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Feasibility of Biogas Upgrading at Ejby Mølle Wastewater Treatment Plant

Bachelor Project

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Preface and Acknowledgements

This document is the bachelor thesis of Rune Dal Andersen and Rune Kvols Rasmussen, two sixth semester students of Energy Technology, from the University of Southern Denmark in Odense, Denmark.

The project counts for 15 ECTS points and was started on the 1st of February 2017, with a deadline on the 22nd of May 2017.

The target audience are VandCenter Syd and others interested in the feasibility of a biogas upgrading plant.

A special thanks to Ib Pedersen and Bjarne Christensen from VandCenter Syd A/S for providing data and for good cooperation.

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Thanks to the supervisors Lars Yde, Abid Rabbani and Henrik Wenzel for guidance and constructive criticism at our meetings.

Abstract

The purpose of this project was to determine the feasibility of installing a biogas upgrading facility at Ejby Mølle Wastewater Treatment Plant in Odense, Denmark. Currently, the biogas produced at Ejby Mølle Wastewater Treatment Plant is being combusted in two gas engines. The whole plant is owned by VandCenter Syd Holding A/S, which owns companies that each own a part of the plant. The wastewater treating and biogas producing part of Ejby Mølle Wastewater Treatment Plant is owned by VandCenter Syd A/S, and the gas engines are owned by VandCenter Energy ApS. The feasibility of installing a biogas upgrading facility was investigated by investigating the circumstances at the plant, the different possible solutions currently viable and available on the market, and choosing one to compare to the gas engine-solution which is currently being used at the plant. The comparison between the gas engines and the chosen solution has been made through the use of the modeling and simulation software, EnergyPro. The models in EnergyPro are able to simulate the economics of the plant, and thus finding the revenues, expenditures and profits based on data fed to the model. The higher the profits, the more is Ejby Mølle Wastewater Treatment Plant able to lower the cost of water for its consumers. In order to establish the method of modeling, a reference model for the year 2016 was made. Based on this model, a model for the future with gas engines was made, which was used to compare to the model of the future with biogas upgrading. The comparison was made based on an internal selling price of biogas between VandCenter Syd A/S and VandCenter Syd Energy ApS. As VandCenter Syd A/S has a monopoly on wastewater treatment, they are not allowed to have a profit. VandCenter Syd Energy ApS is however allowed to have a profit, but the goal of the whole corporation is for this profit to be at 4%. To hit this goal, the selling price of biogas between the companies is adjusted yearly.

In the model of the future with gas engines, the biogas price that yields a profit of 4% was found to be 2.46 DKK/Nm^3. In the model of the future with biogas upgrading, the price of biogas was found to be 2.99 DKK/Nm^3. This is however without considering the extra costs due to an increase in the heat price for VandCenter Syd A/S, as they can no longer buy cheap heat from VandCenter Syd Energy ApS. This cost was added in a MATLAB script, where the savings for each consumer also was calculated. The savings due to upgrading compared to the gas engines were found to be 0.062 DKK/m^3 of water. The biogas price of 2.46 DKK/Nm^3 found from the model with gas engines, was also used to make three net present values to make another comparison of the possibilities. The net present value of upgrading over 20 years became an impressive amount of 21,851,925 DKK compared to 3,775,824 DKK for gas engines. Furthermore, models have been made for the purpose of sensitivity analysis. The first set of models was for the sensitivity analysis on subsidies. When removing the subsidies for the gas engines, the price of water was found to increase by 0.384 DKK/m^3 and when removing the subsidies on the biomethane produced by gas upgrading, the price of water was found to increase by 0.376 DKK/m^3, both compared to the model of gas engines with subsidies. The second set of models was for the sensitivity analysis of the price of natural gas. The subsidies on electricity produced on biogas and the subsidies on upgraded biogas are regulated according to the natural gas price, so that the subsidy on upgraded biogas plus the natural gas price combined remain constant. For the gas engines, when the natural gas price was low and therefore the subsidies large, the savings on water for the consumers were found to be 0.114 DKK/m^3. When the natural gas price was high and the subsidies small, the price of water was found to increase by 0.114 DKK/m^3. Compared to the biogas upgrading where the savings for the consumers are found to be 0.062 DKK/m^3, this was a change in price between a decrease in price of 0.052 DKK/m^3 or an increase in price of 0.176 DKK/m^3.

The project concludes that in the current subsidization form, installing a membrane upgrading facility is better than installing new gas engines for Ejby Mølle Wastewater Treatment Plant in the future. This conclusion is vulnerable to the future of natural gas in Denmark though, along with its price and the subsidies on biogas. Therefore, it is important to conduct further investigation into the future of natural gas in Denmark, in order to know if the development is likely to be in favor of biogas upgrading or not.

Contents

Symbols and abbreviations

Symbol	Meaning	Unit
CHP	Combined Heat and Power	-
EAA	Equivalent Annual Annuity	DKK
ETP	Ejby Mølle Wastewater Treatment Plant	-
n	Number of years	-
NPV	Net Present Value	DKK
PE	People Equivalents	-
r_i	Inflation rate	%
r_n	Nominal discount rate	%
r_r	Real discount rate	%
VAT	Value Added Tax	%
VCS	VandCenter Syd	-

Table 1: List of symbols and abbreviations

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Chapter 1

Introduction

With the consequences of the rising CO_2-levels in the atmosphere being increasingly apparent, more and more effort is being put into slowing this negative development. Denmark aims to be a frontrunner in this effort, and has the ambitious goal of being independent of fossil fuels by 2050.

Especially in wind turbine development is Denmark a frontrunner, and in 2015, 50.9 PJ of electricity was produced by wind power, which is 41.8% of the electricity produced in Denmark and roughly 7% of the total energy consumption of Denmark (Energistyrelsen, 2016). The production of electricity from wind turbines fluctuates with the weather and winds though, and when there is no wind, no electricity is produced. This calls for alternative environmental friendly ways of producing energy, which can be used when desired. One such way is through the use of biogas.

In 2015, only 4.7 PJ of energy was produced on biogas. Biogas is however estimated to have a huge potential. The Danish Energy Agency estimates, that the potential of biogas is a yearly production of 42 PJ, of which the first 19 PJ can be produced through use of 50% of manure from farmlands (Energistyrelsen, 2014).

Biogas is also desired by the Danish politicians to be a larger part of the Danish energy sector. With the energy agreement of the 22nd of March, 2012, better conditions for biogas were agreed upon. Among other good initiatives, the agreement expanded the support for alternative uses of biogas. One such alternative use, is storage either in a biogas net or storage of upgraded biogas, so called biomethane, in the natural gas grid. Here the biomethane is treated equally to natural gas. By upgrading the biogas and storing it in the natural gas grid, it is possible to use the gas when desired.

The first biogas upgrading facility in Denmark was installed at Fredericia Watewater Treatment Plant in 2011 in a collaboration between Fredericia Municipality and DONG energy A/S (IEA Bioenergy, 2014). This plant paved the way for further development and expansion of the technology in Denmark, and as of the 2nd of May, 2017, there are 20 upgrading facilities that are connected to the natural gas grid (Energinet, 2017).

This project investigates the feasibility of installing an upgrading facility at Ejby Mølle Wastewater Treatment Plant, in short ETP, in Odense, Denmark. The current situation at the plant will be briefly presented, along with the theory behind the biogas production at the plant. Then the three most used and tested technologies are evaluated, in order to determine which is the most suitable choice for ETP, based on the circumstances at the plant. As the most optimal upgrading technology is determined, models in EnergyPro are developed and used in order to analyze the economics of the plant. A base model is made for the year 2016, which is used as a base- and reference model when investigating the economics of different future scenarios of the plant. In the end, the feasibility of the project is determined based on the potential savings for water consumers in the municipalities as well as net present value calculations. And finally the, results are evaluated based on a sensitivity analysis of different parameters.

Chapter 2

Ejby Mølle Wastewater Treatment Plant

Ejby Mølle Wastewater Treatment Plant (ETP) was build back in 1908, to clean the wastewater and put an end to the massive pollution of Odense Å. Since then the plant has gradually increased in size and the technology has been improved, leading to the advanced plant existing today (VandCenter Syd).

ETP is the biggest treatment plant in Odense. In 2016 it received wastewater from 212,000 population equivalents (PE), which can be increased to almost the double, as the maximum capacity on the plant is 410,000 PE. The term PE is further explained in subsection 5.5.2. The plant has a cleansing limitation of $6700m^3$ pr. hour, which means excess water on rainy days has to go to water tanks for later cleansing.

The plant consists of a mechanical cleaning unit, an active sludge system, two Anammox tanks, two biological filters, a sand filter and a sludge treatment and dewatering unit. The sludge treatment happens in four digestion tanks, where the sludge from the primary clarifier, the biological cleaner and the secondary clarifier goes (Fagerberg, 2016).

In the digestion tanks, biogas which goes to two gas engines is produced. The engines are connected to a generator and it produces an amount equal to 100-110% of their own electricity consumption. The heat produced from the engines is used for heating ETPs own buildings and the digestion tanks, while surplus heat is sold to the district heating grid (VandCenter Syd, 2014).

The gas engines at the plant have a total lifetime of 120,000 hours, and run 12,000 hours each year combined. With one of the engines being rather old, and the other one being installed a few years ago, it is soon time to have a plan for the future use of the biogas. Thus it has to be decided if investing in new gas engines is feasible or if it is better investing into a gas upgrading system.

