

Opinnäytetyö (AMK)

Biotekniikka

NBIOTs12W

2016

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Feasibility analysis for power to biogas

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FEASIBILITY ANALYSIS FOR POWER TO BIOGAS

Biokaasun eri tuotantomenetelmien analysointi

Fossiilisten polttoaineiden käyttö on vähentynyt maailmanlaajuisen innovoinnin myötä. Näiden käytön korvaamiseen on etsitty jo pitkään kestävä kehityksen energiavaihtoehtoja. Tämän kaiken tavoitteena on saavuttaa kestävyttä energian käytössä, toisin sanoen tuottaa energiaa ilman, että se tuottaa haittaa seuraaville sukupolville. Viime aikoina vety on osoittautunut kiinnostavaksi vaihtoehtoisen energian tuotannossa. Vedyn tuotannossa on monia epäselvyyksiä, mutta tärkeintä on, että puhtaasta polttoaineesta syntyy puhdasta jätettä. On olemassa kaksi tapaa tuottaa vetyä: sen reformointi ja hydrolysointi. Opinnäytetyössä keskitytään vedyn tuotantoon elektrolyysimenetelmällä, joka perustuu hydrolysointiin.

Opinnäytetyön tavoitteena oli laajentaa Suiker Unie -nimisen sokerialan yrityksen metaanin tuottoa ja määrittää sen kustannuksia kahdella eri tuotantotavalla. Nykyinen tapa tuottaa metaania on käyttää mädätystankkia, jossa biohajoavana tuotteena käytetään sokerituotannossa syntynyttä orgaanista jätettä. Ensimmäinen suunniteltu tuotantotapa on käyttää mädätystankkia siirrostamalla vetyä tankkiin. Vedyn siirrostus kasvattaa metaanin tuottoa. Toisessa metaanin tuotantotavassa käytetään biometanointitankkia mädätystankin lisäksi. Biometanointitankin käytön tarkoituksena on kierrättää metaanin tuotannossa syntynyttä hiilidioksidia ja muuttaa sitä metaaniksi. Opinnäytetyössä päädyttiin yhteisymmärryksen kustannuksiin, kun määriteltiin tuotannon pääoma- ja toimintakustannuksia.

Johtopäätöksenä voidaan sanoa, että tutkittu menetelmä on ympäristöystävällinen. Sillä ei havaittu olevan haittavaikutusta ympäristöön tai työntekijöihin. Tuottavuuden kasvussa biometanointimenetelmä tuotti vaikuttavinta tulosta ja oli tässä opinnäytetyössä kestävin menetelmä tuottaa metaania.

Projektin laskelmien mukaan näillä menetelmillä ei saavutettu yritykselle taloudellista tuottoa. Yrityksellä on mahdollisuus valita mikä tahansa seuraavista taloudellisista vaihtoehtoista: Yritys voi investoida nykyisen tuotannon laajentamiseen ja lisätä tuotannon laajuutta. Näin tuotannon hinta on silti alhaisempi kuin myyntihinta, ja investoitu pääoma voidaan saada vuosien varrella takaisin voittojen avulla. Toinen vaihtoehto on pyrkiä mihin tahansa aiemmin mainituista menetelmistä, mutta intensiivisemmällä taloudellisella suunnitelmalla ja käyttäen tukimuotoja, kuten yrityslainaa tuoton saavuttamiseksi. Viimeinen vaihtoehto on odottaa ja seurata, miten markkinat muuttuvat.

ASIASANAT:

bio-gas, bio-methane, anaerobic digestion, electrolysis & wind turbine

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FEASIBILITY ANALYSIS FOR POWER TO BIO-GAS

With the progression of innovative global trends the motive to move away from fossil fuels is strong. This is a result of fossil fuels becoming scarcer in the near future due to their finite amount on the planet. This has driven a need for a shift away from fossil fuels as the standardized source of global energy, and thus for bringing about new innovations ready for exploitation. This is all being pursued with the undertone of accomplishing sustainability in energy policies. Sustainability requires the ability to produce energy without jeopardizing future generations' ability to follow in our footsteps. For decades now hydrogen has been on the tip of many entrepreneurs tongues for an alternative fuel for running infrastructure and transport. It has multiple implications but most important of all it is a clean fuel producing clean waste. There are round about ways of getting hydrogen as a product. The 2 most popular methods are steam reforming and water electrolysis. In this thesis the mode of interest will be hydrogen production via electrolysis

At the beginning of this thesis project, the goal was to determine the cost of production of methane for three different scenarios. The first scenario (current situation) where methane is produced conventionally, with the use of a digester tank. The second scenario (case1) were methane is produced by means of a digester tank with hydrogen inoculated and the third scenario (case2) were methane is produced by means of a digester tank and a bio-methanation tank. The cost of production was determined through an aggregation of the capital cost and the operational cost of the three different processes and a consensus was reached. In conclusion from the results presented it is safe to say that the operations investigated are environmentally safe and would not have any adverse impact on the environment or operational workers. In terms of the increase of productivity, digestion with a bio-methanation tank yielded the most impressive results and is the most sustainable method of producing bio-methane for natural gas conversion. However, financially none of the newer techniques are feasible because they do not produce any profit. The advice to the client is that they need to choose any of the following options. They could invest in expansion of current production and increase the scale of production. By doing so the production price is still lower than the selling price and invested capital can be retrieved through profits over the years. The other option is to use any of the other techniques but with an intensive financial plan using liabilities such as loans and credits to achieve profits. The final option is to wait and see how the market changes. Even if not feasible now, the scenarios might be feasible in the future.

KEYWORDS:

bio-gas, bio-methane, anaerobic digestion, electrolysis & wind turbine

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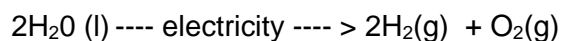
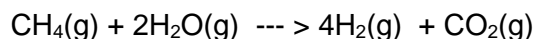
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1 INTRODUCTION

In this thesis the focus is set on comparing the characteristics of 3 different processes and their financing. Hydrogen is being synthesized to act as feed stock for methanogenesis. The commissioner of this thesis, Suiker Unie, have their own facility which they have invested in for digesting their waste from sugar beet into biomethane. The true capacity for methane can be produced has been unexploited. Due to a recent inquiry on the subject by Suiker Unie, technologies are present for hydrogen to be utilized in increasing biomethane yields in anaerobic digestion. The client is interested in 2 different possibilities for an expansion investment, one of which is a bio-methanation process and a hydrogen inculcation (into anaerobic digester). In the thesis's life span of 20 weeks Avans University of Applied Science is to look into the question of whether it is feasible to invest in this new technology and whether the capital can be regained through turnovers.

With the progression of innovative global trends the motive to move away from fossil fuels is strong. This is a result of fossil fuels becoming scarcer in the near future due to their finite amount on the planet. This has driven a need for a shift away from fossil fuels as the standardized source of global energy and thus for bringing about new innovations ready for exploitation. This is all being pursued with the undertone of accomplishing sustainability in energy policies. Sustainability means to produce energy without jeopardizing future generations' ability to follow in our footsteps. For decades now hydrogen has been on the tip of a lot of entrepreneurs tongues for an alternative fuel for running infrastructure and transport. It has multiple implications but most important of all it is a clean fuel producing clean waste. There are round about ways of getting hydrogen as a product. The 2 most popular methods are steam reforming and water electrolysis. In this thesis the mode of interest will be hydrogen production via electrolysis.



Formula 1. The first formula is the steam reforming process and the second is electrolysis process.

What makes electrolysis most fascinating is that it can be coupled with other forms of energy. In practice it is just a process that acts as an energy converter and uses hydrogen as an energy carrier. Rather than use steam reforming which utilizes natural gas from fossil fuels, hydrogen can be produced from energy derived from a renewable source. Energy sources for possible incorporation could range from solar, hydro, biomass or even geothermal; however the spear head of focus is on wind as a renewable source of energy. By coupling an electrolyser to a wind turbine it is possible to synthesize hydrogen using wind energy.

The goal of this thesis is to determine the cost of production of methane for 3 different scenario models, a model where methane is produced conventionally, with the use of a digester tank, a model where methane is produced by means of a digester tank with hydrogen inoculated and a model where methane is produced by means of a digester tank and a biomethanation tank. The cost of production would be determined through an aggregation of the capital cost and the operational cost of the 3 different processes. This thesis will be completed in 20 weeks.

2 THEORY

In this part of the thesis the theory of biogas, the effect of hydrogen addition and the importance of wind turbines are discussed.

2.1 Biogas

Biogas is the term given to a group of elements and compound molecules produced through the biotransformation of various types of biological matter. Chemicals within this group are water vapor (H_2O), hydrogen (H_2), carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), and methane (CH_4). These are the by-product of and anaerobic metabolism of biomass by microbes for their energy supplies. Typical sources that are used as feed stock to produce biogas are sewage sludge, organic waste, energy crops and manure. In the municipal treatment of waste from house olds and communities in general, sludge is digested in a bio reactor in order to increase the energy recover from the waste stream. Similarly the digestion of organic waste in waste plant get also digested for the same for the same purpose of getting as much out of the waste streams. Energy crops are plant life specifically grown for the sake of producing bio fuel and gas. They are low cost and low resource agricultural produces. Manure is a great source for bio gas because it is rich in methane and there is a large supply of it. Manure comes largely in relation with the animal feed stock in agriculture.

Based on the source of biogas it is possible that the produced biogas may differ in composition of compound gasses within it. An example of this is in biogas produced by manure, the methane concentration would be exceptionally high because the feed for the animals would be carbohydrate based and thus a high methane percentage yield. Nitrogen and sulfur based compounds would be more present in sources like sludge or waste from waste plant because of the wider array of molecules that are present. (1)

2.1.1 Application of biogas

As biogas's importance in society continues to flourish so do the different techniques of its application in day to day life. The biogas offers a wide variety of use possibilities. This is also mainly due to the circumstance that biogas refers to a number of compounds (not just methane, which is the focus of this thesis).

Methane (CH₄)

Not only is methane the most common component in biogas, it also has the largest variety of applications. As a hydrocarbon it is nonpolar, odorless and combustible. The more important property lies in its combustibility. There are many motorized systems that rely on methane as a fuel. It produces a relatively large amount of energy in the form of mostly heat and light when combusted. Therefore methane is largely used as a fuel source for cooking. This can also be related to its use as a heating agent because it can be used to heat water which can be used for washing, or circulated around a home for house warming purposes. Methane is also used in the production of electricity. The gas is used to power the electrical generator in order to produce energy for an energy grid. (2)

Carbon dioxide CO₂

Carbon dioxide, although controversial, has its uses. It is widely used in greenhouses in agricultural areas in order to grow crops more effectively. It is used as an additive for the production of many industrial chemicals. It is also used as a preservative in the food industry, for the preservation of packaged goods and drinks. (3)

Nitrogen N₂

Nitrogen is primarily used as a reactant in the Haber process. This is the production of ammonia from nitrogen and hydrogen. This is mainly crucial in agriculture because ammonia is a vital agent in the production of fertilizer for growing crops. It is also used industrially to synthesize other chemicals, ranging from pharmaceuticals to compounds containing the element. As a liquid it is used for refrigerating and skin therapy. (4)

Hydrogen H₂

Hydrogen is the most common element there is. However, in biogas it makes up a small percentage. Hydrogen possesses some unique properties making it widely used in current industry. As mentioned previously it is used for producing ammonia in the Haber

process. It is also used as a reducing agent for the synthesis of many compounds and chemicals. In the food industry it is used as a means of creating oils from fat. It is also the lightest element available, so it is used as a lifting agent. Hydrogen is also used in fuel cells to produce electricity. (5)

Hydrogen sulfide H₂S

Hydrogen sulfide is an aspect of biogas that is met with much distaste. This is at large understandable because of its foul odor. However it has its uses, mainly in the precipitation of metal ions, formation of organic compounds, and in other industry specific processes. (6)

Table 1. Biogas constituents with percentages and the compositions (7).

| Compound | Formula | Percentage range (%) |
|------------------|------------------|----------------------|
| Methane | CH ₄ | 50-75 |
| Carbon Dioxide | CO ₂ | 25-50 |
| Nitrogen | N ₂ | 0-10 |
| Hydrogen | H ₂ | 0-1 |
| Hydrogen sulfate | H ₂ S | 0-3 |
| Oxygen | O ₂ | 0-0 |

2.1.2 Storage

When biogas is produced it needs to be stored as it will not always be used on site. This can be done for a number of reasons. There could be a large surplus of gas to the point where it cannot all be used although it is needed. Biogas can also be stored for the purpose of upgrading and it quite simply might need to be stored because it is needed at another location and need to be transported. When biogas is upgraded, the carbon dioxide and hydrogen sulfides are removed and it becomes bio-methane.

