction of auction price of renewable energy (wind and solar) to know how much cost will be spent for implementation of the research. The research is giving more finding such as the different CO_2 resources and the outcome from continuing Sillman (2016) and Liu et al. (2016) research.

Production cost in this research is showing lower result than InnovatieNetwork (2015) outcomes with the same calculation approach. All The production cost of this research is similar with InnovatieNetwork (2015) finding, it calculated around 1.300.000 €/year which is promising for pilot and commercialize phase in the future. In addition, all of the production cost seems cheaper than Oesterholt et. al (2017) calculation which is lower than 2000 €/ton. However, the differences of production capacity could be the reason of the big difference from 2600 €/ton to around lower than 1500 €/ton. Also, two of previous research are utilizing H_2 from outside the process, it gives additional cost of the production since the price utilizing H_2 will be added in variable cost of production. Moreover, InnovatieNetwork (2015) and Oesterholt et. al. (2017) are adopting the renewable energy sources for the process as well as this research which is mentioned before. Utilizing CO_2 from residual gas fermentation would be the best option to implement this research, this finding is related to InnovatieNetwork (2015).

Based on Sillman (2016) and Liu et. al. (2016), hydrogen oxidizing reactor with in-situ water electrolysis is still in early stage of implementation which is totally confirmed on this research since not much data is available data to know the precise price of reactor. In addition, using LCOE calculation method (Fasihi et. al. 2016; Breyer, 2017) is giving different impact to the final production cost. It could be the precise approach to know the price of power-to-x technologies product. However, the production cost of this reaction still hard to compare with other power-to-x technologies since different process and not in the same field (this research is focusing on animal feed and food). This research is still lacking the calculation method presented by Tredici et. al. (2015) to get precise total cost of chemical plant. It would be easy to implement if every unit inside the process are well-known available on the market, which is in contrast from this research.

In addition, the sensitivity analysis is adding wide perspective by applying two different scenarios. Scenario 1 which is the base case of this innovation process shows the electricity is the one of major parameter for the production cost calculation and it gives big impact to the final result. The reason is electricity is important and the core of the process. In this case, electricity is the resource for whole production cost. This phenomenon is similar like Liu et. al (2017) research about bio jet fuel development, they found the oil cost to produce the fuel is the most impactful parameter since the oil is the core of the process. Moreover, from scenario 1, it appears CO_2 cost as second impactful parameter since CO_2 is take big part as input of the system. This research is implementing direct air capture technology to get CO_2 from ambient air and the technology is quite new, also still under development to big market. In this case, the cost of utilizing this energy is quite high, 50-1000 €/ton (APS, 2011).

On the other hand, scenario 2 shows different result which is efficiency of electricity to biomass is more impactful compare to CO_2. This result could be happened since the efficiency of electricity to biomass in scenario 2 is lower than base scenario which is 30%. As the purpose of this research about utilizing electricity to produced food, efficiency also play big role to the system. It shows from direct method sensitivity analysis with base scenario the maximum price of production cost is lower than scenario 2 because of scenario 1 is using 54% for efficiency of electricity to biomass. For this efficiency perspectives, the phenomenon is a bit similar like previous research from Swanson et. al. (2010) about biomass-to-liquids production. They found compression of install factor is also impactful parameter for calculating production cost. Install factor has relation with efficiency since install factor in Swanson et. al. (2010) is focusing how much liquid could produces from the biomass.

The finding from the result is shows the trends of the CAPEX would lower when the production capacity is increasing which is in this case show the innovation process is already more than institutional level and start to find relation with disruptive technologies (Kramer 2017). Moreover, the phenomenon of the utilizing some scenario is to achieve economic disruption and environmental disruption. From the result, the decreasing price is real example of disruptive technologies because more capacity, the cheaper production cost in the final. In addition, the approach of this research is to overcome from Northian condition (Kramer, 2017), which is condition when the institution try to prevent climate change issues.

From the result and data collection, this research is likely in the condition of Randersian since start to be implementing new things to the environment (Kramer, 2017).

The process of this research, if try to make relation with stage of food development, this research would be in transitional stage (Reardon et. al. 2017). This research is still in transitional stage because of a lot of early born technologies which are utilized in this process. Also, this research could be followed up the analysis of major implications food innovation to fill the gap of economic infrastructure and pursue to finalizing policy enviro

6. Conclusions

This research is follow-up of previous master thesis from Sillman (2016), that is discovering protein from electricity. However, this works is focusing on production cost of protein from electricity with techno-economic assessment approach. As the result, production cost is lower than 1500 €/ton based on LCOE calculation or lower than 2 €/kg. In addition, the result of production cost is showing various prices based on different CO_2 sources and Electricity sources.