2.1 VandCenter Syd

VandCenter Syd (VCS) is a group of companies under one holding company; VCS Holding A/S. The division of VCS makes it possible to put different responsibilities into specific companies. ETP is one of many plants under VCS and because of this division in the structure of VCS, ETP is also divided into parts owned by different companies. The structure of VCS involving ETP can be seen in figure 2.1.1.

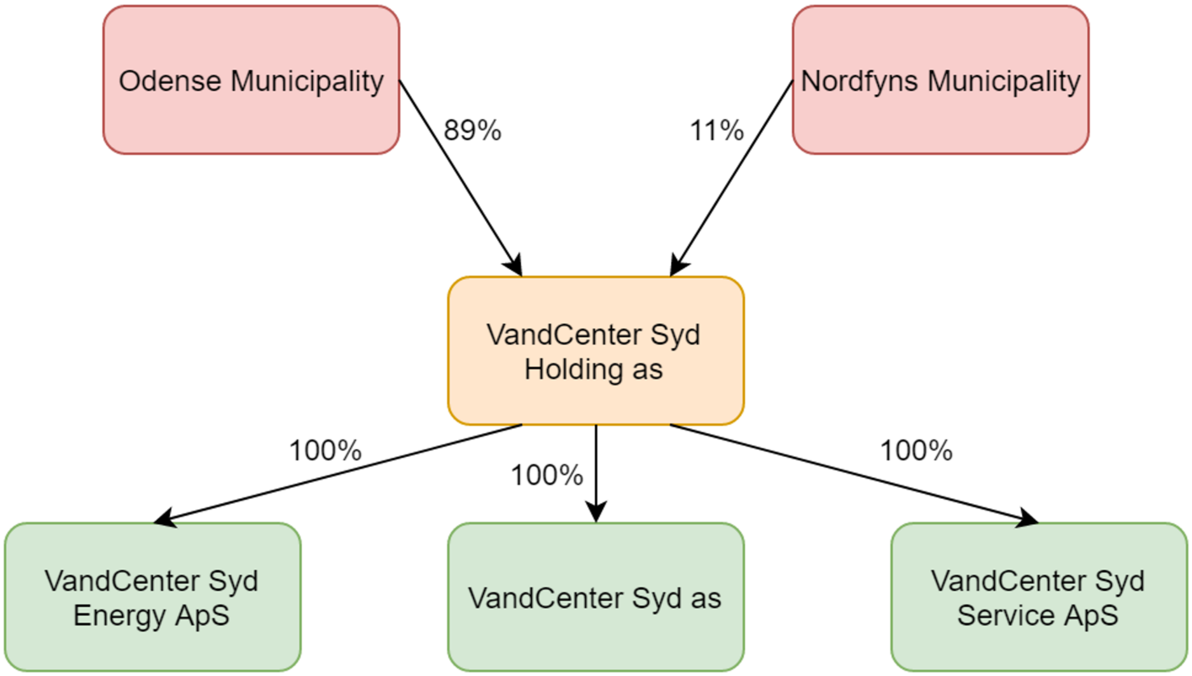

Figure 2.1.1: *The structure of VandCenter Syd*

The plant itself, containing all the cleansing facilities, the administration buildings and the digestion tanks, belongs to VCS A/S. This company sells the produced biogas and as water cleansing is a monopoly, the biogas selling price affects the residents water price.

The biogas is sold to VCS Energy ApS. This company owns the two gas engines and utilizes the biogas to produce heat and electricity. The economic aspects of doing it this way are discussed in chapter 5.

The employees at ETP are hired in VCS Service ApS and from here their hours are divided onto the different companies depending on what they work on.

VCS Holding as is owned partly by Odense Municipality and Nordfyns Municipality, which own 89% and 11% respectively (VandCenter Syd).

Chapter 3

Biogas production

In recent times, energy production at large Danish water treatment plants has moved from being a small side benefit, to being one of the main focuses of the plants. Depending on the wastewater received by the plants, they are able to produce a substantial amount of energy. At ETP they receive sludge from two nearby treatment plants in addition to the sludge they produce themselves, and the sludge from all three plants is ideal for biogas production.

The production of biogas happens through the process of ‘sludge stabilization’, where the production of biogas used to be a side effect, and in many cases the biogas would simply be flared. In the last couple of decades though, the gas has been used beneficially in gas engines and the process of sludge stabilization has been optimized to increase the amount of biogas produced.

Sludge stabilization can be done in a variety of ways but at ETP an anaerobic, single stage process is used. This will therefore be the focus in this section.

In the anaerobic, single stage process the sludge is pumped into a tank where no oxygen is present. Here the decomposition of organic material happens, in a process that can be simplified into two phases. In the first, sour phase the anaerobe microorganisms break the carbohydrates, proteins and fat down into organic acids and alcohol. Then in the alkaline phase the other microorganisms that require the oxygen-free environment break the acids and alcohol into methane and carbon dioxide. Simplified, the process can be summarized as:

$$CH_3COOH \rightarrow CH_4 + CO_2$$
$$4\ CH_3OH \rightarrow 3\ CH_4 + CO_2 + 2\ H_2O$$
$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

For the microorganisms to be able to turn the organic material into methane the most efficiently, they need stable surroundings. Small changes can slow the process down a lot, and it is therefore important to keep several factors constant. These include temperature, pH and stirring. Usually all of these factors will be somewhat satisfied by steadily letting new sludge into the tank as old sludge is taken out. At ETP the process is mesophilic, which means the process runs at roughly 37 °C. To maintain the 37 °C in the tank, heating is usually needed. At this temperature, the optimal time for the sludge to be in the tank is between 21-31 days. It is however not a batch process. As new sludge is loaded into the tank and stirred into the mix, old sludge is removed as well (Henze, M. et al., 2000).

Finally, a summarization of the process at ETP. The biogas production happens in four parallel one-stage tanks at a size of 2800 m^3 each. They are loaded with 360 m^3 to 410 m^3 of sludge with 7% dry-matter each day, depending on the amount of wastewater received at the plant. Here it is kept at 37 °C for 21-31 days, also depending on the amount of wastewater received. Inside the tanks, the amount of dry-matter is at 4% and the heat is supplied by the plant’s own CHP gas engines. Data can be seen in appendix D.0.5.

The plant yearly produces roughly 4.5 mio. Nm^3 of biogas with a methane-content of 63 vol%.

Chapter 4

Biogas upgrade to biomethane

Biogas usually consists of roughly 35% carbon dioxide and 65% methane, as well as smaller parts of other gases such as oxygen, nitrogen and hydrogen sulfide. If the gas is combusted this is usually not a problem as the carbon dioxide, oxygen and nitrogen will be released, and the gas engines have been designed to tolerate the hydrogen sulfide and other corrosive gases in certain amounts, if they are not filtered off. However, for the gas to be suitable for storage in a national gas grid, certain requirements must be met. Vastly different volume-% of methane in the gas also makes the combustion value vary. Therefore, the gas has to consist of a certain amount of methane to be allowed into the national gas grid. In Denmark, the requirement is roughly 97.3 vol%, based on a requirement of the Wobbe Index to be at least 50.76 MJ/Nm^3 (Erhvervs- og Vækstministeriet, 2012). Furthermore, corrosive gases such as hydrogen sulfide have to be reduced to a very low level, in order to not damage the grid.

To make biogas suitable for the gas grid it is upgraded to biomethane. In the upgrading-process, as much as possible of the carbon dioxide and the other unwanted gases are removed, leaving the methane as pure as possible. There are several ways that this can be done, of which the three most used and tested will be explained and evaluated here. It could also be interesting to include the 4th most used technology, pressure swing adsorbtion, as it is close behind the other technologies, but it has not been included in this project. The three evaluated methods are water-scrubbing, amine-scrubbing and membrane-separation.

4.1 Water scrubbing

When using the water-scrubbing technology water is used to separate the carbon dioxide from the biogas. The process exploits the fact that methane and carbon dioxide have different solubilities in water. When the pressure rises, carbon dioxide becomes much more soluble in water compared to methane, and the optimal pressure for water scrubbing facilities to operate at, has been found to be between 6 and 8 bars (Hulteberg et al., 2016)