Table 2. Showing the different biogas storage means and specifications (8).

| DURATION OF STORAGE | PRESSURE (KPA) | STORAGE DEVICE | MATERIAL | SIZE (M³) |
|----------------------------|-----------------------|-------------------------|-------------------------------|-----------------------------|
| SHORT TERM | <0.68 | Floating cover | Reinforced plastic and rubber | Variable volume |
| | <13.7 | Gas bag | Reinforced plastic and rubber | 4.24-311 |
| | 13.7-41.3 | Water sealed gas holder | Steel | 99.1 |
| | | Weighted gas bag | Reinforced plastic and rubber | 24.9-792 |
| | | Floating roof | Reinforced plastic and rubber | Variable volume |
| LONG TERM | 68.9-19992 | Propane/butane tank | Steel | 56.6 |
| | >19992 | Commercial gas | Alloy steel | 9.910 |

A lot of different options exist for storing biogas but the choice is tailored to client situation specifications. Storage systems could be simplified to being high pressured or low pressured. Before storage it is always recommended to pretreat the biogas because hydrogen sulfide and any present water can cause corrosion of tanks of a certain material.

In the case of storing biomethane, a common technique is converting the gas into a liquid. By turning the gas into a liquid a few advantages are created. Transporting biomethane becomes cheaper due to the larger content/ volume. It is also favorable for installations because it enables easier inoculation. However, it is also disadvantageous because over long storage periods of over a week, temperature increases would result in evaporation of bio-methane. If this is allowed to happen the economic loses can be high. (8)

The bio-methane can be suitable for direct use as vehicle fuel or it can be fed into the natural gas network. Therefore bio-methane requires to be in a higher purity standard in order to transfer via natural gas network.

1.1.1 Natural gas network

A natural gas network is a transportation system for fossil fuel. It is a network of pipelines and operation stations over the topography of an area. Like the name implies the transported materials is natural gas; however, this is a collection of multiple compounds. The content is mostly hydrocarbons such as methane, ethane, propane and butane. Gases such as carbon dioxide, nitrogen and hydrogen sulfide are also present, however, in considerably small concentrations.

Table 3. Natural gas constituents (9).

| COMPOUND | FORMULA | PERCENTAGE RANGE (%) |
|--------------------------|--------------------------------|-----------------------------|
| METHANE | CH ₄ | 87.0 - 97.0 |
| ETHANE | C ₂ H ₆ | 1.5 - 7.0 |
| PROPANE | C ₃ H ₈ | 0.1 - 1.5 |
| ISO-BUTANE | C ₄ H ₁₀ | 0.01 - 0.3 |
| CARBON DIOXIDE | CO ₂ | 0.1 - 1.0 |
| HYDROGEN SULPHIDE | H ₂ S | trace - 0.2 |
| OXYGEN | O ₂ | 0.1 - 0.1 |

Natural gas is normally transported by first lightly compressing the mixture into a liquid, referred to as natural gas liquid. This is typically done in the oil production facilities where natural gas is extracted. The use of vehicular transport is common when dealing with natural gas liquids before they are introduced into a network. In such cases the gases are compressed under a pressure of 275 kPa. (10) When inoculated into a pipeline network the pressure that the liquid travel, at can be as high as 1723 kPa. (10)

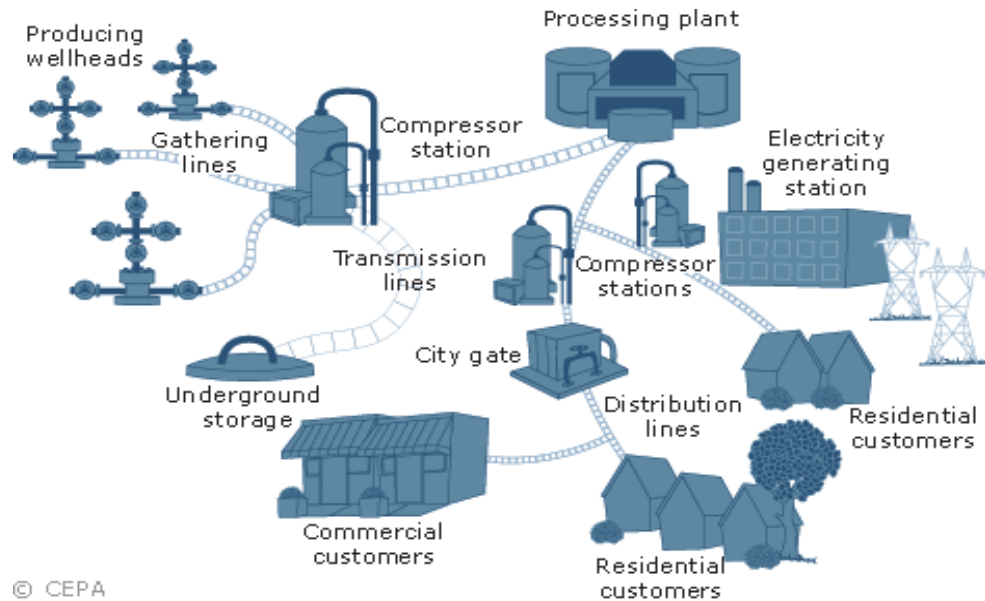


Figure 1. Depiction of a general Natural gas network (note: the configuration is subject to variations). (32)

A natural gas network is an intricate composition of different interrelated pieces that are widely used to serve different functions. These installations are most of the time buried in order to evade unnecessary exposure and accident risks. However when the pipeline network intersects with a valley or river it is designed to be on the surface. The advantages of having the installation underground is that it becomes slightly easier to protect against corrosion, because the contaminants are more predictable. In sub surface cases the mode of protection is cathode protection. By electrically changing the potential difference of the pipe to be negative, it does not react with the compounds in surrounding the soil. There are 3 main pipe types that serve functionalities in networks when it comes to the distributions and transportation of natural gas (liquids). These are gathering pipelines, transmission pipelines and distribution pipelines.

Gathering pipelines – These are a group of smaller phase pipes with the function of feeding natural gas from production sites towards a nexus. These pipes are normally short and narrow in diameter

Transmission pipelines – These are longer and larger pipes. They are normally the best option of trans-city/county transportation of gas. They can be as long as 435200 km in length and 50-106 cm in diameter. They can also be coupled with compressor stations for the purpose of keeping pressure constant over long distances.

Distribution pipelines – Similar to gathering pipes these are smaller networking pipes used for end phase processes. These pipes are used for the delivery of gas to household areas and business facilities.

The technology behind the functioning of a large scale natural gas network is somewhat complex although it is simple. By integrating various processes and applying them a synergic system for transportation is shaped. The number of parts that make up a gas network can be rather ambiguous. It is something that is tailored to the purpose and scale of the system. Nevertheless, a few common components can be observed.

Injection stations/gathering systems – In any gas network this is a constant. It is the initial point where the pressurized gas or liquid is introduced into the system. It is comprised of a series of pumps and compression gears. It is also optional to treat and remove any concentration of impurities that can be found in the medium. This includes carbon dioxide, water or hydrogen sulfides.

Transmission systems – these are the actual pipes that transport the gas/liquid for the bulk of the distance. The pipelines carry mediums that are under pressures ranging from 1378-10342 kpa. These pipes are designed to handle much more pressure but these pressures are never reached.

Compression/ pump stations- depending on whether a gas or a gas liquid is being transported, compression units or pumps can be found along the pipe route. Compressors are found when transporting gases in order to keep the pressure constant, especially over the greater distances. Pumps stations are found when transporting liquid gases at a constant flow rate. The frequency of these stations is related to the topography of the pipe channel.

Line pack – When a gas network is in use, 80 km of transmission pipes can contain up to 5,000,000m³ of natural gas. This is what is referred to as a “line pack”. The importance of the line pack comes into play when supply and demand of pipe content come into play computer modules manipulate the pressure of the line pack in order to store gas/liquid within the pipes. This way there is always gas available for the consumer.

Block valve station – these are installations that can be located at approximately every 48 km on a pipeline network. They are primarily used for maintenance or to limit losses when pipes are damaged. The function is to stop the flow of the gas/liquid.

The distribution system – in the final stages of the network the gas come to a distribution system where it is then distributed the client. The process begins with the gas coming through a gate station where the flow rate of gas is measured. It is then decompressed to and an odorant is added to the gas for leak detection. After the gate station the gas is fed into distribution pipes about 5-60 cm in diameter and is sent to consumers. The operation pressure is variable.

2.1.3 Anaerobic digestion

Anaerobic digestion is the natural process of microbial life breakdown biodegradable matter. In a series of steps it involves decomposition of carbohydrates, fats and proteins in the absence of oxygen producing biogas and the energy necessary for cell life in the form of ATP. It is a world renowned process that can be found in nature as well as the food and agricultural industry. In nature it is a form of decomposing matter and releasing nutrients back into the atmosphere. In the food industry it is present in the form of fermentation where yeast are used to make bread rise, or produce alcohol in beverages.

In agriculture it is used as a result of the large amount of waste that is produced as a form of crop and manure. By anaerobically digesting manure or biomass the biogas, methane can be used to meet some of the on-site energy demands of a farm and also surplus gas can be fed into a natural gas network. As a result of the latter development interested in anaerobic digestion as boomed in this era for sustainability. An advantage to it is that alternatives for electrical energy generation is produced, moving away from the current situation which is primarily fossil fuel dependent. A disadvantage is that development have moved towards the direction of growing crops specifically for the purpose of anaerobically digesting them, turning biomass into bio-methane. This raises the issue of competition between energy crop and the growing demand for agricultural produce for feeding. To be more accurate the biological process of interest for this thesis is methanogenesis. (11)

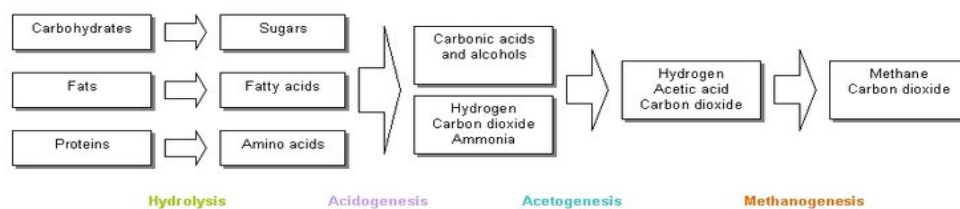


Figure 2. Flow chart of the processes leading methanogenesis (18).

The process of anaerobic digestion is actually a collection of process, hydrolysis, acidogenesis, acetogenesis and most importantly methanogenesis. These processes are a result of activity of group of microbes known as methanogens. Methanogen belong to the group of bacteria called archaeobacteria. Within the genus for producing bacteria, many different species exist and so do the conditions they thrive in. Over all methanogens can live in a wide range of temperature; starting from below 0°C to above 100°C however methane is produced in temperature ranging from 15°C-85°C. They are also subject to living in fresh to saline environment and thriving quite comfortably. The optimal pH for methanogenesis to occur is favorably differs from species to species.it is common the best results show in a pH near neutral or at 6. (12)

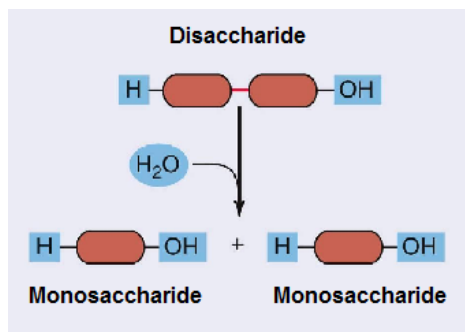


Figure 3. Hydrolysis of a glycosidic bond between a disaccharide (20).

Hydrolysis – hydrolysis involves the breaking down of macromolecules into smaller sub-units. It is an enzymatic process within microbes when they come in contact with polymers. In order to make the compound more water soluble the long chains which bind each macromolecule is hydrated and split using water.

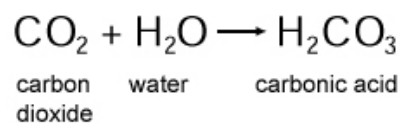


Figure 4. Formation carbonic acid (21).

Acidogenesis – the next step proceed to converting the products of monosaccharaides, amino acids and fatty acids into smaller acid molecule. In the process of breaking down monosaccharides they are turned into carbonic acid.

Acetogenesis – the next step involved the conversion of hydrocarbon based acids into acetic acid which is the final precursor for the final step of producing methane.

Methanogenesis – Final phase of the process is methanogens were acetic acid is oxidized to methane.