The techno-economic analysis in this research applies sensitivity analysis from the financial perspective. As The result, electricity price plays important rule to find out the production cost of this innovation process. As well as, CO_2 cost, efficiency of electricity, and WACC which are also giving more impact when calculating the production cost. The techno-economic assessment in this thesis is using two different methods, direct method and indirect method. The purpose is to emphasise the production cost analysis and showing which parameter is contributing to determine the production cost.

The production cost is having sensitivity with electricity price since the main resources of whole production is electricity. The final determination of the production cost is quite comparable with some power-to-X technologies products which already existed or beginning to take place. Also, the production cost looks promising like similar project in the same field. Moreover, the focus of this research is explaining the method of production cost analysis by using sentivity analysis. Then, the relation with techno-economic assessment is knowing the connection between development of technology and economic point of view. The relation between the technology itself and economic can be seen from how the effect of parameter to the production cost.

The production cost from these studies, could be based for implementing techno-economic assessment of power-to-x technologies in the similar field which is for animal feed and food. The reason is the calculation model would be easy to adopt for practical tool. In addition, the reaction process of this research is kind of similar with ex-situ process and the result looks promising. However, the efficiency of the process is still not in satisfactory.

The research is conducted with some limitation which is already described extensively in some previous parts. There is some cost waiver for calculation of LCOE and normal total cost calculation specifically for other unit process instead of reactor. Moreover, the electricity price for own solar panel is based on 2015. Same situation applied for electricity price from Nordpool since this research was using data based on October 2017. The analysis is still in beginning stage, it could not rely with chemical factory economic analysis.

Furthermore, the scope of this research is to show the analysis process of production cost from protein produced from electricity energy. The analysis itself is adopting techno-economic analysis, however, the type of techno-economic assesments are quite variative. Based on previous research about techno-economic analysis in power-to-X technologies field, sensitivity analysis would be possible to conduct. In conclusion, this research implemented sensitivity analysis to find out production cost and also giving some beneficial parameters which are essential for future development of the process and the technology.

Since this research still has a lot of space to improve, in the future, would be better to conduct chemical factory economic calculation for whole process. In addition, using wind energy as option of electricity could yield different result. Also, the production cost prediction could be better by using various price from Nordpool or other electricity market provider since it still easy to access. Moreover, the future research could be focused on comparing ex-situ and in-situ process with specific approaches (life cycle analysis, techno-economic analysis, or land use analysis).

To conclude, this research could be further improved in more market analysis and feasibility studies since the technology which is used in this research is still emerging in the near future. However, the lack of information (in term price of some technologies and similar research) could be a hinderance to conduct deeper research. On the other hand, looking from the result of production cost and analysis, the food innovation project in this research would be a significant breakthrough to address food demand issues in the future. By analyzing the above arguments and findings, this kind of research should be continued with great tenacity as it would be immensely beneficial for the future as well as make society more aware of power-to-X technologies.

References

Akiyama, M, Tsuge, T, Doi, Y. 2003. *Environmental life cycle comparison of polyhydroxyalkanoates produced from renewable carbon resources by bacterial fermentation.* Polymer Degradation and Stability, vol. 80, issue 1, pp. 183-194.

Alibaba.com. (n.d.). Map 12-61-00 Monoammonium Phosphate Can Be Placed In Close Proximity To Germinating Seeds Without Concern For Nh3 Damage. - Buy Map 12-61-00,Monoammonium Phosphate 12-61-00,Ammonium Dihydrogen Phosphate Adp Product on Alibaba.com. [online] Available at: https://www.alibaba.com/product-detail/MAP-12-61-00-Monoammonium-phosphate_60735734197.html?spm=a2700.7724838.2017115.160.511158e0iHvUGC [Accessed 1 Nov. 2017].

Alibaba.com. (n.d.). Sodium Bicarbonate Food Grade 99% Manufacturer Price Nahco3 - Buy Sodium Bicarbonate Food Grade,Sodium Bicarbonate 99.7% Manufacturer,Sodium Bicarbonate Price Of Nahco3 Product on Alibaba.com. [online] Available at: https://www.alibaba.com/product-detail/Sodium-Bicarbonate-food-grade-99-Manufacturer_60731029137.html?spm=a2700.7724838.2017115.89.3c0a215fWZ9PLe [Accessed 1 Nov. 2017].