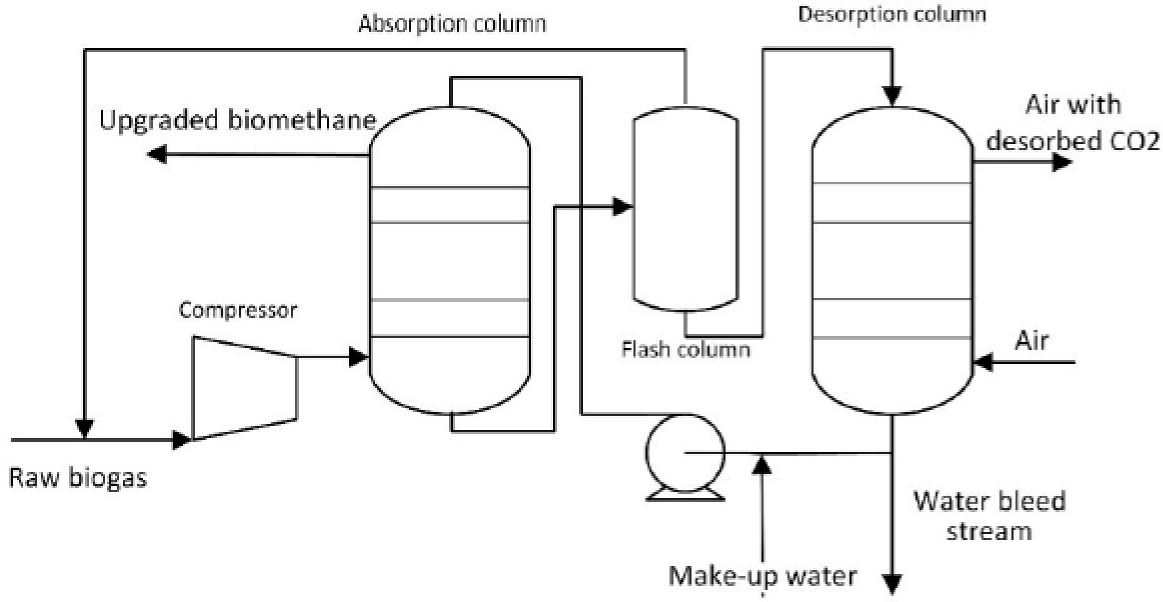

Figure 4.1.1: System overview of a water scrubber. Image source: (Hulteberg et al., 2016)

The general process of a water scrubber can be seen in figure 4.1.1. The plant basically consists of two columns. For the first column, the gas is compressed and lead in at one end and the water at the other end. The water and the gas counter-flows, and the carbon dioxide in the biogas is absorbed by the water. Once the biogas reaches the other end of the column it has been stripped of carbon dioxide and has become biomethane. Hereafter it is dried and leaves the system. The water which now contains carbon dioxide is lead into a flash tank. Here it is exploited that methane is more easily desorbed than carbon dioxide. Most of the methane absorbed in the water is released with some carbon dioxide as the pressure in the flash tank is dropped, and is led back to be recirculated in the plant. The remaining carbon dioxide is scrubbed from the water in the second column, where air is used to desorb the remaining carbon dioxide. The regenerated water is pumped back to be reused as scrubbing liquid once again (Bauer et al., 2013)

This is a general description of a water scrubber. However, more components are usually added depending on the effectiveness wanted, as well as pre- and post-treatment of the gas.

Hydrogen sulfide is also increasingly soluble in water as the pressure rises, in the same way that carbon dioxide is. Therefore, it is possible to remove hydrogen sulfide by water scrubbing as well. Hydrogen sulfide is damaging to the upgrading plant though, and some producers of upgrading plants do not design their plant to allow for any hydrogen sulfide in the biogas. Other producers only design their plants to allow for a certain amount. Exceeding the limitations set by the producers most likely shortens the lifetime of the plant (Miljøstyrelsen, 2015)

4.2 Amine Scrubbing

Amine scrubbing is similar to water scrubbing, as it has an absorption column where the unwanted gases are scrubbed from the biogas, and a desorption column where the scrubbing liquid is regenerated. The main difference between the two technologies is, that the water in the water scrubber has been switched out with a water-based amine solution in the amine scrubber. Instead of only physically absorbing the unwanted gases as the water does, the amines also chemically react with the unwanted gases giving the amines a loading capacity several times higher than that of water. The chemical used, can be chosen to target the unwanted gases that are to be removed.

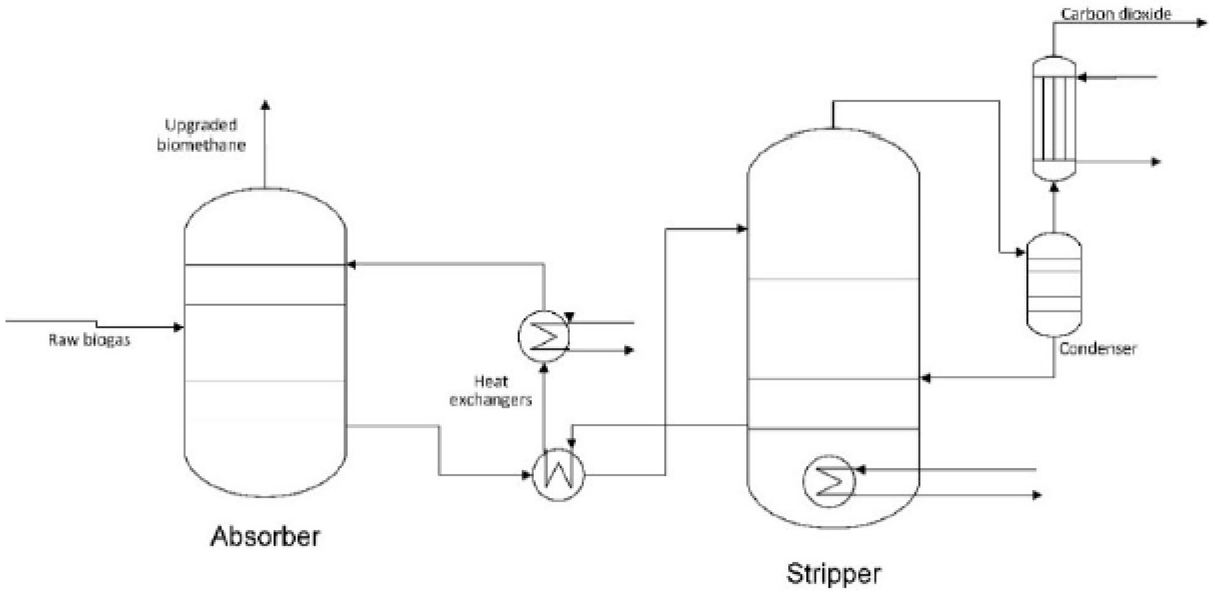

Figure 4.2.2: System overview of an amine scrubber. Image source: (Hulteberg et al., 2016)

On the figure it can be seen, that the amine scrubber looks rather similar to the water scrubber although they are somewhat different in their operation. The use of amines instead of water means that the biogas does not have to be pressurized more than it usually already is. However, the use of amines are a disadvantage in the desorption column, as the loaded amine solution requires rather high temperatures in order to release the carbon dioxide, and even higher temperatures in order to release hydrogen sulfide. Further, some of the amine solution is lost to the biomethane due to evaporation and reaction with the oxygen in the biogas, which means that the scrubbing liquid has to be replenished frequently. A more detailed account of advantages and disadvantages between the technologies is given in section 4.4.

4.3 Membrane Seperation

Membrane separation is vastly different from the two technologies previously described. In membrane separation, it is used that the different components of the biogas have different permeability through the membrane fibers that are used. Most importantly, the membranes allow CO_2-molecules to easily pass through whilst the larger CH_4-molecules only to a small extent pass through.

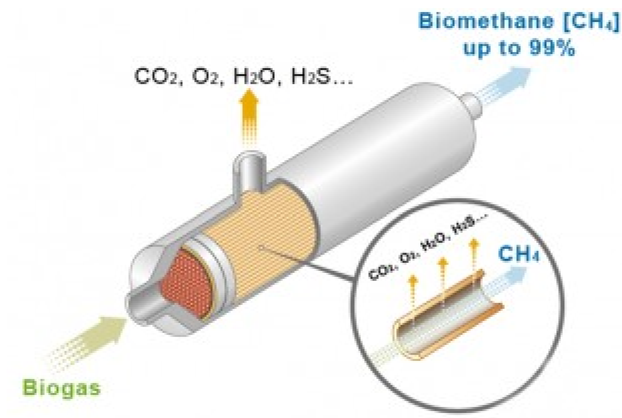

Figure 4.3.3: Internal view for a membrane and the gas flows. Image source: (Air Liquide, 2016)

The biogas is fed into the membranes on one side. The membranes consist of thousands of long and thin fibres. The biogas is pushed through the interior of these fibers at a pressure of between 10 and 20 bars. On the outside of the fibers, the pressure is much lower. The components of the biogas are separated due to the fact that some components more easily permeate through the boundaries of the fibers. The rate at which the gas components permeate through the boundaries of the fibers depends on the size of the molecules as well as their solubility in the fiber material. Gases which have a high solubility and small molecules permeate the fibers faster than gases which have a low solubility and larger molecules.

Gases that easily permeate the fibers will at large leave the membrane on the permeate side. That is, they will permeate through the membrane fibers, and leave the membrane in the off-stream of unwanted gases. The gases that do not will mostly leave the membrane on the retentate side. That is, they will be retained and move all the way through the fibers to leave at the end of the membrane. Most importantly, carbon dioxide mainly leaves the membrane on the permeate side and methane leaves the membrane on the retentate side.

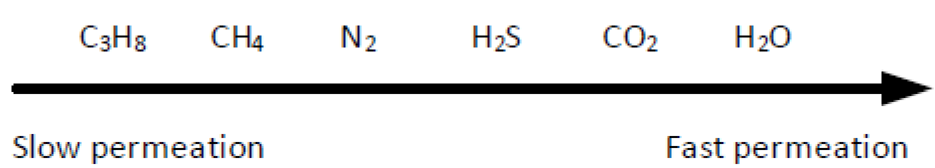

Figure 4.3.4: The relative speed at which the different gas components permeate the membrane fibers. Image source: (Bauer et al., 2013)

Relatively, the separation of gases will commonly look as in figure 4.3.4, where the permeability of the gas components through the fiber boundaries are depicted from fast to slow. The membranes can be designed to have different selectivity though, depending on the composition of the biogas.