2.1.4 Upgrading biogas technologies

There are several unwanted component in the biogas which decrease the efficient of the use of biogas, so that they need to be removed. Those concentration depend on the composition of the input for the anaerobic. In this study, only carbon dioxide is mentioned as a primary achiment for enriching biogas in order to enhance the energy value of the biogas. At the current situation, there are several technologies that are already available for upgrading the biogas by reduceing the CO₂ within the biogas, this can result in a growth in energy density for natural gas network. (13)

Water/amine scrubbing

This techniques can be utilized to remove both carbon dioxide and hydrogen sulphide from biogas due to their high solubility in water and amines solvent compared with methane. The biogas is pressureized at about 9-12 bar and fed to the bottom of a packed collumn where the solvent is pumped on the top in the counter current flow. By this, the scrubbing column is packed with high surface area media to provide a significant contact between solventand the biogas. (14) CO₂ is dissolved within a flash tank during the biogas moving against the water flow. In the end, the upgraded biogas leaves the top of the comlumn. The flask tank also can capture some dissolved CH₄ by depressurising the water at 2-4 bar and then return the CH₄ back to the bottom of the column.

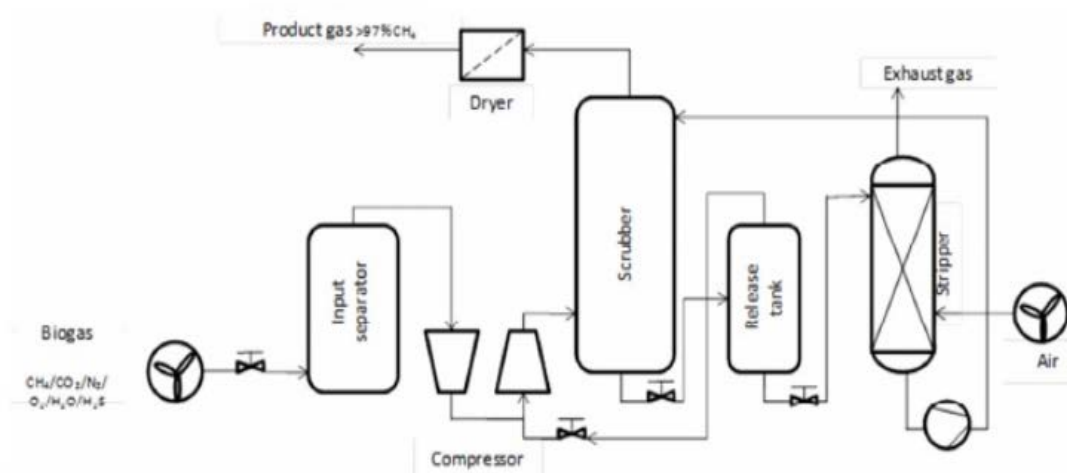


Figure 5. Flow sheet for water scrubbing technology (Adapted after ISET, 2008).

This method is also effective to remove other substance such as: H₂S, however, moisture and particulates within the raw biogas must be removed before the process.

Pressure swing absorption (PSA)

Pressure swing absorption, is known as carbon molecular sieves, is composed of vessels in series which are filled with absorbent media to remove carbon dioxide, oxygen, nitrogen, etc.,. Dry biogas goes through the bottom of absorber in which operates in an alternating cycle of adsorption, gases like CO₂, N₂, O₂ are absorbed on to the surface of the media though vessel. It results in the gases release on the top with a purity of at least 97% of CH₄. (14)

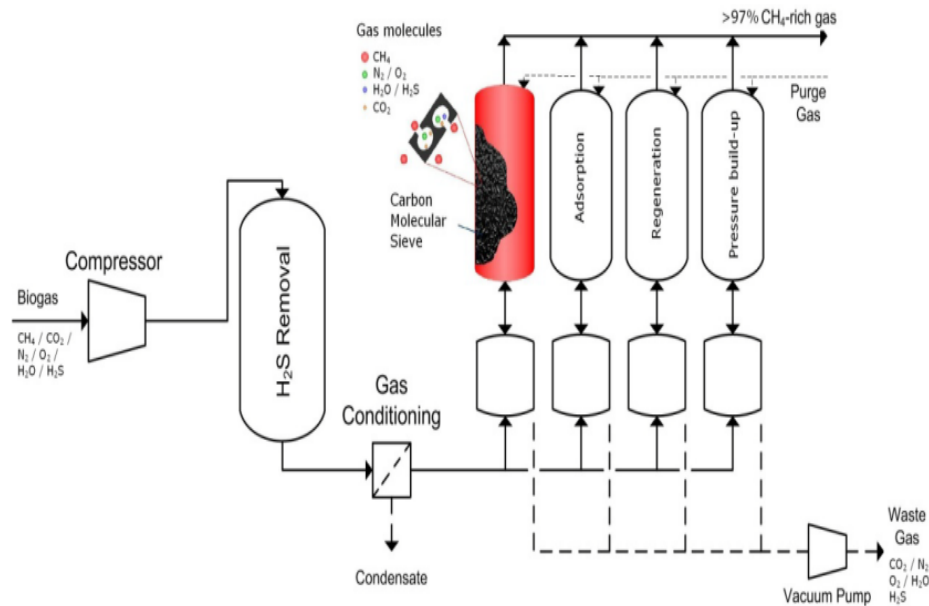


Figure 6. Diagram of Pressure swing absorption (26).

There are 4 phases occur in the absorber:

1. Pressure build-up: the pressure is built up by equilibrating pressure with a vessel and then the raw biogas is injected. The higher the pressure, the more gas can be absorbed.
2. Adsorption: all of gaseous CO_2 , N_2 , O_2 , H_2S are absorbed in this phase by the media and only CH_4 can be released. However, H_2S can poison the adsorption material so a preliminary H_2S removing is required before the operation of PSA process.
3. Depressurization: by balancing with the second pressurizing vessel and regeneration, the leaving gas is able to be re-circulated with CH_4 at high concentration.
4. Regeneration: by desorbing the adsorbed gases, the bed can be regenerated which is occurred by decreasing the pressure in the bed while some of the concentrated gas product can be used to back-flush the bed. To reduce the energy consumption a compressor capital by using gas pressure from one vessel for the other. (14)

This technique requires 4-9 vessels working in parallel to keep the process stable while it requires low power demand, emission and is able to remove N_2 and O_2 . The considerable drawback of this technique is that H_2S removal step is obligatory.

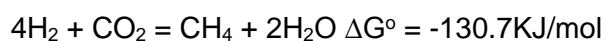
Membrane separation

There are 2 ways for removing CO₂ with membrane purification:

- High pressure gas separation: with high pressure gas separation on both side of the membrane. The activated carbon bed is used to remove pressurized gas at 36 bar to remove hydrocarbons and hydrogen sulphide. And then the gas is filtered through a particle filter and a heater, the waste gas can be recycled to recover more methane. In the last stage, the gas is upgraded to get biogas with 96% of methane or more.
- Gas-liquid absorption membranes: the gasous is sepeated from a micro-porous hydrophobic membrane from the liquid phase. The molecules from the gas stream are diffused through the membrane in one direction and absorbed on the other side by the liquid flowing in counter-current at approx. atmospheric pressure (1 bar). (14)

2.2 The addition of hydrogen

For the biogas upgrading CO₂ together with H₂ can be seen as an significant to enrich the concentration of methane in the biogas by hydrogenotrophic methanogens. The CO₂ in the biogas reactor can be consumed by H₂ to be converted; in this case which lead to the decrease of CO₂.



With the same situation as in Netheland, in Denmark, the excess energy from windturbine can be use to produce H₂ by electrolysis so that H₂ is pumped within or without biogas reactor while the CO₂ can be collected from the biogas produced from digestion process. So the hydrogenotrophic methanogen process can be taken place.

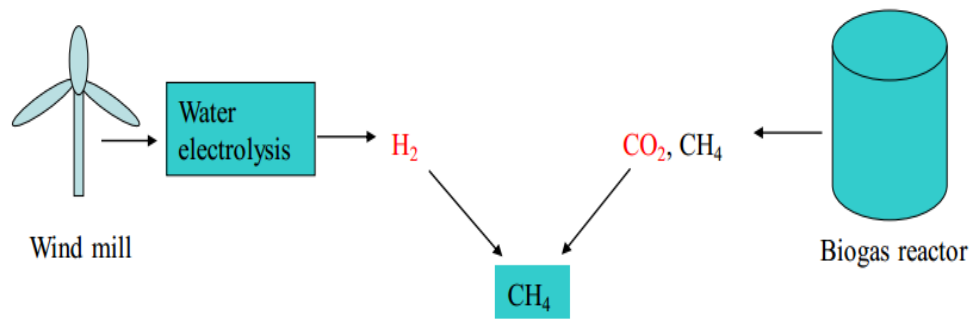


Figure 7. Upgrading biogas by hydrogenotrophic methanogens (15).

With this techniques, the amount of methane increases without any loss, moreover, the requirement for energy and chemical is minimal. As those advantage mentioned, the electricity can be stored in this way while it is cheaper to be contained and distributed CH_4 than H_2 with less requirement. There are 2 ways that this techniques can be applied for the process.

In-situ biogas upgrading

Produced hydrogen is led directly into the biogas reactor together with the organic waste so the hydrogenotrophic methanogens reaction occur inside the reactor. The addition of H_2 can decrease the CO_2 concentration considerably, while the pH can be increased due to H_2 so the pH needs to be controlled. It is researched that is not all of the H_2 consumed (about 80%) while other part left in the biogas.

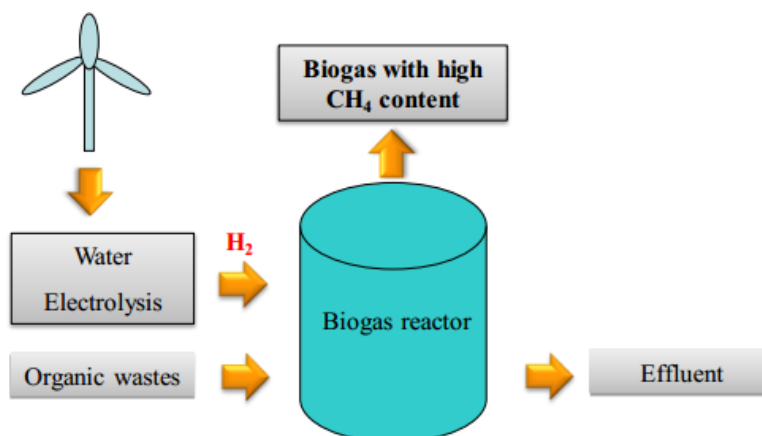


Figure 8. In-situ biogas upgrading (15).

There are several steps that occur for this process. The anaerobic digestion is launched in a bioreactor containing: substrate and anaerobic hydrogenotrophic methanogenic organisms, and then the bioreactor is fed with acidic waste with pH less than 5. Then biomass is added into the bioreactor before H_2 is injected into the bioreactor. In the end, the upgraded biogas can be collected.

Mainly the percentage of gas is about 55% CH_4 and 45% of CO_2 at pH about 7.3 however, by adding H_2 directly into the reactor, the concentration of CH_4 accounts for about 68%, while the for CO_2 is only 8% left, the other 24% is the excess H_2 with the pH at about 7.8. This result is proven by DTU Environment group in Denmark with cattle manure and whey from cheese factor. (15)

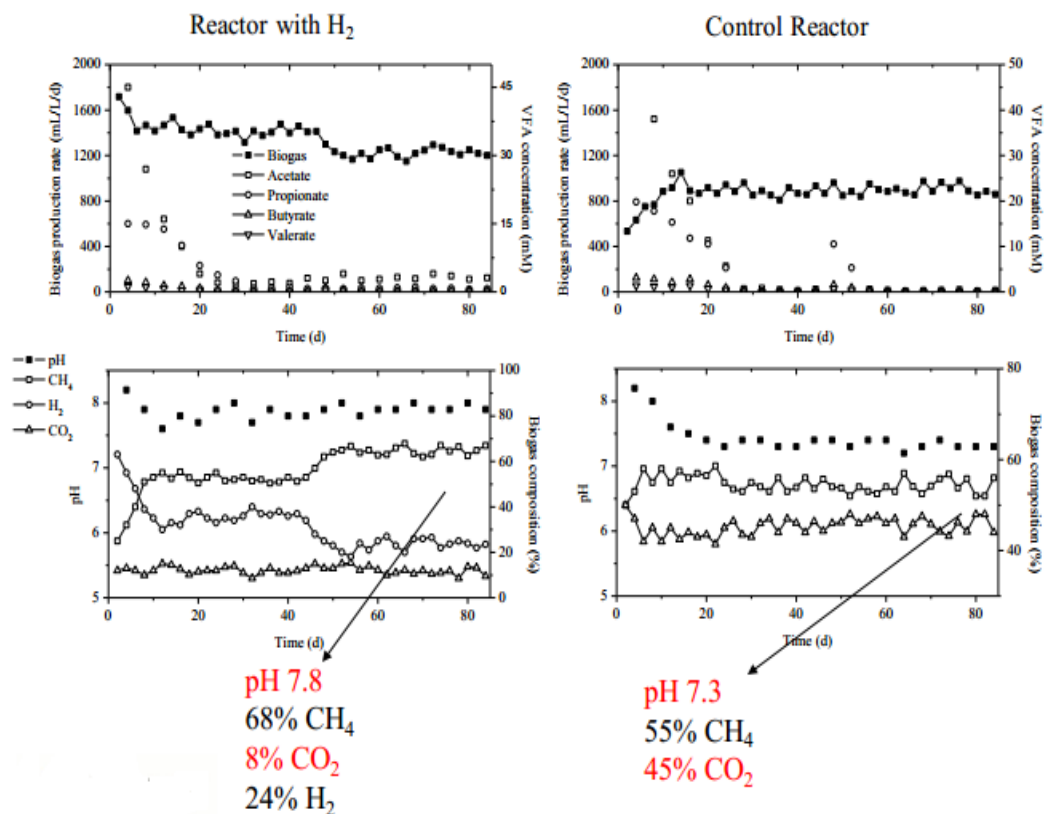


Figure 9. The result of experiment from DTU (15).