ABPDU. (n.d.). Techno-Economic Analysis - ABPDU. [online] Available at: http://abpdu.lbl.gov/capabilities/techno-economic-analysis/ [Accessed 1 Apr. 2018].

APS (2011). *Direct Air Capture of CO2 with Chemicals*. [online] POPA, pp.37-43. Available at: http://large.stanford.edu/courses/2011/ph240/mccurdy1/docs/aps.pdf [Accessed 1 Jan. 2018].

Boon, W. and Moors, E. (2008). Exploring emerging technologies using metaphors – A study of orphan drugs and pharmacogenomics. Social Science & Medicine, 66(9), pp.1915-1927.

Breyer, C. (2017). Energy Resources Lecture.

Choi, S, Drese, J.H, Eisenberg, P.M, Jones, C.W. 2011. Application of Amine-Tethered Solid Sorbents for Direct CO2 Capture from the Ambient Air. Environmental Science and Technology, vol. 45, issue 6, pp. 2420-2427.

Corporate Finance Institute. (n.d.). Overview of Sensitivity Analysis - What is Sensitivity Analysis. [online] Available at: https://corporatefinanceinstitute.com/resources/knowledge/modeling/what-is-sensitivity-analysis/ [Accessed 1 Apr. 2018].

Daniell, J, Köpke, M, Simpson, S. 2012. *Commercial Biomass Syngas Fermentation*. Energies, vol. 5, issue 12, pp. 5372-5417.

Day, G. and Schoemaker, P. (2000). Avoiding the Pitfalls of Emerging Technologies. California Management Review, 42(2), pp.8-33.

Earle, M.D., and Earle, R.L. (2000). Building the future on new products. Leatherhead Publishing, England. 112 pages.

Emard, A. (2015). Turning the power of the sun into food. Renewable Energy Focus, 16(5-6), pp.111-112.

FAO (2006). Food product innovation. [online] Rome, pp.1 - 26. Available at: http://www.fao.org/fileadmin/user_upload/ags/publications/J7193_e.pdf [Accessed 1 Apr. 2018].

FAO (2009). *Global Agriculture towards 2050*. [online] Available at: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf [Accessed 16 Oct. 2017].

Fasihi, M. (2016). *Techno-Economic Assessment of LNG and Diesel Production and Global Trading Based on Hybrid PV-Wind Power Plants and PtG, GtL and PtL Technologies*. [online] Wilma.finna.fi. Available at: https://wilma.finna.fi/Record/doria_lut.10024_123730 [Accessed 20 Oct. 2017].

Fishman, A., Notea, A. and Segal, Y. (1981). Gamma transmission gauge for assay of integral water content in soil. Nuclear Instruments and Methods, 184(2-3), pp.571-576.

Green, D. and Perry, R. (2008). Perry's Chemical Engineers' Handbook, Eighth Edition. New York: McGraw-Hill Publishing.

Grudzinskas, C. and Gombar, C. (2012). Portfolio and Project Planning and Management in the Drug Discovery, Evaluation, Development, and Regulatory Review Process. Principles of Clinical Pharmacology, pp.487-506.

Hannula, I. (2015). Synthetic fuels and light olefins from biomass residues, carbon dioxide and electricity: Performance and cost analysis. [online] Urn.fi. Available at: http://urn.fi/URN:ISBN:978-951-38-8343-0 [Accessed 1 Apr. 2018].

Horizon 2020. (2018). Future and Emerging Technologies - Horizon 2020 - European Commission. [online] Available at: http://ec.europa.eu/programmes/horizon2020/en/h2020-section/future-and-emerging-technologies [Accessed 15 May 2018].

Hussain, A., Arif, S. and Aslam, M. (2017). Emerging renewable and sustainable energy technologies: State of the art. Renewable and Sustainable Energy Reviews, 71, pp.12-28.

Iea.org. (2017). *Announced wind and solar average auction prices*. [online] Available at: https://www.iea.org/newsroom/energysnapshots/announced-wind-and-solar-average-auction-prices.html [Accessed 8 Jan. 2018].

InnovatieNetwork (2015). Power to Gas to Protein: Protein at farm scale feed compatible components. 15.2.334. [online] Utrecht, pp.6-16. Available at: http://www.innovatieagroennatuur.nl/sitemanager/downloadattachment.php?id=KbVU4Nu1jm7_xhDutJ0Nm. [Accessed 1 Jan. 2018].