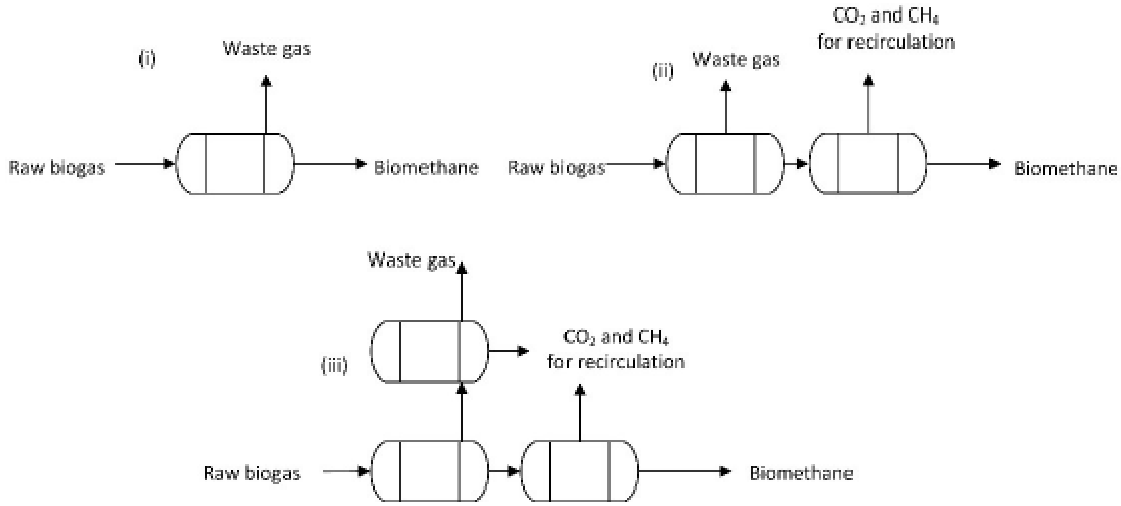

Figure 4.3.5: *System setup for systems with more membranes in series. Image source: (Bauer et al., 2013)*

The membranes are rarely very effective when only one is used. In order to have as small a methane loss as possible, the membranes are commonly set up in series of two or three as can be seen in figure 4.3.5. This is done to capture the small amount of methane that does pass through the fibers to the permeate side, or to capture the carbon dioxide that makes it all the way through to the retentate side.

4.4 Reasons to choose one technology over the others

All of the introduced technologies are widely used and they are each the most suitable solution in different cases. There are advantages and disadvantages to each technology which have to be weighed, when choosing what kind of plant to install.

4.4.1 Removal of gas components

Probably the most important aspect to consider when choosing the upgrading technology, is the composition of the biogas. The components of the biogas affect the process, as well as set requirements for further pre- or post-treatment depending on the upgrading technology.

As previously mentioned, the water- and amine scrubber are rather robust technologies and can in most cases handle certain amounts of impurities such as hydrogen sulfide. The hydrogen sulfide is removed along with the carbon dioxide, but this is only somewhat effective in the water scrubber. In the amine scrubber, the removal of hydrogen sulfide is not as effective and may therefore require further post-treatment of the product gas. Furthermore, when the amines have reacted with the hydrogen sulfide, it requires higher temperatures to regenerate. In either case, post-treatment of the waste gas may be needed.

Membranes are also effective in the removal of hydrogen sulfide etc., but in the event of condensation inside the membrane, it will take damage and lower the efficiency of the facility. Therefore, impurities are often removed before entering the membranes. Ammonia is often removed when the gas is dried, where it leaves the gas along with the condensate. There are various ways to remove the hydrogen sulfide, but one of the most commonly used, especially at low concentrations of hydrogen sulfide, is through the use of active carbon filters. The active carbon filters will often be included in a combined package with the upgrading facility.

Inert gases such as oxygen, nitrogen and hydrogen will not be removed in the water- and amine scrubber plants, and is therefore passed on to the product gas. Furthermore, since the water-scrubber uses air to scrub the carbon dioxide from the water some of the oxygen and nitrogen from the air is dissolved into the water, and passed on to the product gas. With the membrane technology, the inert gasses are also partially removed along with the carbon dioxide. Nitrogen has close to the same diffusion rate as methane though, which means that most of it goes to the product gas. Therefore, the methane pureness of the biomethane largely depends on the amount of nitrogen in the biogas.

4.4.2 Energy consumption and pressure

The energy consumption of all of the technologies is around 0.2-0.3 kWh electricity for each normal cubic meter of biogas upgraded. The one exception though, is that the amine scrubber uses a bit less electricity but instead uses heat in the desorption of carbon dioxide etc. from the scrubbing liquid. Having a cheap heat source could therefore be an argument for installing an amine scrubber, as the operation costs will be relatively lower.

The pressure levels at which the different plants operate are not the same, and it is therefore relevant to consider what the desired pressure level is for the end use of the upgraded gas.

The technology operating at the lowest pressure is the amine scrubber. The working pressure in the absorber column of an amine scrubber plant is usually between 1-2 bars. The pressure in the stripper column is usually slightly higher, at 1.5-3 bars. This means, that for the gas to be used for grid injection, it would most likely need to be further pressurized.

The water scrubber operates at a pressure slightly higher than this. As previously mentioned, the optimal pressure in the absorber column has been found to be around 6-8 bars. This is ideal pressure for grid injection at the distribution level, and would therefore not require any further compression or decompression.

The membrane technology operates at the highest pressure-level of the three, which is usually at 10-20 bars. This means that the pressure level has to be dropped slightly in order for the upgraded gas to be injected into the distribution grid.

4.4.3 Economics of the different technologies

The investment cost of all types of plants vary with size. Generally, the cost for each unit of capacity (cubic meter of biogas upgraded per hour) is decreased as the upgrading capacity of the plant is increased. The investment cost for all of the plant types is close to the same, and can in general terms be seen in figure 4.4.6 below.

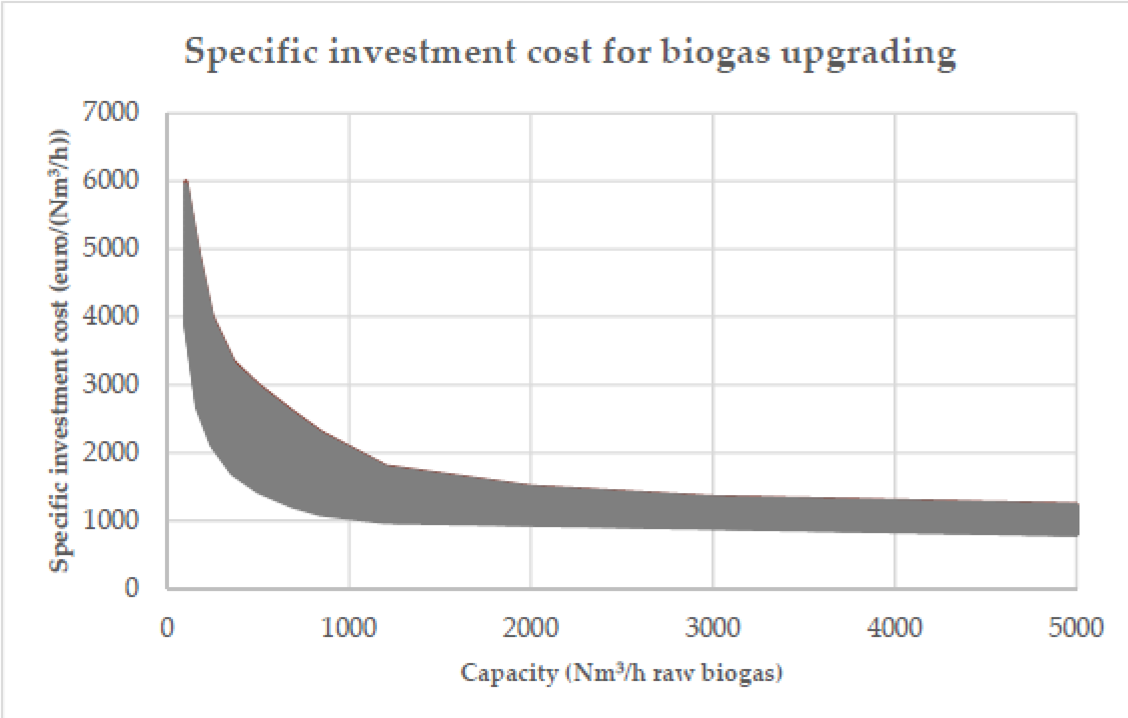

Figure 4.4.6: *The general investment cost of an upgrading facility in euro pr. normal cubicmeter pr. hour, based on the capacity of the plant. Image source: (Hulteberg et al., 2016)*

The cost for each unit of capacity is very large for very small capacity plants. At the small/medium size plants the cost of each unit of capacity has already decreased a lot, down towards 1/3 or 1/4 the price of a very small plant, and as the size increased to large plant above 2000 cubic meters of biogas an hour, the cost of each unit of capacity finds a somewhat steady level. There is a rather large price span for the very small and small plants. This is both due to differences in price between the technologies, but also differences in prices between the different manufactures.