Based on this technique, the upgraded biogas has a CH_4 content of at about 90% without taking excess H_2 into account.

Ex-situ biogas upgrading

The separate reactor is needed for this techniques, where both H_2 and produced biogas contained at hydrogenotrophic culture and react to form biogas with high CH_4 content.

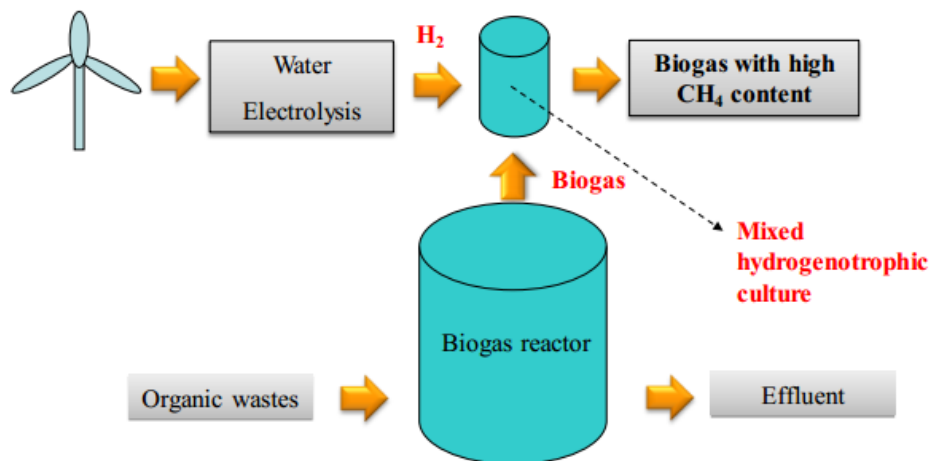


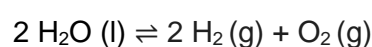
Figure 10. Ex-situ biogas upgrading (15).

Same as in-situ biogas upgrading for first steps. The anaerobic digestion is launched in a bioreactor containing: substrate and anaerobic hydrogenotrophic methanogenic organisms, and then the bioreactor is fed with acidic waste with pH less than 5. Then biomass is added into the bioreactor before H₂ is injected into the first bioreactor. After that, the produced biogas is transferred from the first bioreactor to a second bioreactor in which anaerobic digestion has been processed with nutrient and anaerobic hydrogenotrophic methanogenic organisms. For the next steps, the second bioreactor is fed with more nutrient and injected with H₂ gas. In the end, the upgraded biogas can be collected. (15)

In the enriched mixed cultures, the thermophilic temperature is remained at 55°C which lead to the bioconversion between CO₂ and H₂ with high rate of CH₄ which is 60% higher than going with Mesophilic temperature (37°C). The high CH₄ content gas need to be obtained under lower gas retention time (about 2h).

2.2.1 Electrolysis

In this paragraph the hydrogen production by electrolysis, or electrolyzer will be discussed. As already mentioned before, electrolysis is the chemical name for splitting water (H₂O) into hydrogen (H₂) and oxygen (O₂), resulting in the following reactive equation:



The principle of this electrolysis is that it consists of a continuous circulating current, directly through the water. This way the water molecules will be split into separate hydrogen and oxygen. In order to be able to send the current through the water, two electrodes must be separately and immersed into an electrolyte, which is in this case the water. These electrodes have to require certain conditions, for example they must be resistant to corrosion and they also must have a good electrical conductivity. Also the electrolyte must be restricted to certain conditions; it may of course not react with the electrolytes.

The electrolyzer must contain some kind of separation (a diaphragm) between the two electrodes in order to be able to separate the products, hydrogen and oxygen, which is generated at the electrodes. The three elements named above, the electrodes, the electrolyte and a diaphragm, are necessary to create an electrolyzer (electrolytic cell), see figure 13.

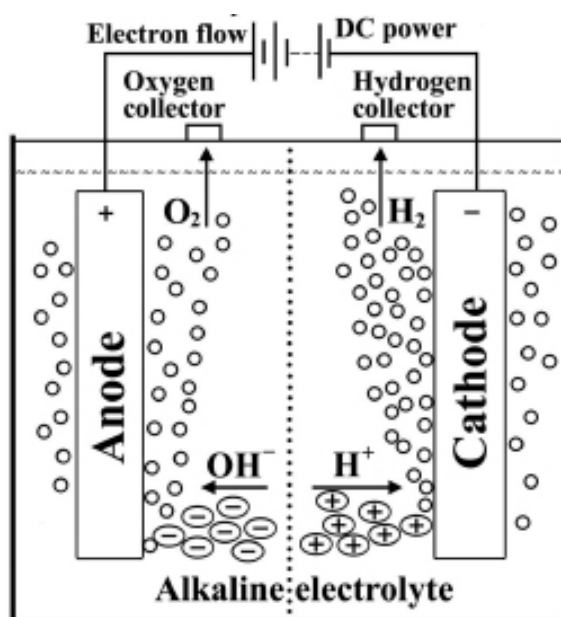
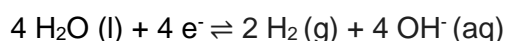
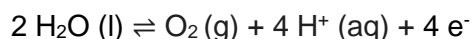


Figure 11. Schematic overview of electrolyzer. (16)

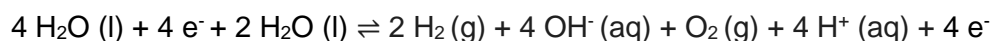
The products, hydrogen and oxygen, are released at the surface of the electrodes, the point where they are formed due to separation of water molecules. Then the reduction half reaction is happening at the cathode where hydrogen is formed (17):



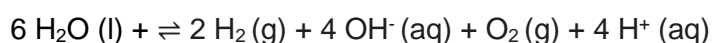
And the oxidation half reaction happens at the anode where oxygen is formed:



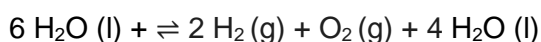
When you put the two half reactions together you get:



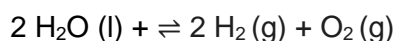
Then the water can be added together and the electrons can be scraped before and after the arrow:



The H^+ and the OH^- molecules will form water together (H_2O):



Then correct the amount of water molecules before and after the reaction in order to get the final result of the electrolysis reaction as how it was described in the beginning of the paragraph:



Electrolysis is one of the main methods to generate hydrogen from water. The hydrogen produced by this method can reach purities up to 99,999 vol % once the hydrogen is dried up and oxygen is removed. Traditionally the electrolytic hydrogen production plants were built nearby hydroelectric plants in order to be able to profit from the electric supply during the low priced hours. Nowadays the use of renewable energy becomes more interesting for the supply of electricity, although these opportunities are still limited due to research and development. From a technological viewpoint it can be stated that the advanced alkaline electrolyzers are at present sufficiently developed to be able to produce hydrogen in significant amounts. However it is already clear that in order to be able to meet the current industrial demand for hydrogen, the capacity of the electrolyzers must be much higher than the existing ones. Therefore research is already going on for PEM (polymer electrolyte membrane) electrolyzers, which are already available on the market, but are quite expensive while they seem to be more applicable for low-scale production. Also research is done for making solid oxide electrolyzers (SOEs), which can make hydrogen from steam, these are not available yet (figure 14).

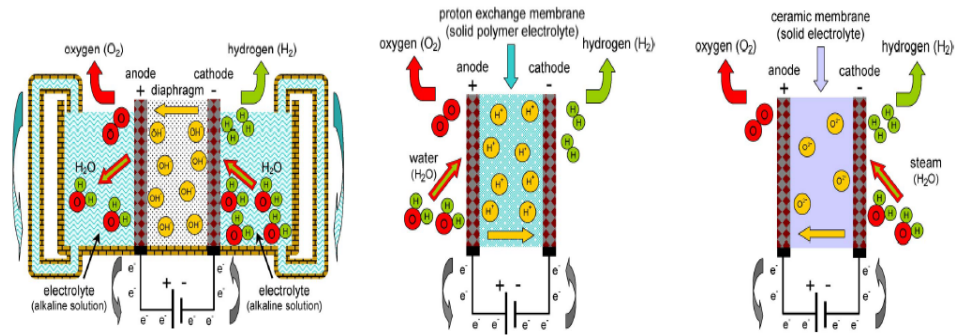


Figure 12. Schematic overview of alkaline electrolyzer (left), a PEM electrolyzer (middle) and a SOE (right) (18).

The electrolysis cell is the main element in the electrolytic hydrogen production concept. These cells, as described earlier, consisting of a cathode, an anode and a diaphragm, can be connected either parallel or in series. When the cells are connected in parallel (monopolar), the electrodes of each cell are connected to their own power supplier. When the cells are connected in series (bipolar), the same current will flow through all of the cells (figure 15).

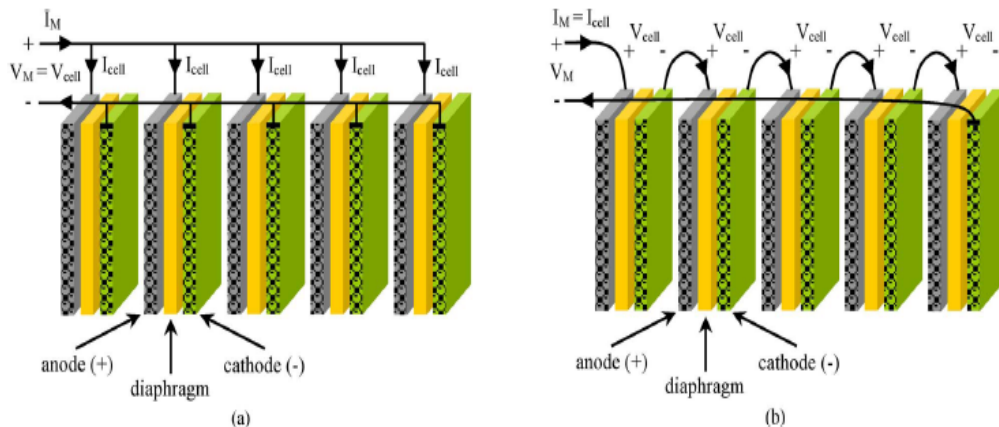


Figure 13. Electrolytic cells connected in parallel (a) and in series (b) (18).

Each of these types (parallel connected and series connected) has his own pro's and con's. So is the parallel connected cell a simple model, but it requires a lot of space. Series connected cells are a little more complex configuration, but are smaller in size. Also the fact that parallel connected cells each needs their own power supply, results in more external connections that comes with additional losses. Therefore also the current density of series connected cells are higher. Of course there is also a big difference in supply of voltage. The general hydrogen production is higher in parallel connected cells

above series connected cells. Another advantage of parallel connected cells is that reparation or maintenance can be easily done without disturbing the production process of hydrogen. There is also an option to mix compartments with both parallel and series connected cells. To get an idea of the different kind of electrolyzers that are on the market at the moment, an overview with different manufacturers and performance data is given in table 4 (18). The table gives the specifications of PEM cells from 22 different manufacturers from North American and Europe. The majority of the electrolyzer cells are alkaline water electrolyzers and are connected in series (bipolar). With an efficiency between 42.9% and 82.3 % all cells have a production purity ranging from 99.3%-99.9%; However the specific energy consumption does not sure much variation between each model (between 4-6), given the difference in size.