Investopedia. (n.d.). Sensitivity Analysis. [online] Available at: https://www.investopedia.com/terms/s/sensitivityanalysis.asp [Accessed 1 Mar. 2018].

Kramer, G. (2018). Energy scenarios—Exploring disruption and innovation. Energy Research & Social Science, 37, pp.247-250.

Li, X., Mupondwa, E. and Tabil, L. (2018). Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies. [online] Available at: http://dx.doi.org/10.1016/j.biortech.2017.09.183 [Accessed 1 March 2018].

Liu, C., Colón, B., Ziesack, M., Silver, P. and Nocera, D. (2016). Water splitting–biosynthetic system with CO2reduction efficiencies exceeding photosynthesis. Science, 352(6290), pp.1210-1213.

MacKerron, D. and Waister, P. (1985). A simple model of potato growth and yield. Part I. Model development and sensitivity analysis. Agricultural and Forest Meteorology, 34(2-3), pp.241-252.

MacKerron, D. (1985). A simple model of potato growth and yield. Agricultural and Forest Meteorology, 34(4), pp.285-300.

MacKerron, D. (2007). Mathematical Models of Plant Growth and Development. Potato Biology and Biotechnology, pp.753-776.

Maltus, T.R., 2006. An essay on the principle of population (Vol. 1). Cosimo, Inc.

Matassa, S., Verstraete, W., Pikaar, I. and Boon, N. (2016). *Autotrophic nitrogen assimilation and carbon capture for microbial protein production by a novel enrichment of hydrogen-oxidizing bacteria*. [online] power-to-protein. Available at: https://www.powertoprotein.eu/wp-content/uploads/water-research-101-2016-137-146-matassa-autotrophic-nitrogen-assimilation.pdf [Accessed 3 Jan. 2018].

Martin, B. (1995). Foresight in science and technology. Technology Analysis & Strategic Management, 7(2), pp.139-168.

Matche.com. (2014). Matches' Dryer cost - hollow-flight, drum, roto-louver, rotary,tray.. [online] Available at: http://www.matche.com/equipcost/Dryer.html [Accessed 1 Nov. 2017].

Munasinghe, P.C, Khanal, S.K. 2010. *Biomass-derived syngas fermentation into biofuels: Opportunies and challenges*. Bioresource Technology, vol. 101, issue 13, pp. 5013-5022.

Nelhydrogen. (2017). [online] Available at: http://nelhydrogen.com/assets/uploads/2017/01/Nel_Electrolyser_brochure.pdf [Accessed 5 Apr. 2018].

Nordpool. (2017). Market data | Nord Pool. [online] Available at: https://www.nordpoolgroup.com/Market-data1/#/nordic/table [Accessed 1 Nov. 2018].

NREL (n.d.). Energy Analysis | NREL. [online] Available at: https://www.nrel.gov/analysis/ [Accessed 1 Apr. 2018].

O'Connor, T., Yang, X., Tian, G., Chatterjee, S. and Lee, S. (2017). Quality risk management for pharmaceutical manufacturing. Predictive Modeling of Pharmaceutical Unit Operations, pp.15-37.

Oesterholt, F., Matassa, S., Palmen, L., Roest, K. and Verstraete, W. (2017). *Pilot scale production of single cell proteins using power-to-protein concept*.

Onarheim, K., Santos, S., Kangas, P. and Hankalin, V. (2017). Performance and costs of CCS in the pulp and paper industry part 1: Performance of amine-based post-combustion CO 2 capture. *International Journal of Greenhouse Gas Control*, 59, pp.58-73

Onarheim, K., Santos, S., Kangas, P. and Hankalin, V. (2017). Performance and cost of CCS in the pulp and paper industry part 2: Economic feasibility of amine-based post-combustion CO 2 capture. *International Journal of Greenhouse Gas Control*, 66, pp.60-75

P.L. Spath and D.C. Dayton, 2003. Preliminary Screening - Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas. NREL/TP-510-34929

Peters, M.S., Timmerhaus, K.D., West, R.E., Timmerhaus, K. and West, R., 1968. *Plant design and economics for chemical engineers* (Vol. 4). New York: McGraw-Hill.

Porter, A., Roessner, J., Jin, X. and Newman, N. (2002). Measuring national 'emerging technology' capabilities. Science and Public Policy, 29(3), pp.189-200.