A membrane plant is generally the cheapest option for small size plants and a water scrubber is generally the cheapest option for medium size plants. For large plants, all of the technologies are roughly at the same price, except for membrane plants which are slightly more expensive. For a small sized plant, the membrane solution may therefore be the most desirable.

In regards to the operation and maintenance costs, there are also some differences. As mentioned in the section about energy consumption, the amount of energy used in each technology is close to the same. Therefore, the operation expenses in regards to the energy consumption are also close to the same. There are also some other costs in regards to the operation and maintenance of some of the plants though. All of the technologies use pumps and compressors to drive the gas through the facility, and these pumps and compressors need replacement oil to run optimally. But more than this, the water- and amine scrubbers have other challenges that need consumables to be overcome. Both need anti-foaming agents to prevent foaming in the adsorption column, as foam sometimes can prevent the plant from operating at all. One cause of problems with foam can be microbiological growth, especially in the water scrubber. The problem with microbiological growth can even become so severe, that some parts need to be changed due to clogging. Futhermore, if hydrogen sulfide is oxidized to sulfuric acid in the water scrubber, the rate of corrosion will increase and damage the plant. Therefore, an alkalinity may need to be added in order to keep the pH-value at a desirable value. All of these additional additives are an extra expense for the scrubbers, especially water scrubbers, compared to the membrane technology. To summarize, in general the operation and maintenance of a membrane plant is simpler and less time consuming, than that of the other types of upgrading plants.

4.5 Circumstances at Ejby Mølle Wastewater Treatment Plant

When weighing the advantages and disadvantages of each technology against one another, it has to be with the circumstances at the place of use in mind. In this case, Ejby Mølle Wastewater Treatment Plant.

4.5.1 Biogas composition

As previously mentioned, one of the most important aspects to consider when choosing which technology to use, is the composition of the biogas. The composition of the biogas produced at ETP can be seen in the table below.

Component	Amount	Unit
Methane	63.7	$vol\%$
Carbon dioxide	37	$vol\%$
Nitrogen	0.2	$vol\%$
Oxygen	<0.1	$vol\%$
Hydrogen sulphide	89	ppm
Ammonia	0.2	mg/m^3
Silicon-compounds	9.3	mg/m^3
Silicon	3.5	mg/m^3

Table 4.1: The composition of the biogas produced at ETP. The results are from a test from 2009, which can be seen in appendix F, figure F.0.1

This biogas is currently being combusted in gas engines at the facility. Hydrogen sulfide is also a problem to gas engines though, where the hydrogen sulfide increases the rate of corrosion. Furthermore, combustion of hydrogen sulfide leads to emissions of sulfur dioxide which is harmful to the environment. The silicon-compounds are a problem for the gas engines too. When burned the white powder silicon oxide is formed, which is bad to have in the engine. Therefore, the biogas at ETP is currently being treated in an activated carbon filter before being burned. Here the gas is cleansed of hydrogen sulfide and the silicon-compounds, so these components will not need to be accounted for when choosing upgrading technology.

4.5.2 Gas Grid Injection Requirements

For the upgraded biomethane to be allowed into the Danish natural gas grid, the gas has to live up to certain standards. The most important can be seen in the table below (Erhvervs- og Vækstministeriet, 2012).

Component	Amount	Unit
Upper Wobbe Index	50.76-55.8	MJ/Nm^3
Ammonia	<3	mg/Nm^3
Oxygen	<0.5	$mol\%$
Carbon dioxide	<3	$mol\%$
Hydrogen sulphide and carbonyl sulfide	<5	mg/Nm^3
Total sulfide	<30	mg/Nm^3
Siloxanes	<1	mg/Nm^3

Table 4.2: Requirements for biomethane injected into the gas grid

The Wobbe Index of at least 50.76 MJ/Nm^3 is achieved when the upgraded gas contains at least roughly 97.3 vol% methane.

Apart from this, the gas also must be provided at a certain pressure. There is no set value for this, as it is an agreement between the gas producer and the local distribution company or Energinet.dk. Most commonly the agreement is with the local distribution company, where the gas is to be delivered to the distribution grid at 4 bars.

4.5.3 Suitable choice for Ejby Mølle Wastewater Treatment Plant

With these circumstances in mind, a choice of technology can be made. In regards to the gas composition, there is not much difference but the membrane technology is slightly favorable. Hydrogen sulfide and ammonia has proven to be a problem a problem for the membrane technology if it condensates within the membranes, but as the hydrogen sulfide is already being removed by activated carbon filters and the ammonia is usually removed when drying the gas before upgrade, this should not be an issue. The existing removal of hydrogen sulfide also makes the benefit of the robustness and small removal in the scrubber technology irrelevant.

The requirement of less than 3 mol% carbon dioxide has proven to be easily overcome by all of the different technologies, but the requirement of less than 0.5 mol% oxygen has proven to be more challenging. The biogas at ETP contains less than 0.1 vol% oxygen, meaning that it should not be a problem for the membrane technology. However, when using water scrubbers, some of the air used to desorb the carbon dioxide from the scrubbing liquid has been found to be dissolved into the water. This can led to problems if the plant is not designed properly, or the operation parameters are not configured correctly.

In regards to the pressure, there is not much difference. The pressure in the water scrubbers is ideal for gas delivery to the distribution grid, which is the most likely point of delivery. The pressure in the membranes is at a slightly odd level, where it could be high enough for delivery at the transmission level. But most likely, the pressure level would need to be dropped to connect to the distribution grid. For the amine scrubber, the pressure would have to be slightly elevated to reach the 4 bars.

The remaining points seem to be favorable towards the membrane technology, with the size of the plant being the main argument for a membrane plant. With an hourly production of roughly 515 m^3 biogas per hour, ETP would be characterized as a small biogas production facility. As previously mentioned, when investing in a small upgrading plant the investment costs are the lowest for a membrane plant. Also in regards to the operation and maintenance, a membrane plant is a better choice. There are fewer parameters to keep ideal and overall less work to do once the plant is running.

Therefore, the recommended type of upgrading plant is a membrane plant which will be the focus for the remainder of the report.

4.6 Location for a membrane separation plant

If an upgrading plant is to be installed, it would be preferable to install it close to the digestion tanks, so the produced gas can go directly into the upgrading plant. A membrane separation plant has a size a bit larger than two containers, which makes it possible to fit in smaller areas. A picture of a membrane separation plant at Zastrow Bioenergi ApS on North Funen can be seen in figure 4.6.7.

Figure 4.6.7: *Membrane separation plant at Zastrow Bioenergi Aps*

In figure 4.6.7 a cooling unit can be seen to the left and the containers to the right, containing the membranes.

There are two reasonable positions for a membrane upgrading facility, which can be seen in figure 4.6.8.

Figure 4.6.8: A1 and A2 are proposed positions for a membrane upgrading unit. Image source: (Google Maps)

Figure 4.6.8 shows the four digestion tanks and the areas around them. Area 1 noted as A1 on the figure is a plausible area for setting up the upgrading unit, as it is right next to where the gas is getting cleansed for sulfur. After this cleansing the gas would be ready for upgrading. Another possible area is area 2, noted as A2. In this area there is plenty of space, and there is space to install extra cleansing units, if something unforeseen in the gas, could damage the membranes.

Chapter 5

Economy

At Ejby Mølle Wastewater Treatment Plant (ETP) the gas engines that are running on the produced biogas are approaching the end of their lifetime and will be out of service within 5 years. This demands for an analysis of what the best future solution would be for the plant. As biogas will continue to be produced it strictly limits the possible solutions. If ETP should continue as a heat and electricity producing plant, it either needs a complete overhauling of the gas engines or else the gas engines should be removed and replaced with new ones. Another solution is if ETP ends as a heat and electricity producing plant and instead gets a biogas upgrading facility installed. This chapter includes explanations of how it works at ETP right now, it introduces different models to look at the feasibility of upgrading, it includes Net Present Value calculations and it ends up with investigating the results with sensitivity analysis.

5.1 Current situation at ETP

As explained in chapter 2 VandCenter Syd (VCS) is divided into different companies under one holding company. These companies are VCS A/S, VCS Energy ApS and VCS Service ApS. VCS A/S is not allowed to have any profit and are following the break-even principle, due to its monopoly on water cleansing, while VCS Energy ApS can have a profit. The goal is for this profit to be 4%, so the biogas price is found from the energy company's expenses subtracted from the revenues and is adjusted according to the profit of 4%. The reason for the profit of 4% is a recommendation from the accountants department, see the e-mail in appendix D, figure D.0.4.

The higher the biogas price becomes, the bigger are the revenues for VCS A/S and because of the break-even principle, it lowers the water price for the residents. Figure 5.1.1 shows how VCS A/S produces and sells the biogas, while VCS Energy ApS buys and utilizes it to produce heat and electricity. It all ends up affecting the water price, as it changes what VCS A/S has to take for cleaning the wastewater coming in.