Table 4. Overview of electrolyzer manufacturers and their performance data (18).

| Manufacturer | Technology (configuration) | Rated production (Nm ³ /h) ^a | Rated power (kW) ^b | Specific energy consumption (kWh/Nm ³) ^c | Efficiency (%) ^d | Maximum pressure (bar) | Hydrogen purity (vol.%) | Location | Ref. |
|--|-----------------------------------|--|-------------------------------|---|-----------------------------|--|----------------------------------|-------------|------|
| AccaGen | alkaline (bipolar) | 1-100 | 6.7-487 | 6.7-4.87 ^g | 52.8-72.7 | 10 (optional 30 and 200 ^f) | 99.9 (99.999 ^k) | Switzerland | [57] |
| Avalence | alkaline (monopolar) | 0.4-4.6 (139 ^f) | 2-25 (750 ^f) | 5.43-5 ^h | 65.2-70.8 | 448 | n.a. | USA | [58] |
| Claind | alkaline (bipolar) | 0.5-30 | n.a. | n.a. | n.a. | 15 | 99.7 (99.999 ^k) | Italy | [59] |
| ELT | alkaline (bipolar) | 3-330 | 13.8-1518 | 4.6-4.3 ^h | 76.9-82.3 | atmospheric | 99.8-99.9 | Germany | [60] |
| ELT | alkaline (bipolar) | 100-760 | 465-3534 | 4.65-4.3 ^h | 76.1-82.3 | 30 | 99.8-99.9 | Germany | [60] |
| Erredue | alkaline (bipolar) | 0.6-21.3 | 3.6-108 | 6-5.1 ^g | 59-69.8 | 2.5-4 | 99.3-99.8 (99.999 ^k) | Italy | [61] |
| Giner | PEM (bipolar) | 3.7 | 20 | 5.4 ⁱ | 65.5 | 85 | n.a. | USA | [82] |
| Hydrogen Technologies, division of Statoil | alkaline (bipolar) | 10-500 | 43-2150 | 4.3 ^h | 82.3 | atmospheric | 99.9 (99.999 ^k) | Norway | [62] |
| Hydrogenics | alkaline (bipolar) | 10-60 | 54-312 | 5.4-5.2 ^g | 65.5-68.1 | 10 (optional 25) | 99.9 (99.998 ^k) | Canada | [52] |
| Hydrogenics | PEM (bipolar) | 1 | 7.2 | 7.2 ^g | 49.2 | 7.9 | 99.99 | Canada | [52] |
| H2 Logic | alkaline (bipolar) | 0.66-42.62 | 3.6-213 | 5.45-5 ^g | 64.9-70.8 | 4 (optional 12) | 99.3-99.8 (99.999 ^k) | Denmark | [63] |
| Idroenergy | alkaline (bipolar) | 0.4-80 | 3-377 | 7.5-4.71 ^h | 47.2-75.2 | 1.8-8 | 99.5 | Italy | [64] |
| Industrie Haute Technologie | alkaline (bipolar) | 110-760 | 511.5-3534 | 4.65-4.3 ^h | 76.1-82.3 | 32 | 99.8-99.9 | Switzerland | [65] |
| Linde | alkaline (bipolar) | 5-250 | n.a. | n.a. | n.a. | 25 | 99.9 (99.998 ^k) | Germany | [66] |
| PIEL, division of ILT Technology | alkaline (bipolar) | 0.4-16 | 2.8-80 | 7-5 ^g | 50.6-70.8 | 1.8-18 | 99.5 | Italy | [67] |
| Proton OnSite | PEM (bipolar) | 0.265-30 | 1.8-174 | 7.3-5.8 ^h | 48.5-61 | 13.8-15 (optional 30) | 99.999 | USA | [53] |
| Sagim | alkaline (monopolar) ^e | 1-5 | 5-25 | 5 ^h | 70.8 | 10 ^j | 99.9 | France | [68] |
| Teledyne Energy Systems | alkaline (bipolar) | 2.8-56 | n.a. | n.a. | n.a. | 10 | 99.999 | USA | [69] |
| Treadwell Corporation | PEM (bipolar) | 1.2-10.2 | n.a. | n.a. | n.a. | 75.7 | n.a. | USA | [83] |

n.a.: not available.
^aGas production rates are commonly given in normal cubic meters per hour (Nm³/h) and kilograms per hour (kg/h): 1 Nm³/h = 0.0899 kg/h.
^bRated power has been obtained either directly from the manufacturers, when the data is available, or as the product of third and fifth columns (rated production and specific energy consumption, respectively).
^cSpecific energy consumption has been obtained either directly from the manufacturers, when the data is available, or as the ratio between fourth and third columns (rated power and rated production, respectively).
^dEfficiency has been calculated as the ratio between the HHV of hydrogen (3.54 kWh/Nm³) and the specific energy consumption (fifth column).
^eModule configuration by series-connected monopolar cells.
^fIn development.
^gThe manufacturer indicates that the specific energy consumption refers to the global hydrogen production system.
^hThe manufacturer does not indicate if the specific energy consumption is exclusively of the electrolysis process (module) or it refers to the global hydrogen production system.
ⁱThe manufacturer indicates that the specific energy consumption refers only to the electrolysis process (module).
^jPressurization with internal compressor, not by isothermal process inside the electrolysis module.
^kWith an additional purification system (to remove oxygen and water vapor from the produced hydrogen gas).

2.3 Wind turbines

The idea of the electrolysis is to power it by using wind energy, which means using wind turbines to generate the electricity that can be used for the electrolysis. The technique of using wind turbines is extracted from the former windmills and wind wheels which were used already millenniums ago. The first attempts of generating electricity from wind dates from the end of the 19th century. Half the 20th century they started to build wind turbines that were close to what they look now (figure 16). (19)

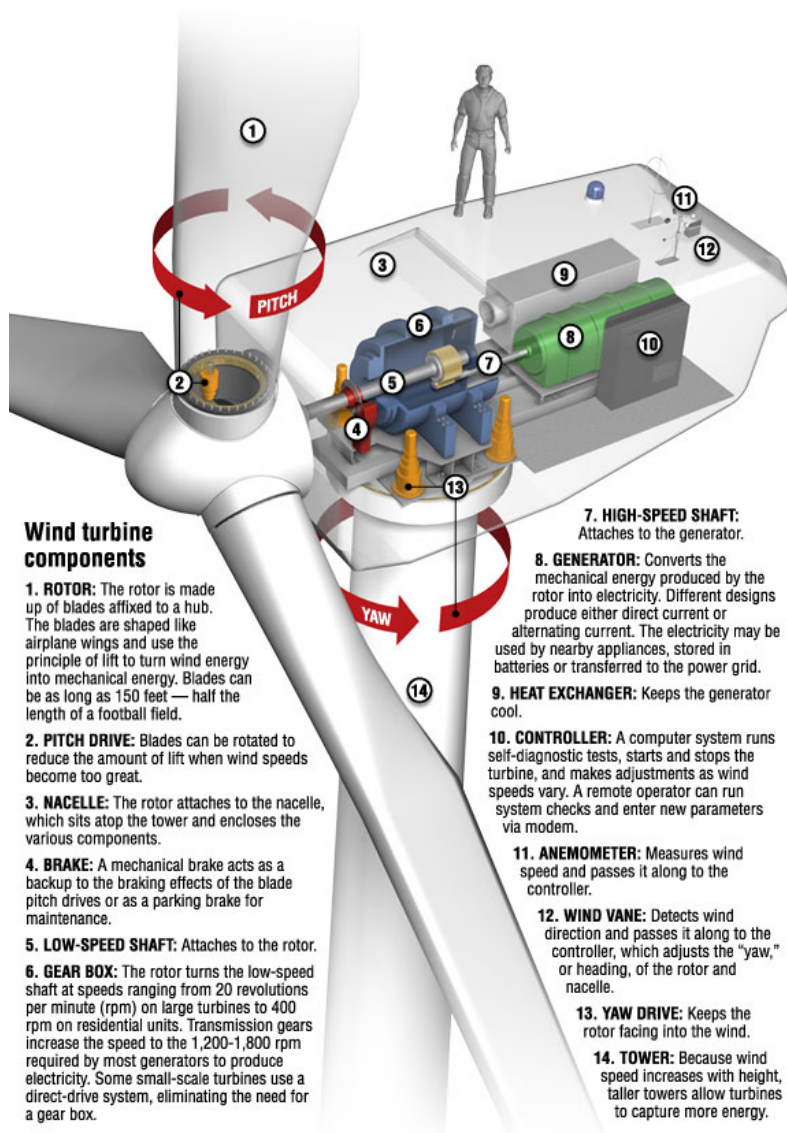


Figure 14. Wind turbine anatomy (20).

2.3.1 Parts of wind turbine

In figure 6 we can see the main parts that a wind turbine consists of. Starting with the rotor-blades, which uses lift to capture the wind's energy. This is because of the special designed shape of the rotor blades, this makes the wind create a pocket of pressure when it passes the blade. This pressure will pull the blade resulting in rotating the blades. Over the years these blades are improved in order to become more efficient. Next there is a generator and a gearbox, the gearbox connects the spinning blades through a serial of gears to the generator. Also the gears increase the rotational speed to the generator. As the generator spins, the electricity is produced. Then there is the tower for the support of the turbine and is used to wire the cables to the ground where they can be connected to the grid. (21)

2.3.2 Wind energy conversion

The primary component of a wind turbine is the energy converter that transforms kinetic energy into mechanical energy. The wind is being considered as moving energy with:

$$E_{kin} = \frac{1}{2} \times m \times v^2$$

For one m³ of air this formula can be rewritten to:

$$E_{kin} = \frac{1}{2} \times \rho \times v^2$$

In order to calculate the wind power there is an area required:

$$P_{wind} = E_{kin} \text{ (J/m}^3\text{)} \times \Phi_V \text{ (m}^3\text{/s)} = \frac{1}{2} \times \rho \times v^2 \times A \times v = \frac{1}{2} \times \rho \times v^3 \times A$$

The formula indicates already that the wind power depends a lot on the wind speed (third power). But in fact, the wind power is not the power a wind turbine can deliver. The wind power that can be delivered by a wind turbine is dependent on the efficiency determined by the power coefficient C_p . This C_p is again dependent on the type of the rotor, the diameter of the rotor and the wind speed. The formula for the power that can be delivered by a turbine is:

$$P_{\text{turbine}} = C_p \times \frac{1}{2} \times \rho \times v^3 \times A$$

The theoretical maximum C_p can be calculated and is called the Betz optimum and is 59.2% (although modern turbines can reach about 70-80% already). (19)

Of course the blades of a wind turbine will not just go and rotate randomly. First there has to be a minimum wind speed which is called cut-in speed in order to be able to rotate the blades and generate electricity. This cut-in speed is in general about 3 or 4 m/s. From that point the level of power output will increase by the third power compared with the wind speed. Then in between 12 and 17 m/s the power output will reach a limit that the electrical generator is capable of. This limit is called the rated power output and the associated wind speed is called the rated output wind speed. At higher wind speed the wind turbine will limit itself to the rated power output, so no more power than the maximum can be generated. Then if the wind speed becomes too high, the turbine will shut down for safety issues, this is called the cut-out speed. This cut-out speed is in general about 25 m/s. This description is also visible in figure 17.

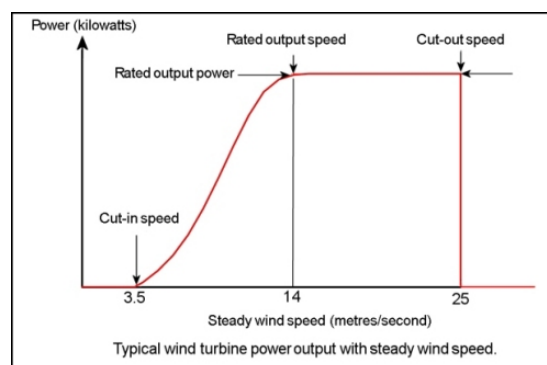


Figure 15. Typical wind turbine power output with steady wind speed (22).