Reiter, G. and Lindorfer, J. (2015). *Evaluating CO2 sources for power-to-gas applications – A case study for Austria*. [online] www.elsevier.com/locate/jcou. Available at: http://dx.doi.org/10.1016/j.jcou.2015.03.003 [Accessed 20 Oct. 2017].

Rotolo, D., Hicks, D. and Martin, B. (2015). What is an Emerging Technology?. Research Policy, 44(10), pp.1827 - 1843.

Saunders, M., Lewis, P. & Thornhill, A. 2009. *Research methods for business students*. 5th ed. Harlow: Prentice Hall.

Small, H., Boyack, K. and Klavans, R. (2014). Identifying emerging topics in science and technology. Research Policy, 43(8), pp.1450-1467.

Sillman, J. (2016). *Sustainability of protein production by bioreactor processes using wind and solar power as energy sources*. [online] Wilma.finna.fi. Available at: https://wilma.finna.fi/Record/doria_lut.10024_124654 [Accessed 20 Oct. 2017].

Sinnott, R. and Towler, G. (2009). Chemical engineering design. Oxford: Butterworth-Heinemann, pp.52 -148.

Siriwongwilaichat, P. (2001). Technical information capture for food product innovation in Thailand. PhD Thesis. Massey University, New Zealand.

Stahl, B.C., 2011. What does the future hold? A critical view of emerging information and communication technologies and their social consequences. In Researching the Future in Information Systems (pp. 59-76). Springer, Berlin, Heidelberg.

Swanson, R., Platon, A., Satrio, J. and Brown, R. (2010). Techno-economic analysis of biomass-to-liquids production based on gasification. Fuel, 89, pp.S11-S19.

Tanaka, K., Miyawaki, K., Yamaguchi, A., Khosravi-Darani, K. and Matsusaki, H. (2011). Cell growth and P(3HB) accumulation from CO2 of a carbon monoxide-tolerant hydrogen-oxidizing bacterium, Ideonella sp. O-1. *Applied Microbiology and Biotechnology*, 92(6), pp.1161-1169.

Tredici, M., Rodolfi, L., Biondi, N., Bassi, N. and Sampietro, G. (2015). *Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall Panel (GWP®) plant*. [online] www.elsevier.com/locate/algal. Available at: http://dx.doi.org/10.1016/j.algal.2016.09.005 [Accessed 20 Oct. 2017].

USDA (2011). Solar Energy Use in U.S. Agriculture Overview and Policy Issues. [online] USDA. Available at: https://www.usda.gov/oce/reports/energy/Web_SolarEnergy_combined.pdf [Accessed 1 Apr. 2018].

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2009). Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water

Electrolysis. [online] Golden, Colorado: National Renewable Energy Laboratory. Available at: https://www.hydrogen.energy.gov/pdfs/46676.pdf [Accessed 1 Nov. 2017].

Vainikka, P. (2017). *Power-to-X.*

Vartiainen, E. (2016). Solar energy technologies, markets and competitiveness.

Volova, T.G, Barashkov, V.A. 2010. *Characteristics of Proteins Synthetisized by Hydrogen-Oxidizing Microorganisms*. Applied Biochemistry and Microbiology, vol. 46, No. 6, pp.574-579.

Volova, T.G, Kislev, E.G, Shishatskaya, E.I, Zhila, N.O, Boyandin, A.N, Syrvacheva, D.A, Vinogradova, O.N, Kalacheva, G.S, Vasilev, A.D, Peterson, I.V. 2013. Cell growth and 112 accumulation of polyhydroxyalkanoates from CO2 and H2 of a hydrogen-oxidizing bacterium, Cupriavidus eutrophus B10646. Bioresource Technology 146, pp. 215-222.

Yu, J. 2014. *Bio-based products from solar energy and carbon dioxide*. Trends in Biotechnology, vol. 32, issue 1, pp. 5-10.

Zhang, W, Liu, H, Sun, C, Drage T.C, Snape, C.E. 2014. Capturing CO2 from ambient air using a polyethyleneimine – silica adsorbent in fluidized beds. Chemical Engineering Science, vol. 116, pp. 306-316

Zhang, F, Ding, J, Shen, N, Zhang, Y, Ding, Z, Dai, K, Zeng, R.J. 2013. In situ hydrogen utilization for high fractionacetate production in mixed culture hollow-fiber membrane biofilm reactor. Applied Microbiology and Biotechnology, vol. 97, issue 23, pp. 10233-10240.