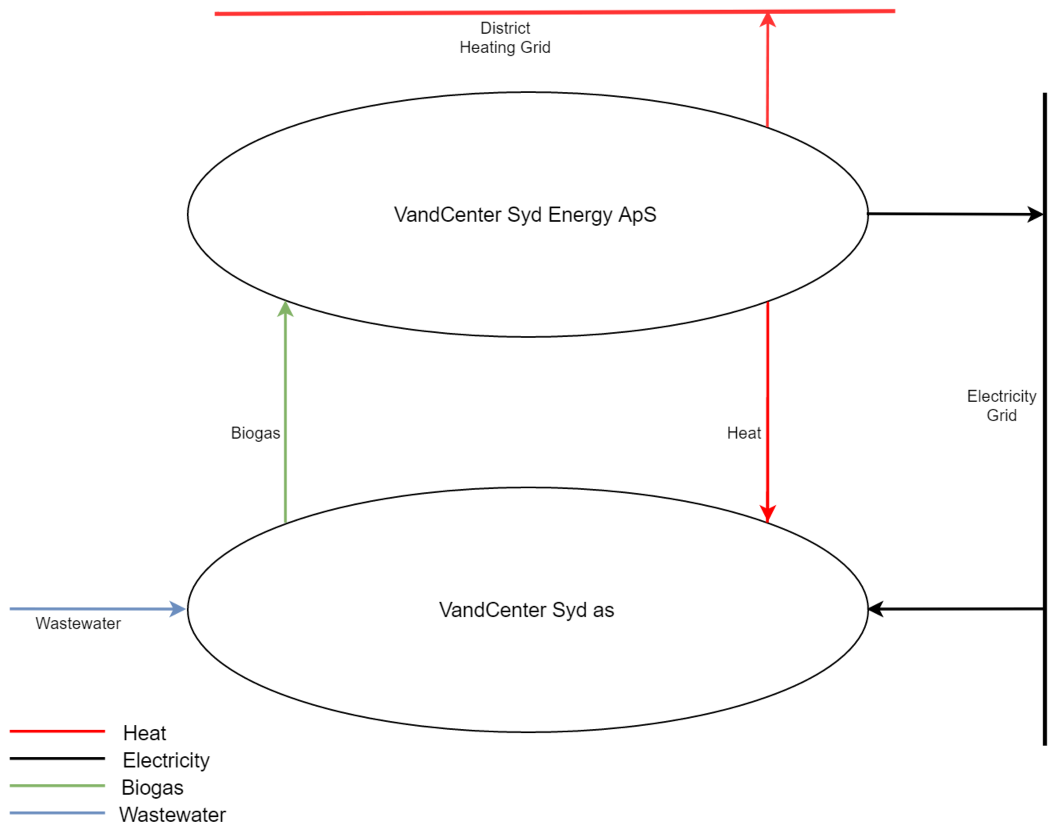

Figure 5.1.1: How the current situation is at ETP.

5.2 Method description, developing a model in EnergyPro

In order to easily calculate the economy of current and future scenarios of ETP, models in EnergyPro have been developed. EnergyPro is a program for modelling and simulation of energy systems, which can be used to optimize operation strategies and energy flows, and calculate cash flows of the system.

5.2.1 Structure of the models

EnergyPro can be used for many things and the main reasons for using it in this project are;

· its easy inclusion of electricity prices from earlier years, as these can be found as timeseries included in EnergyPro.

· its swift calculations of Net Present Values, as it can do it by itself, when all numbers are included.

· its benefits of showing cash flows, income statements and payback period.

· its good overview over which energy related units that are used.

These are all great benefits which have been used throughout the project. For the project many different models have been made, which include biogas price calculations, NPV calculations and different sensitivity analysis. But all of these are modifications of two basis models explained in this subsection. One, where a model of ETP with gas engines is made and another, which is a model with gas upgrading.

In this subsection only the structure of the models are explained. All numbers regarding energy flows and economy are explained and discussed in the upcoming sections and subsections.

The first model made was ETP with gas engines. Figure 5.2.2 shows how the structure of the model is.

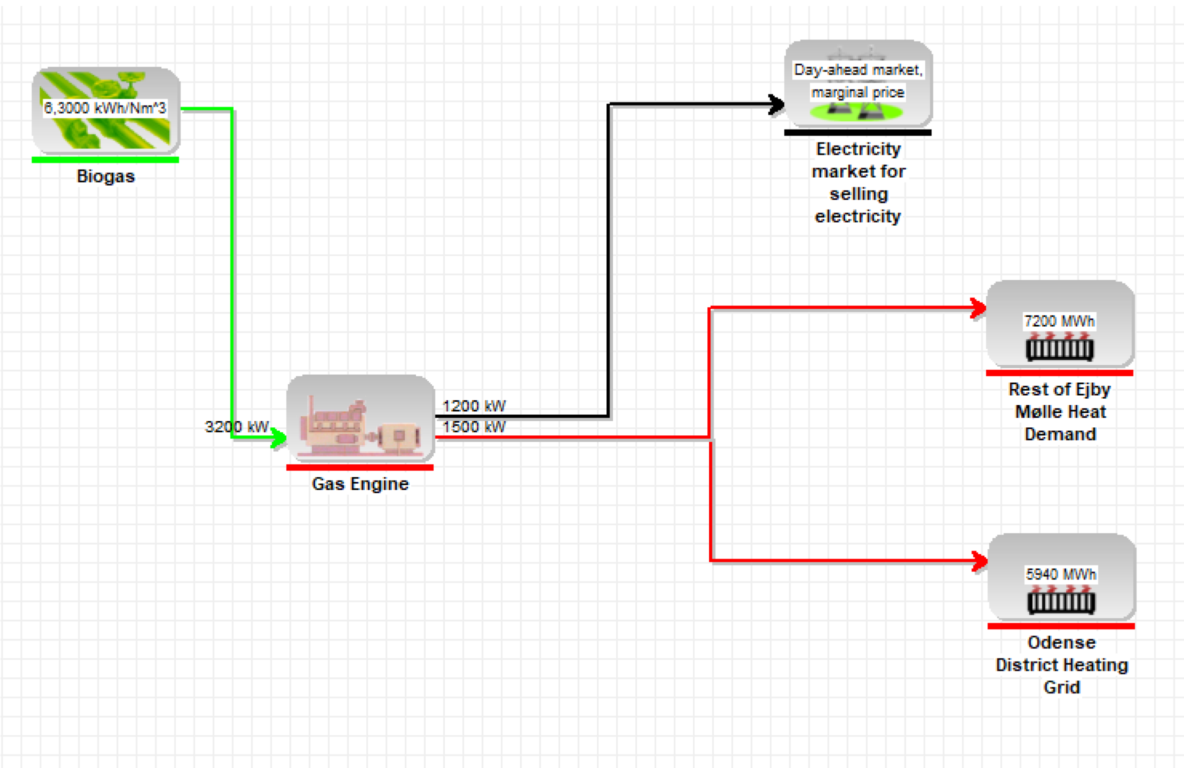

Figure 5.2.2: *EnergyPro model of ETP with gas engines*

In the top left corner of figure 5.2.2 the biogas can be seen. This biogas is what VCS Energy ApS buys from VCS A/S. The biogas is sent to the gas engines, which is illustrated by the green line. In the models both gas engines have been illustrated as one under the name "Gas Engine", to simplify them. The outputs of the gas engines are heat and electricity, which can be seen going out from the right side of "Gas Engine" as the red and black lines. Heat is sold back to VCS A/S and the extra heat is sold to the district heating grid. The electricity is in most models sold at a fixed price, but under the sensitivity analysis in subsection 5.7.1, regarding no subsidies, the spot market, seen in the model, is used.

The second model, which is regarding upgrading at ETP, can be seen in figure 5.2.3.