3 BASELINE SITUATION AND PROCEDURE

Before the accomplishment of the goal is possible it is very important to establish the traits that each model being developed will work on. It is important to do so because only then can the different parameter also be established. As with any scientific procedure there are variable that need to be in order to produce realistic and coherent data. In this thesis independent, dependent and controlled variable would be used. The independent variable would be the parameters that will be changed in order to view its effects of the production price. These independent variable would be the capital and operational prices that will be accounted for in a model (see appendices for full recollection of all variables). The dependent variable in this thesis would be the production cost, it is going to be the yard stick in which the results would be deemed favorable or unfavorable. It is directly related to the independent variables (a full recollection of the dependent variables are in results). In this thesis the controlled variables are the parameters that would be left the same in order to create some relativity in the judgment of the different models. These are the parameters that will remain constant across the different models. Important controlled variable to establish for the proceeding calculations are that the raw gas output of the digester will be (2100m³/h), the operational time will be 4000 hours and the depreciation time will be over 20 years (see appendices for full rundown of controlled variables). The 4000 hours is derived from the analysis of demand and supply of the produced electricity. Because the produced electricity cannot be stored, a run time of the turbine which favors balance in the supply has to be chosen (this is 4000 hours). The price of the electricity will go down if it is not balanced which would in turn cause a loss of profit.

Table 5. Controlled variable data

| <i>Data</i> | <i>Value</i> | <i>Units</i> |
|------------------------|--------------|-------------------|
| flow rate out (Biogas) | 2100 | m ³ /h |
| Operational time | 4000 | h |
| Depreciation time | 20 | y |

3.1 Current situation

The current process where methane is produced conventionally with the use of a digester tank.

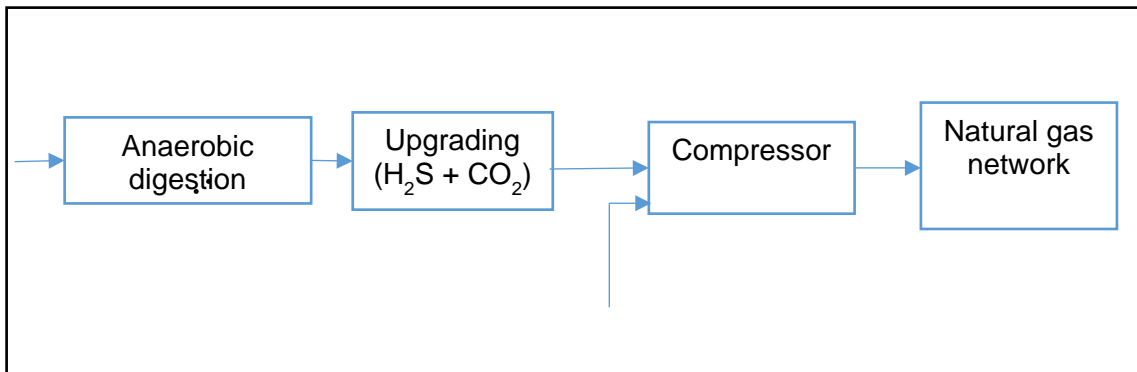


Figure 16. Current situation.

Figure 18 is a schematic of the designed process for Suiker Unie current production line for bio-methane. What you see is that all recyclable organic matter from the production process is fed into an anaerobic digester. After digestion what you have is an upgrading process where the biogas is freed of a significant percentage of its impurities. The targeted impurities are hydrogen sulfide (H₂S) and carbon dioxide. The hydrogen sulfide needs to be removed because of its corrosive attributes and the CO₂ needs to be taken out because of it being a greenhouse gas and emissions need to be taxed. Overall the upgrading step makes for a better energy quality within the bio-gas. For upgrading the chosen mode was a pressure swing absorption technique by Cirmac. The product is then compressed with nitrogen till it makes up 10% of the total volume. Everything is then fed into the natural gas grid.

Table 6 Current situation attributes.

| Item | Fixed asset | Current asset | Price |
|----------------|-------------|---------------|---------------------------------|
| Digestion tank | x | - | 0.23 €/m ³ of biogas |
| PSA (Cirmac) | x | - | 0.25 €/m ³ of biogas |

Table 6 shows the capital and operation for the investment that is already implemented into the current situation in Suiker Unie. The use of capital in this model is being allocated to the digester and PSA as well. The price of 0.23 euros/m³ is a value that includes the investment and operation of a digester tank per volume of bio-methane produced. (23) This applies for PSA as well having the price of 0.25 euros/m³. The method for achieving the production would result from calculating the methane produced annually and then multiplying by the costs.

3.2 Case 1

The first designed process model were methane is produced by means of a digester tank with hydrogen inoculated.

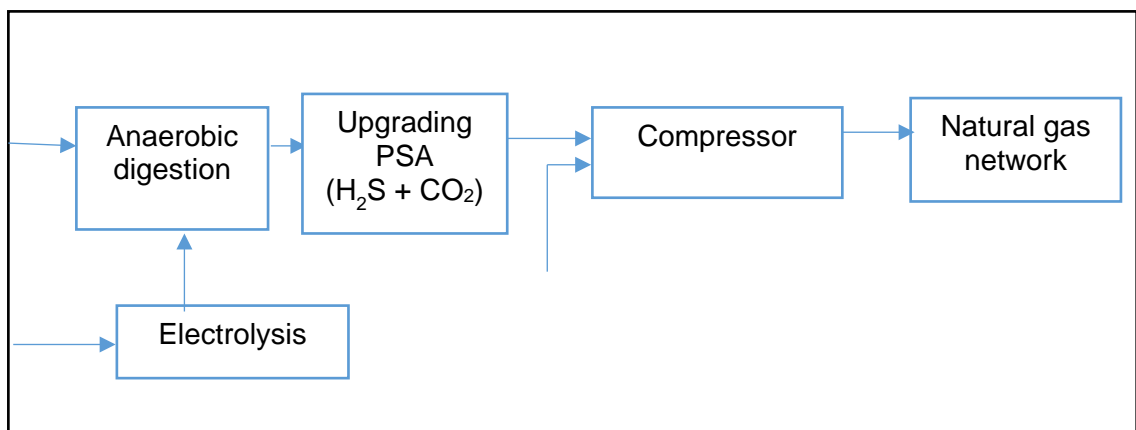


Figure 17. Case 1.

In figure 19 a schematic is shown for the invested modification that will be made to the current situation in order to increase bio-methane production efficiency. The added component to the scheme is an electrolyser and a windmill (the windmill capital is being left out of capital use because it causes little deviation between production cost values). The electrolyser is used for the hydrogen synthesis through electrolysis, which will increase the metabolic capacity of methanogenesis within the digester.

Table 7. Case 1 attributes.

| Item | Fixed asset | Current asset | Price |
|-------------------|-------------|---------------|-----------------------|
| Digestion tank | x | - | 0.23 €/m ³ |
| PSA (Cirmac) | x | - | 0.25 €/m ³ |
| Electrolytic cell | x | - | 6,000,000 € |
| Electricity | - | x | 0.235 €/kWh |

In this case the invested capital would be in the prior assets discussed along with a new fixed asset, the electrolyzer. For this thesis we would be going with a 6 million euros electrolytic cell because it would be able to fulfil the requirement demanded; with this size cell this can be used for scenarios with larger demands. The only current significant current asset worth mentioning is the electrical cost. This is in direct correlation with the compressor that would be used to compress the bio-gas into different standards. The electricity for the electrolyzer will come directly from the wind turbine, so it is not directly paid for. The areas around Dinteloord will be best suited for the facilitations of the wind turbines. The production cost would be the aggregation of the weighted some of these parameters (see appendix 3 for full detail of all parameters).

3.3 Case 2

The second designed process a model were methane is produced by means of a digester tank and a bio-methanation tank with hydrogen inoculated.

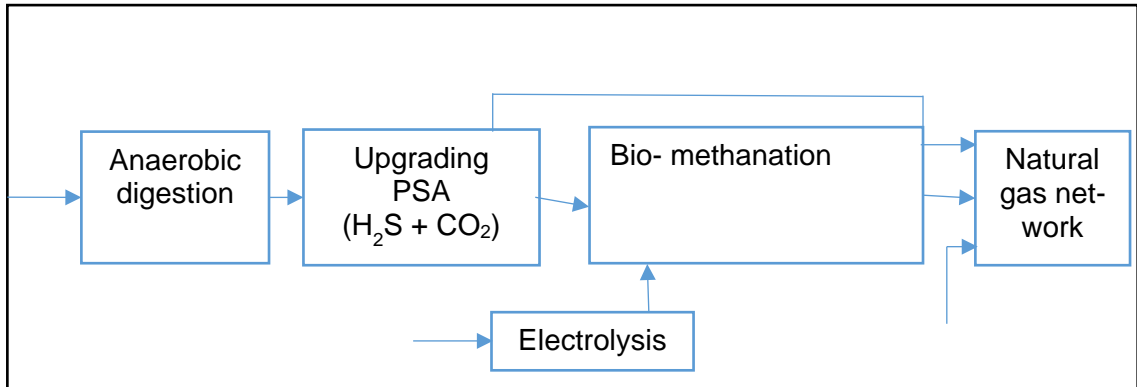


Figure 18. Case 2.

In figure 20 a schematic of the invested modification on financed assets is shown for case 2. In this case the capital would be allocated to the investment in an electrolyzer and a bio-methanation tank. The inclusion of the bio-methanation tank is to increase the efficiency of methane production by recycling waste carbon dioxide and converting it into bio-methane.

Table 8. Case 2 attributes.

| Item | Fixed asset | Current asset | Price |
|-------------------|-------------|---------------|-----------------------|
| Digestion tank | x | - | 0.23 €/m ³ |
| PSA (Cirmac) | x | - | 0.25 €/m ³ |
| Methanation tank | x | - | 3,900,000 € |
| Electrolytic cell | x | - | 7,000,000 € |
| Electricity | - | x | 0.235 €/kWh |

In this case the invested capital would be in the prior assets discussed along with a new fixed asset, the electrolyzer and a bio-methanation tank. For this thesis we would be going with a 7 million euros electrolytic cell because it would be able to fulfil the requirement demanded this is a bigger installment than in case 1. The bio-methanation tank would have an investment cost of 3,900,000 euros due to the capacity of methane being handled. Once again the only significant current asset worth mentioning now is the electrical cost. This is in direct correlation with the compressor that would be used to compress the bio-gas into different standards. The production cost would be the aggregation of the weighted some of these parameters (see appendix 4 for full detail of all parameters).

4 RESULTS & ANALYSIS

In this part the results and analysis of the thesis are discussed.

The purpose was to determine the cost of production of methane, to conduct an environmental impact assessment (EIA) and to calculate carbon dioxide emission for all 3 different scenario models.

In the acquisition of the final product cost the producer will as follows:

1. Determine the flow rate of gas through all schemes and then fill in process data
2. Find cost of the invested assets, current assets and quality management process
3. Determine the annual capital cost. The cost of production = the annual capital cost + current assets + quality management prices
4. Cost allocation is determined by annual cost of production/ annual volume

Table 9. Raw process data.

| <i>Data</i> | <i>Value</i> | <i>Units</i> |
|-------------------------------|--------------|-------------------|
| <i>flow rate out (Biogas)</i> | 2100 | m ³ /h |
| <i>Operational time</i> | 4000 | h |
| <i>Depreciation time</i> | 20 | y |
| <i>Volume CO2</i> | 840 | m ³ /h |
| <i>Volume CH4</i> | 1155 | m ³ /h |
| <i>Volume H2 needed</i> | 3129 | m ³ /h |
| <i>CH4</i> | 771000 | g |
| <i>H2 needed</i> | 280000.00 | g |
| <i>CO2</i> | 1540000 | g |
| <i>CH4</i> | 48200.00 | mol |
| <i>H2 needed</i> | 141000.00 | mol |
| <i>CO2</i> | 35200.00 | mol |

Table 9 is a presentation of the results of the base data. By knowing the amount of biogas out-flow, it was possible to determine the volume of concentration of matter during the process. As a result of this being purely a theoretical study these 10 data points were crucial in determining the fundamental characteristic for each model. They are presented in volume over time, grams and mols. A lot of the other calculations can thus be done based on these 10 values. Appendix 1 shows a complete recollection of the parameters that were essential for coming up with the cost of production.

Current situation (original situation of Sukie Unie) shows the result as 0.5 euros per m^3 . This is the value adopted from literature as what it should be. The production price calculated is set at 1.25 euros/ m^3 of methane produced, which is wrong. The value produced can be perceived as far too expensive and would cause the company to run at a loss because the methane is normally priced at 0.5-0.55 euros/ m^3 . (23) This can be negated because for this model Suiker Unie has a different mode for calculating cash flow within production time. There are several factors not being accounted for such as startup capital or equity and liabilities that could have been within the client's possession. Also, technically this value is not of interest because by knowing the selling price, the cost of production for Suiker Unie can be estimated to be somewhere below 0.5 euros. The method of calculating production price does not reflect this.

Case 1 illustrates the result for the first scenario. As can be seen here, in terms of efficiency the technique is able to increase the yield of methane by 60%. The amount of waste produced in the form of carbon dioxide is also reduced. It dropped by 37.5%. This is noteworthy because not only does it increase the sustainability of the process but it also provides some financial relief on the upgrading of the gas because there are less impurities, thus leading to cheaper upgrading. Economically it is quite interesting to mention that the production price is 0.5 euro per m^3 , although this is not the desired result because it means that Suiker Unie would just be breaking even and not making a profit from their investment.

Case 2 illustrates the result for the first scenario. As can be seen, in terms of efficiency the technique is able to increase the yield of methane by 90%. The amount of waste produced in the form of carbon dioxide is also reduced. It dropped by 80%. This is very noteworthy because not only is it quite impressive, it increases the sustainability of the

process. It also provides some financial relief on the upgrading of the gas because there are less impurities, thus leading to cheaper upgrading. It may even be possible to move towards a more effective method for trapping H₂S. Economically it is important to mention that the production price is 0.8 euro per m³. This not a desired result because Suiker Unie would not be making any profit from the sales of natural gas produced using this method.

Table 10. Overall results from case 1 and case 2.

Process data

| Current situation | | | | | |
|--------------------------------|---------------|-------------------|------------------------|-----|------------------|
| | Scaler | Units | | | |
| Total methane | 1155.0 | m ³ /h | Production cost | 0.5 | €/m ³ |
| CO ₂ produced | 840.0 | m ³ /h | | | |
| Annual methane yield | 4620000.0 | m ³ | | | |
| Annual CO ₂ yield | 3360000.0 | m ³ | | | |
| Methane relative to | | | | | |
| Current situation (CS) | 100.0 | % | | | |
| CO ₂ relative to CS | 100.0 | % | | | |
| Input energy | 23200000.0 | MJ/year | | | |
| Sugar beet input | 86100.0 | MJ/year | | | |

| Case 1 | | | | | |
|--------------------------------|---------------|-------------------|------------------------|------|------------------|
| | Volume | Units | | | |
| Total methane | 1856.3 | m ³ /h | Production cost | 0.55 | €/m ³ |
| CO ₂ produced | 525.0 | m ³ /h | | | |
| Annual methane yield | 7420000.0 | m ³ | | | |
| Annual CO ₂ yield | 2100000.0 | m ³ | | | |
| Methane relative to | | | | | |
| CS | 160.7 | % | | | |
| CO ₂ relative to CS | 62.5 | % | | | |
| Input energy | 232000000.0 | MJ/year | | | |
| Sugar beet input | 86100000.0 | ton/year | | | |

| Case 2 | | | | | |
|--------------------------------|---------------|-------------------|------------------------|-----|------------------|
| | Volume | Units | | | |
| Total methane | 2196.5 | m ³ /h | Production cost | 0.8 | €/m ³ |
| CO ₂ produced | 168.0 | m ³ /h | | | |
| Annual methane yield | 8780000.0 | m ³ | | | |
| Annual CO ₂ yield | 672000.0 | m ³ | | | |
| Methane relative to | | | | | |
| CS | 190.2 | % | | | |
| CO ₂ relative to CS | 20.0 | % | | | |
| Input energy | 232000.0 | GJ/y | | | |
| Sugar beet input | 86100.0 | tons | | | |

4.1 Environmental impact assessment

Environmental Impact Assessment is a formal process used to predict the environmental consequences (positive or negative) of a plan, policy, program, or project prior to the implementation decision. It proposes measures to adjust impacts to acceptable levels or to investigate new technological solutions. Although it can lead to difficult economic decisions, strong political and social commitments, it protects the environment to provide a sound basis for effective and sustainable development.

The purpose of the assessment is to ensure that decision makers consider the environmental impacts when deciding whether or not to proceed with the recommendations of a project. The International Association for Impact Assessment (IAIA) defines an environmental impact assessment as “the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made”. EIAs are unique in that they do not require adherence to a predetermined environmental outcome, but rather they require decision makers to account for environmental values in their decisions and to justify those decisions in light of detailed environmental studies and public comments on the potential environmental impacts. Another important basic characteristic of an EIA report is the collection of information throughout different authorities. However, this will not be utilized in this thesis because these authorities/stake holders are not directly involved, and thus, these resources remain outside our possession (24).



Figure 19. Likelihood times severity chart. (33)

Figure 21 is a severity chart that is going to be instrumental and key in the assessment of the urgency of a circumstance. On both axes of the chart there are 5 levels of both likelihood and severity. Severity refers to, if an assessed event were to take place, just how big of an impact it would have on the environment. Likelihood refers to the possibility of the assessed circumstance actually occurring. 1 is allocated as the lesser value while 5 the highest acquirable value. When it comes to the definition of danger levels, there are ranges of impact, all denoted by a specific colour (green, yellow and red). Green class impacts are described as not having any noticeable impacts of adverse effects and can be left alone. Orange ranged impact can be classed as being tolerable impact and can be left alone but it would be advisable to change or mitigate the circumstances in the immediate future. Red classed impacts are described as having impacts of adverse effects and it is advised for operation to be stopped and mitigation protocols to be initiated as quickly as possible (33).

Relevant to the thesis the EIA will be conducted for the 3 cases. The case with anaerobic digestion (current situation), the case with anaerobic digestion facilitated by hydrogen inoculation (case 1) and the case with the anaerobic digestion facilitated by bio-methanation (case 2). The circumstances that each process is being assessed on span across all aspects of environment, reading into water quality, air quality, soil quality, topography and ecological impacts.

Table 11. Scoring for current situation, case 1 and case 2.

| Impact | Likelihood severity score | | |
|--|----------------------------------|---------------|---------------|
| | Current situa- tion | Case 1 | Case 2 |
| Fauna & flora | | | |
| Disturbance of ecosystem | 3 | 3 | 3 |
| Disturbance of biodiversity | 3 | 3 | 3 |
| Disturbance of fauna | 3 | 3 | 3 |
| Disturbance of flora | 3 | 3 | 3 |
| Soil quality | | | |
| Erosion | 2 | 4 | 4 |
| Water quality | | | |
| Alter river level (Due to water table) | 3 | 3 | 3 |
| Increase COD of nearby source | 6 | 6 | 6 |
| Air quality | | | |
| Increase in particulate matter | 6 | 9 | 9 |
| noise pollution | 4 | 4 | 2 |
| Topography | | | |
| View obstruction | 1 | 3 | 3 |
| Sociological | | | |
| Affect construction workers | - | 9 | 9 |
| Affect operational workers | 6 | 6 | 6 |
| <hr/> | | | |
| Current situation | | | |
| Total: | Low Risks | Medium Risks | High Risks |
| Amount: | 7 | 4 | 0 |
| <hr/> | | | |
| Case 1 | | | |
| Total: | Low Risks | Medium Risks | High Risks |
| Amount: | 6 | 6 | 0 |
| <hr/> | | | |
| Case 2 | | | |
| Total: | Low Risks | Medium Risks | High Risks |
| Amount: | 7 | 5 | 0 |

In comparison, all of 3 cases have fairly similar low risks and medium risks while there are no such a high risks at all. The number of medium risks shows that natural disasters may lead damage while there are some risks related to the emission and building processes. Sociological impacts can be a considerable problem though constructional and operational activities. The difference between case 1 and 2 and the current situation is that the electrolyzer has to be built while case 2 needs to build an extra reactor so the impact of particle matter is higher but it still remains a medium risk. Altogether there is no real risk found which could result in negative advice.

Table 12. CO₂ balance.

| | Current situation | Case 1 | Case 2 |
|---|--------------------------|--------------------------|------------------------|
| CO₂ relative to Current situation | 100% | 62.5% | 20,0% |
| CO₂ produced | 840 m ³ /h | 525 m ³ /h | 168 m ³ /h |
| Annal CO₂ yield | 3 360 000 m ³ | 2 100 000 m ³ | 672 000 m ³ |

For the CO₂ balance, based on table 12, it is clear that the current situation has the highest amount of CO₂. While the amount of CO₂ is reduced in case 1, it is obvious that high amounts of greenhouse gasses and eventually taxes can be significantly reduced in case 2. In this case, the risk about emission is lower for both case 1 and case 2.

5 CONCLUSION AND ADVICE

In the beginning of this thesis the goal was to determine the cost of production of methane for 3 different scenario models, namely a model where methane is produced conventionally, with the use of a digester tank; a model where methane is produced by means of a digester tank with hydrogen inoculated; and a model where methane is produced by means of a digester tank and a bio-methanation tank. The cost of production was determined through an aggregation of the capital cost and the operational cost of the 3 different processes and a consensus was reached (this is depicted by table 10). In conclusion from the results presented it is safe to say that the operations being investigated are environmentally safe and would not have any adverse impact on the environment or operational workers. In terms of the increase of productivity, case 2 yielded the most impressive results and is the most sustainable method of producing bio-methane for natural gas conversion.

Table 13. Cost comparison.

| | CURRENT SITUATION | CASE 1 | CASE 2 |
|---|------------------------------|---------------|---------------|
| PRODUCTION PRICE €/M³ | 0.5 | 0.55 | 0.8 |

However, financially none of the newer techniques are feasible because they do not produce any profit. The advice to the client is that they can choose any of the following options. They could invest in expansion of current production exploits and increase the scale of production. By doing so the production price would still be lower than the selling price and invested capital could be retrieved through profits over the years. The other option is to peruse any of the other techniques but with an intensive financial plan using liabilities such as loans and credits, whereby profits can be achieved. The final option is to wait and see how the market changes since although the cases are not feasible now, they might be feasible in time.

6 REFERENCES

1. Biogas. *Xebecinc*. [Online] 21. 10 2014. <http://www.xebecinc.com/applications-biogas.php>.
2. Biogas FAQ. *Electrigaz*. [Online] 21. 10 2014. http://www.electrigaz.com/faq_en.htm.
3. Sources of Greenhouse Gas Emissions. *EPA*. [Online] 21. 10 2014. <http://epa.gov/climatechange/ghgemissions/sources/lulucf.html>.
4. Uses of Nitrogen. *Uses of*. [Online] 22. 10 2014. <http://www.usesof.net/uses-of-nitrogen.html>.
5. Uses of Hydrogen . *Uses of* . [Online] 22. 10 2014. <http://www.usesof.net/uses-of-hydrogen.html>.
6. Hydrogen Sulfide. *Infoplease*. [Online] 22. 10 2014. <http://www.infoplease.com/encyclopedia/science/hydrogen-sulfide.html>.
7. Biogas. *USDA*. [Online] 21. 10 2014. http://www.usda.gov/oce/reports/energy/Biogas_Opportunities_Roadmap_8-1-14.pdf.
8. Krich, Ken. Storage and Transportation of biogas and biomethane. [kirjan tekijä] Ken Krich ;ym. *Biomethane from Dairy Waste*. s.l. : USDA Rural Development, 2005, ss. 71-80.
9. Chemical Composition of Natural Gas. *Uniongas*. [Online] Uniongas. <https://www.uniongas.com/about-us/about-natural-gas/Chemical-Composition-of-Natural-Gas>.
10. Natural gas distribution . *naturalgas.org*. [Online] Federal Emergency Management Agency. [Viitattu: 22. 10 2011.] <http://naturalgas.org/naturalgas/distribution/>.
11. What is anaerobic respiration . *americanbiogascouncil.org*. [Online] americanbiogascouncil. [Viitattu: 22. 10 2014.] https://www.americanbiogascouncil.org/biogas_what.asp.
12. methanogens. *The Biology of Methanogenic Bacteria*. [Online] kenyon university. [Viitattu: 22. 10 2014.] <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC414011/pdf/bactrev00056-0156.pdf>.
13. *Biogas upgrading technologies-developments and innovations*. Anneli Petersson, Arthur WeLLInGer. s.l. : IEA Bioenergy, 2009.
14. PSA System for Biogas Upgradation. *Bioenergy Consult*. [Online] 19. October 2014. <http://www.bioenergyconsult.com/tag/pressure-swing-adsorption/>.
15. *Innovative methods for biogas upgrading by the addition of hydrogen to anaerobic reactor*. Gang Luo, Irini Angelidaki. s.l. : DTU Environment.
16. scielo. *Hydrogen production by alkaline water electrolysis*. [Online] [Viitattu: 13. 11 2016.] http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-40422013000800017.
17. Abe, Isao ja Compeer, Alexander. *Energy carriers and conversion systems - Alkaline water electrolysis*. Chiba, Japan : Enceyclopedia of Life Support Systems, 2014.
18. Alfredo Ursu´a, Member IEEE, Luis M. Gandi´a, and Pablo Sanchis, Member IEEE ja Compeer, Alexander . Hydrogen Production From Water Electrolysis: Current Status and Future Trends. [Online] February 2012. https://www.researchgate.net/publication/220473374_Hydrogen_Production_From_Water_Electrolysis_Current_Status_and_Future_Trends.
19. Hau, Erich ja Heijmans , Juriaan. *Wind Turbines - Fundamentals, Technologies, Application, Economics*. Germany : Springer, 2013.