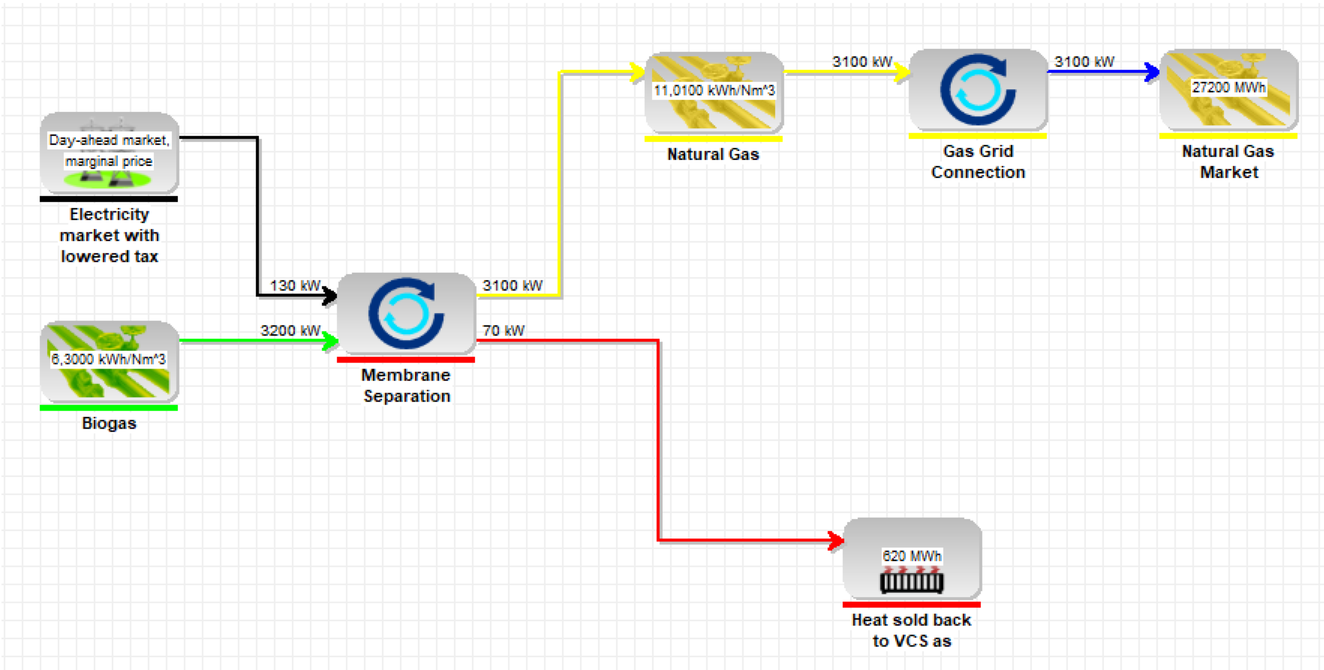

Figure 5.2.3: EnergyPro model of ETP with upgrading

Starting from the left in figure 5.2.3, the electricity market for buying electricity to the upgrading unit can be seen. Underneath it, is the biogas once more. These are both input to the upgrading unit called "Membrane Separation", which is a user defined unit in EnergyPro. "Membrane Separation" produces natural gas and heat. The heat is the waste heat from upgrading and is sold back to VCS A/S. The natural gas goes to "Natural Gas", which is a fuel unit. As EnergyPro has no way of selling natural gas to a natural gas market, this fuel is converted into cooling to make it sellable. The user defined unit which changes the natural gas into cooling is called "Gas Grid Connection" and the unit called "Natural Gas Market" is actually a cooling demand. This is also the reason why the line between the two units is blue. Then the sold cooling is sold at the natural gas price, to make it "act" like it is natural gas being sold.

As mentioned, both of the two models are in many different versions and the modifications made for the different versions are explained in the following sections. Therefore the energy flows and demands changes depending on what is being investigated. This is further explained, when each model is explained. But before any concrete model can be made, an overview of the relevant taxes and subsidies is useful. This is made in the following section.

5.3 Taxes, tariffs and subsidies now and for future scenarios for ETP

This section covers the taxes, tariffs and subsidies that are relevant for ETP now and in the future, as they greatly affect the economy of the plant.

5.3.1 Tax on biogas production

As mentioned, VCS A/S yearly produces roughly 4.5 mio. Nm^3 biogas. As of the 1st of January 2015, biogas which is produced with the intention to be used as fuel for heating, to be sold as fuel for heating or to be used for combined heat and power production in a stationary engine, is taxed at 0.098 DKK/Nm^3. This is for biogas with a lower combustion value of 39.6 MJ/Nm^3, which is the lower combustion value of natural gas. No biogas is 100% methane though, and this tax is corrected to reflect the combustion value of the biogas. At VCS A/S, the vol% of methane in the biogas is roughly 63%, which means that the tax is down to roughly 0.062 DKK/Nm^3. As the production of biogas is the same in all the modeled future scenarios of ETP though, this tax is also the same (Skatteministeriet, 2014)

5.3.2 Tax on biogas combustion

Currently, the produced biogas is being sold to VCS ApS Energy which combusts the biogas in two gas engines. When biogas is combusted in a gas engine, there are different taxes that have to be paid based on the emission of various gases. Biogas is exempt from the CO_2-tax, but taxes on sulfide, NO_x-tax as well as methane-tax still have to be paid.

The sulfide tax depends on the amount of sulfide in the combusted fuel. This tax is at 23.30 DKK/kg in 2017. As ETP cleanses the biogas of sulfide using activated carbon filters, this tax is not relevant.

The NO_x-tax on biogas used in gas engines with a fuel input of more than 1000 kW is 1.00 DKK/GJ in 2017.

The methane-tax on biogas used in gas engines with a fuel input of more than 1000 kW is 1.20 DKK/GJ in 2017 (PriceWaterhouseCoopers, 2016).

These are the expenses in form of taxes that have to be paid due to the production of electricity and heat with biogas. The electricity and heat also generates some revenues for the company, both in form of actual sales revenues as well as revenues from subsidies. And the added subsidies even mean, that the company can sell electricity at a price higher than it is bought at.

5.3.3 Heat at ETP

The heat produced at VCS ApS Energy is used internally, and the surplus is sold firstly to VCS A/S and secondly to Fjernvarme Fyn, who transports and resells it in the district heating grid. The price at which the heat is sold is 51.13 DKK/GJ, which can be seen in appendix D figure D.0.2.

5.3.4 Subsidies on electricity produced on biogas

The electricity produced at VCS Energy ApS is sold to the electricity grid and VCS Energy ApS is paid by energinet.dk in subsidies. There are a total of four subsides on electricity produced on biogas (Energi-, Forsynings- og Klimaministeriet, 2016).

Subsidy 1 is a subsidy set, so that the subsidy combined with the market price was 0.793 DKK/kWh in 2012. As such a fixed price is received no matter the spot price. This subsidy is yearly index-regulated based on 60% of the increase in the net price index, and as of 2016 and 2017, the subsidy is 0.810 DKK/kWh and 0.813 DKK/kWh respectively.

Subsidy 2 is a subsidy which is granted in addition to the spot price, and in 2012 the subsidy was set at 0.431 DKK/kWh. This subsidy too is index-regulated based on 60% of the increase in the net price index. At the beginning of the year, a producer of electricity based on biogas chooses to received on of these subsidies. The remaining two are granted, no matter which of subsidy 1 or 2 is chosen.

Subsidy 3 is a subsidy which is sized according to the price of natural gas in the previous year. The base value of the subsidy is 0.26 DKK/kWh, which is granted at a natural gas price of 53.2 DKK/GJ. For each 1 DKK/GJ that the price of natural gas drops, the subsidy increases in DKK/kWh accordingly, and vice versa. As such, a low natural gas price means that subsidy 3 equally enlarges.

Subsidy 4 is a subsidy which is slowly being out-phased towards 2020. Going forward to 2015 the subsidy is 0.10 DKK/kWh, where after it drops by 0.02 DKK/kWh each year, until it reaches 0 in 2020.

5.3.5 Electricity taxes and tariffs

As mentioned, the price at which ETP buy electricity is lower than their sales price. First time around, the company pays all of the different taxes and tariffs, as well as the spot price. The full electricity price consists of the spot price which fluctuates around 0.20 DKK/kWh (Nordpoolspot, 2017), a distribution tariff which in 2017 is at 0.0831 DKK/kWh (Energi Fyn Net A/S, 2016), a net tariff which in 2017 is at 0.0590 DKK/kWh, a system tariff which in 2017 is at 0.0240 DKK/kWh and the Public Service Obligation (PSO)-tariff which varies for each quarter of the year but has been fluctuating around 0.21 DKK/kWh for the past few years (Energinet.dk, 2017). Furthermore the price includes the electricity tax at 0.91 DKK/kWh as well as a sales tax of 25% (PriceWaterhouseCoopers, 2016). As an example, the total price of the electricity in February 2017 was 1.84 DKK/kWh. (Christensen, 2017)

However, some of these taxes and tariffs are reimbursed. The reimbursed taxes are the sales tax and the electricity tax. When electricity is being used for process-purposes, the tax is reduced to 0.004 DKK/kWh (PriceWaterhouseCoopers, 2016). Process purposes are defined to be e.g.:

- Operation machinery, tools and production facilities
- Lighting and computer equipment
- Pumps and engines
- Ventilation of business rooms (not for space heating or comfort cooling though)
- Electricity used for pumps and ventilation in order to deliver heating or cooling

The process purposes are defined to pretty much only exclude:

- Space heating
- Heating of water
- Comfort cooling

Therefore, all of the electricity used can be defined as being used for process purposes, and the tax is reimbursed. Furthermore, all of the sales tax is reimbursed, as the electricity is being used for a process where a service is conducted, for which a sales tax is being charged. The sales tax is charged as a part of the price for cleaning of water by VCS A/S. If the sales tax was charged both on the cleaning of the water, and the electricity used for the cleaning of the water, the tax would have been charged twice on the electricity.

In the end, the electricity price ends up consisting of the varying spot price as well as the distribution-, net-, system- and PSO-tariffs and totals to around 0.60 DKK/kWh, mainly dependent on the spot price as well as the

PSO-tariff. The PSO-tariff is currently being out-phased towards 2022 though, which means that VCS A/S can look forward to even cheaper electricity in the future.

This big difference in the price of buying and selling electricity is the reason, that the electricity is not being used internally. If the electricity was used internally, VCS A/S would not have to pay the distribution-, net-, system- and PSO-tariffs that amount to roughly 0.38 DKK/kWh. But on the other hand, they would not receive the biogas subsidies on the sold electricity which amount to roughly 1.1 DKK/kWh, making it a bad choice to do so.

The above mentioned prices would stay the same, both if VCS A/S were to overhaul their old gas engines, buy new ones or install a biogas upgrading facility.

5.3.6 Subsidies on biomethane produced on biogas

The subsidies for biogas upgrading are split up close to the same way as for electricity produced on biogas. The subsidies are awarded based on either the lower or the higher combustion value of the gas. In this project, the lower combustion value is used. There are three subsidies which can be received for the upgrading of biogas (Energi-, Forsynings- og Klimaministeriet, 2016)

Subsidy 1 is a subsidy which is granted in addition to the market price of the natural gas and in 2012 the subsidy was set at 79.3 DKK/GJ. This subsidy is index-regulated based on 60% of the increase in the net price index, and as of 2017 the subsidy is at 81.3 DKK/GJ.