20. <http://www.awea.org/Issues/Content.aspx?ItemNumber=5083>. *Anatomy of a wind turbine*. [Online] American Wind Energy Association.
21. ECW ja Heijmans, Juriaan. <http://www.ecw.org/windpower/web/cat2a.html>. *Energy Center of Wisconsin*. [Online] 2012.
22. http://www.wind-power-program.com/turbine_characteristics.htm. *Turbine characteristics*. [Online] Windpower program.
23. Mattheij, Stijn. *Raport vloeibaar methane*. BREDA : Avans hogeshcool, 2013.
24. European Commission . *Environmental*. [Online] 1. May 2014. [Viitattu: 2. May 2014.] <http://ec.europa.eu/environment/eia/eia-legalcontext.htm>.
25. *Methods and apparatus for hydrogen based biogas upgrading*. Irini Angelidaki, Poul Lyhne, Gang Luo. s.l. : Technical University Of Denmark, Vestforsyning A/S, 2013. PCT/DK2012/050390.
26. *google images* . [Online] [Viitattu: 22. 10 2014.] http://www.google.nl/imgres?imgurl=http%3A%2F%2Fupload.wikimedia.org%2Fwikipedia%2Fcommons%2Fthumb%2F2%2F2b%2FStages_of_anaerobic_digestion.JPG%2F800px-Stages_of_anaerobic_digestion.JPG&imgrefurl=http%3A%2F%2Fen.wikipedia.org%2Fwiki%2FAnaerobic_digestion&
27. *google images* . [Online] [Viitattu: 22. 10 2014.] http://www.google.nl/imgres?imgurl=http%3A%2F%2F1.bp.blogspot.com%2F-nvygIA5mbio%2FU8-vpG9VH_I%2FAAAAAAASX4%2FScjgvZGHxEA%2Fs1600%2FHydrolysis.png&imgrefurl=http%3A%2F%2Fbiology4alevel.blogspot.com%2F2014%2F07%2F6-carbohydrates-monosaccharides.html&h=242
28. *Purification Technologies for Biogas Generated by Anaerobic Digestion*. Q. Zhao, E. Leonhardt, C. MacConnell, C. Frear and S. Chen. s.l. : CSANR, 2010.
29. Tim Shea. Thermal Hydrolysis and Acid Hydrolysis - Pre-Conditioning Technologies on the Move . *The straight scoop*. [Online] http://www.imakenews.com/restech/e_article001368484.cfm.
30. JONATAN AGERSBORG, EMIL LINGEHED. *Integration of Power-to-Gas in Gasendal and GoBiGas*. Goteborg, Sweden : CHALMERS UNIVERSITY OF TECHNOLOGY, 2013.
31. Innovative methods for biogas upgrading by the addition . *Balticcompass*. [Online] [Viitattu: 22. 10 2014.] <http://www.balticcompass.org/PDF/Events/Gang%20Luo%20-%20Innovative%20methods%20for%20biogas%20upgradingby%20the%20addition%20of%20hydrogen%20to%20anaerobic%20reactor.pdf>.
32. NBPA APNB. *pipeline infrastructure distribution*. [Online] [Viitattu: 6. 9 2016.] <http://www.nbpa.ca/pipeline-infrastructure-distribution/>.
33. Risk Management with Gordon Wyllie. *mindgenius*. [Online] [Viitattu: 13. 11 2016.] <http://www.mindgenius.de/Resources/Articles/Process-Improvement/Risk-Management-2.html>.

APPENDIX 1: LIST OF RAW DATA

| | | |
|----------------------|------------|-------------------|
| CO2 density | 1,842 | kg/m ³ |
| H2 density | 0,0899 | kg/m ³ |
| CH4 density | 0,668 | kg/m ³ |
| flow rate in (BM) | 2300 | m ³ /h |
| flow rate out (BG) | 2100 | m ³ /h |
| Volume CO2 | 840 | m ³ /h |
| Volume CH4 | 1155 | m ³ /h |
| Volume H2 needed | 3129 | m ³ /h |
| H2 needed | 281323,636 | G |
| CO2 | 1547280 | G |
| CH4 | 48221,25 | mol |
| H2 needed | 140661,818 | mol |
| CO2 | 35165,4545 | mol |
| Methanation temp | 65 | °C |
| CO2 heat content | 0,39352 | Mj/mol |
| LHV methane | 35,22 | Mj/m ³ |
| LHV hydrogen | 10,05 | Mj/m ³ |
| | 121 | Mj/kg |
| CH4 (methanation) | 562,6 | Kg |
| MM H2O | 18 | g/mol |
| MMCO2 | 44 | g/mol |
| MMCH4 | 16 | g/mol |
| MMH2 | 2 | g/mol |
| Electricity price | 0,235 | €/kWh |
| Operation time | 4000 | H |
| Depreciation time | 20 | Years |
| Annual capital cost | 0,087185 | |
| methanation eff (C2) | 0,81 | |
| methanation eff (C1) | 0,73 | |
| Economic life time | ... | |
| seconds (year) | 31536000 | |
| Digestion Cost | 0,25 | €/m ³ |
| \$/€ | 0.8 | |
| Digester efficiency | | |
| Subsidy of digester | | |
| Interest rate | 0,06 | |
| H2 conversion rate | 99.9% | |
| CO2 price | 2,3 | €/m ³ |

| | | |
|--------------------------------|-----------|-----------------|
| H2 price | 3,2 | €/m3 |
| N2 price | 3 | €/m3 |
| [N2] in product | 0,1 | |
| Natural gas price | 0,53 | €/m3 |
| N2 in NGN | 0.10 | |
| Water prices | - | €/m3 |
| €/sek | 9,45 | |
| electricity - CH4 eff | 52 | % |
| Cost of capital | 5 | % |
| Thesis cost | 0,1 | of investment |
| Construction cost | 0,1 | of investment |
| Electrolysis eff | 0,7 | |
| Anaerobic digester eff | 0,55 | |
| Methanogenesis eff | 0,7 | |
| Electrolyzer cost: Case 1 | 7,000,000 | € |
| Electrolyzer cost: Case 2 | 6,000,000 | € |
| Unforeseen costs | 0,1 | of investment |
| Maintenance and services | 0,3 | of investment |
| Consumption compressor | 0,01 | kWhe/kWhmethane |
| Bio-gas upgrading costs | | |
| 200 Nm3/h | 2,2869 | €/kWh |
| 600 Nm3/h | 1,1907 | €/kWh |
| 1200 Nm3/h | 0,8505 | €/kWh |
| PSA (circumac) | 0,12 | €/ct/m3 |
| Sugar Energy intensity | 2,7 | GJ/ton |
| Compressor energy compressor | 384284 | kWh/year |
| | 96,071 | kW |
| | 384284 | MJ |
| E factor | 1 | kWh/MJ |
| N2 E-content | 375 | kWh/ton |

APPENDIX 2: PROCESS DATA BASE CASE

| Process data | | | | | | |
|------------------------------|-----------|-------------------|--|------------------|------|------------------|
| | Scaler | Units | | | | |
| Total methane | 1155 | m ³ /h | | Production price | 1,25 | €/m ³ |
| CO ₂ produced | 840 | m ³ /h | | | | |
| Annual methane yield | 4620000 | m ³ | | | | |
| Annual CO ₂ yield | 3360000 | m ³ | | | | |
| Input energy | 232452000 | MJ/year | | | | |
| Sugar beet input | 86093,3 | tons /year | | | | |

| Energy Consumption Data | | | | | | |
|--|----------------|------|--------|-------------------|------|--------------|
| | Energy content | Unit | Volume | Dimension | Unit | Scaler |
| Beet pulp | 58113 | MJ/h | x | x | | 16142,5 KW |
| CH ₄ | 40679 | MJ/h | 1155 | m ³ /h | | 11299,8 KW |
| CH ₄ prod. | 40679 | MJ/h | 1155 | m ³ /h | | 11299,8 KW |
| CO ₂ waste | x x | | 840 | m ³ /h | x | x |
| N ₂ in end prod. | x | | 115,5 | m ³ /h | x | x |
| Compressor electricity consumption (4000h) | | | | | | 451990,0 kWh |

| Economic data | |
|---------------|------------|
| Energy in | Energy out |
| | |

| Capital Costs | | | | Fixed Operation costs | | Variable Operation costs | |
|--------------------------------|------------|--------------------|---------|-----------------------|-----------------|--------------------------|--|
| | € | | | €/y | | €/y | |
| Investment fraction | 0,08718456 | Water | | xxx | CH ₄ | 2448600 | |
| Project cost | xxx | Maintenance | | xxx | CO ₂ | 7728000 | |
| Construction cost | xxx | Operatio (digeste) | 1155000 | | N ₂ | 1386000 | |
| Investment cost | xxx | PSA (cirmac) | 4620000 | | | | |
| | | electrical cost | xxx | | | | |
| | | Unforseen cost | xxx | | | | |
| Total | | Total | | Total | | Total | |
| Annual investment capital cost | xxxx | €/y | | | | | |

APPENDIX 4 PROCESS DATA CASE 2

| Process data | | Volume | Units | Production cost | 0,8 €/m3 |
|------------------------|--|-----------|-------|-----------------|----------|
| Total methane | | 2196,5 | m3/h | | |
| CO2 produced | | 168 | m3/h | | |
| Annual methane yield | | 8786162,2 | m3 | | |
| Annual CO2 yield | | 672000 | m3 | | |
| Methane relative to CS | | 190,2 | % | | |
| CO2 relative to CS | | 0,2 | % | | |
| Input energy | | 232452 | GJ/y | | |
| Sugar beet input | | 86093,3 | tons | | |

| Energy Consumption Data | | Energy content | Unit | Volume | Dimension | Unit | Power | Unit | Energy content | Unit | Volume | Dimension | Unit | Power | Unit |
|-------------------------|---------|----------------|--------|---------|-----------|------|---------|------|----------------|---------|----------|-----------|---------|---------|------|
| Beets inpu | 58113 | MJ | x | x | | | 16142,5 | KW | CH4 biorec. | 36683 | MJ | 1041,5 | m3/hour | 10189,7 | KW |
| CH4 | 40679,1 | MJ | 1155 | m3/hour | | | 11299,8 | KW | Compressor c | 859580 | kWh/year | x | x | x | KW |
| H2 | 31449,4 | MJ | 3129,3 | m3/hour | | | 8735,9 | KW | Upgrading | x | MJ | x | x | x | KW |
| H2O | x | MJ | 2,5 | m3/hour | | | x | KW | (CH4 product: | 77362,2 | MJ | 2196,5 | m3/hour | 21489,5 | KW |
| Wind pow | 31449,4 | MJ | x | x | | | 12479,9 | KW | | | | | | | |
| N2 input | x | MJ | 219,7 | m3/hour | | | x | KW | | | | | | | |

| Economic data | | Capital Costs | Fixed Operation costs | Variable Operation costs | |
|----------------------|-----------------|----------------------|-----------------------|--------------------------|------------|
| | €/ | | €/y | €/y | |
| Electrolyzer | 7000000 | Water | | CH4 | 4656665,97 |
| Investment fraction | 0,087184557 | Maintenance | 13846031,75 | CO2 | 1545600 |
| Bio-methanation tank | 39153439,15 | Operation (digester) | 2196540,551 | N2 | 2635848,66 |
| Project cost | 4615344 | PSA(cirmac) | 1054339,5 | | |
| Construction cost | 4615343,915 | electrical cost | 20200 | | |
| Investment cost | 46153439,15 | Unforseen sost | 4615349,915 | | |
| Total | | Total | | Total | |
| Annual capital Cost | 4023867,146 €/y | | | | |

APPENDIX 5: CALCULATION BASE CASE METHANE PRODUCTION (ACTUAL COST)

Current case:

Digester output → 2100 m³/hr of raw biogas

Cost of upgrading → 0.12 €/m³ of raw biogas

1m³ natural gas → 90% methane (end product for the grid)

Anaerobic digester eff. → 0.55

Digestion cost → 0.25 €/m³

Cost of 1m³ of methane:

$$\frac{0.25 \text{ €/m}^3}{0.55} = 0.4545 \text{ €/m}^3$$

Product cost of methane = 0.4545 €/m³ + 0.12 €/m³ = 0.574 €/m³

Production cost = 0.9 * 0.5745 €/m³ = 0.5171 €/m³