Subsidy 2 is a subsidy which is sized according to the price of natural gas in the previous year. The base value of the subsidy is 26.0 DKK/GJ, which is granted at a natural gas price of 53.2 DKK/GJ. For each 1 DKK/GJ that the price of natural gas drops, the subsidy increases in DKK/GJ accordingly, and vice versa. As such, a low natural gas price means that subsidy 2 equally enlarges.

Subsidy 3 is a subsidy which is slowly being out-phased towards 2020. Going forwards to 2015 the subsidy is 10.0 DKK/GJ, where after it drops by 2.0 DKK/GJ each year, until it reaches 0 in 2020.

5.3.7 Heat price due to lowered heat production

In regards to heat, the production of heat would be greatly reduced, as the biogas upgrading facility only produces a small amount of waste heat. This means that the revenue generated from selling heat to Fjernvarme Fyn is no longer relevant as they do not sell heat externally anymore, and that VCS A/S cannot have their entire demand met by VCS Energy Aps. Instead, some of the heat for VCS A/S has to be bought from Fjernvarme Fyn who sells heat at 83 DKK/GJ without sales tax and 103.75 DKK/GJ with sales tax, which is quite an expense compared to the price at 51,13 DKK/GJ which was previously used (Fjernvarme Fyn A/S, 2016)

5.3.8 Overview of taxes, tariffs and subsidies

All of these taxes, tariffs and subsidies have been summarized in the table below.

Table 5.1: Taxes, tariffs and subsidies now and for future scenarios of ETP

Name	Amount	Unit
Tax, biogas production	0.098	DKK/Nm^3
Tax, fuel usage, carbon dioxide	0	DKK/ton
Tax, fuel usage, sulfide	23.30	DKK/kg
Tax, fuel usage, NO_x	1	DKK/GJ
Tax, fuel usage, methane	1.2	DKK/GJ
Subsidy, electricity on biogas 1 in 2012	0.793	DKK/kWh
Subsidy, electricity on biogas 2 in 2012	0.431	DKK/kWh
Subsidy, electricity on biogas 3, base value	0.260	DKK/kWh
Subsidy, electricity on biogas 4 in 2012	0.10	DKK/kWh
Tariff, electricity, distribution	0.0831	DKK/kWh
Tariff, electricity, net	0.0590	DKK/kWh
Tariff, electricity, system	0.0240	DKK/kWh
Tariff, electricity, public service obligation	$\approx$ 0.21	DKK/kWh
Tax, electricity	0.91	DKK/kWh
Tax, electricity, reduced for process	0.004	DKK/kWh
Tax, sales	25	%
Subsidy, biogas upgrade to natural gas 1 in 2012	79.3	DKK/GJ
Subsidy, biogas upgrade to natural gas 2, base value	26.0	DKK/GJ
Subsidy, biogas upgrade to natural gas 3 in 2012	10.0	DKK/GJ

All of the values described in this section are used in the model to calculate the economy of the different scenarios.

5.4 Making a reference model and upscaling it

In section 5.2, the way the model is structured is explained. In this section the two first models including numbers are made. The first model is a reference model, which simulates the year 2016 and establishes the method as a base model, and the other is an upscaled model, which is used as a base for simulations of the future scenarios.

5.4.1 The reference model of year 2016

As previously mentioned, VCS Energy ApS aims to have a profit of 4%. In order to hit this specific profit, the price of the biogas sold from VCS A/S to VCS Energy ApS is adjusted. In 2017 the price of biogas is set at 2,31 DKK/Nm^3, which is adjusted based on the economics of the plant in 2016 (Pedersen, 2017). Using the data from 2016, it is possible to make a reference model that can be used as a base model.

In 2016 the assumed biogas production of VCS A/S inserted in the model is roughly 4,040,000 Nm^3 biogas, determined based on heat and electricity production. The vol% of methane in the biogas produced at VCS A/S is 63%, and therefore the lower combustion value of the biogas is 6.3 kWh/Nm^3. This means, that the gas engines of VCS Energy ApS were able to run with an average input effect of roughly 2,900 kW.

Due to one gas engine not running at maximum capacity, the gas engines produced 1,350 kW of heat at a combined thermal efficiency of 46,5% and they produce 1,050 kW electricity at a combined electrical efficiency of 36,2%. This adds up to 11,845,000 kWh of heat and 9,213,000 kWh electricity by the end of the year.

5.4.2 Economics in the reference model

With all of this in mind, it is now possible to take a look at the economics of the model. As mentioned, the gas engines produce roughly 11,845,000 kWh of heat and 9,213,000 kWh electricity in the year 2016. The revenues and expenses due to this production can be seen in appendix B, figure B.0.1. As can be seen, the main expense is the buying of biogas, which is a cost of 9,330,257.7 DKK. Furthermore there are some minor expenses due to taxes that have already been covered. There are also a few expenses that are yet to be covered. The maintenance and operation service expense is due to an agreement with Jenbacher from who the gas engines were bought. Due to a service agreement with them, VCS Energy ApS have to pay 45.17 DKK/h for running the engines as well as 700,000 DKK in running costs through every 60,000 hours the motors run. On top of this, VCS Energy ApS has to spend two man-hours on each engine daily which is covered in the EjbyMøllestaffHours expense. Source on this data can be seen in appendix D, figure D.0.3. Furthermore, VCS Energy ApS still have three biogas boilers in backup, which have to be maintained. This is covered in the Fixed costforboilers expense (Energistyrelsen, 2016). Lastly, there is some payback for the investment in the gas engines. Each gas engines costs 7 mio. DKK and can run for 60,000 hours before it needs a large overhaul which costs 1.7 mio. DKK. For two engines, this is a combined expense 17.4 mio. DKK. As this brings the lifetime of each engine up to 120,000 hours, and the motors in total run 12,000 hours each year, it gives them a lifetime of 20 years. Splitting the costs of the investment onto each year, gives a yearly expense of 870,000 DKK.

This makes the total expenses for the year 11,510,575 DKK. Then there are the revenues. SoldHeat covers the heat sold to Fjernvarme Fyn and SoldHeatinternally covers the heat sold back to VCS A/S. As mentioned, 51.13 DKK/GJ is earned for the heat sales.

SoldElectricity covers the revenues generated through sales of electricity. Here VCS Energy ApS earns the subsidies which were explained in the previous chapter. Here, the earnings come down to the choice between subsidy one and two, as well as the value of subsidy 3 and 4 at the time. In the choice between subsidy 1 and 2, there are certain advantages to each. In 2016, subsidy 1 was at 0.810 DKK/kWh and subsidy 2 was at 0.443 DKK/kWh (Energinet.dk, 2017). The difference between these two is 36.7 DKK/kWh, and this difference has to be made up for by the spot price, if subsidy 2 is to be viable. The average spot price of electricity was in 2016 at 0.1986 DKK/kWh (NordPoolSpot, 2017), which means that for an electricity producer with continuous production such as VCS Energy ApS the optimal choice is subsidy 1. Subsidy 2 would only be viable for producers who target their production at hours with high electricity prices. Furthermore, the natural gas price in 2015 was on average lower than the base price of 53.2 DKK/GJ for subsidy 3. Therefore, subsidy 3 was in 2016 at 0.336 DKK/kWh. Finally, subsidy 4 had in 2016 been reduced to 0.8 DKK/kWh.

All in all, the revenues generated in 2016 total 13,475,056 DKK. This means that VCS Energy ApS ends the year with a profit of 1,964,299 DKK before corporate tax, which is a 14.6% profit. The difference between the 14.6% and the 4% aim is due to model and method error, as well as uncertainties in the used values.

5.4.3 Upscaling for a normal year

The assumed biogas production in 2016 was slightly lower than the production normally expected. Usually VCS A/S expects to produce roughly 4.5 mio. Nm^3 biogas each year, and this amount is expected to increase as the processes at the wastewater treatment plant are continuously improved. Therefore, another model with the right amount of biogas is made, which can then be used for the comparison of technologies and to indicate the future economics of the facility. As the model is used for calculating future scenarios, there are some changes on some of the parameters.

The model has been upscaled to run with 4,444,027 Nm^3 of biogas and the production of heat and electricity has increased accordingly. Furthermore, there are changes in some of the prices used compared to the reference model of 2016. In general, the upscaled gas engine model will work in 2017-prices. However, the natural gas price has been found to fluctuate quite a bit in recent years, and it was especially low in 2016. Therefore, subsidy 2 on natural gas and subsidy 3 on electricity are rather high in 2017. As these subsidies are changed relative to the change in the natural gas price, the amount of money received from the sales of gas remain constant. However, the subsidy on electricity also fluctuates with the natural gas price, and is granted without influence of the spot price of electricity. This means that in years with a low natural gas price and high subsidies, the production of electricity on a gas engine has an advantage compared to biogas upgrading, and in years with a high natural gas price and low subsidies, the gas upgrading has an advantage compared to gas engines. Therefore, to avoid this fluctuating advantage, the base price of natural gas and the base size of the subsidy is used for the modeling of future scenarios. This natural gas price is 53.2 DKK/GJ and the size of the subsidy is 26 DKK/GJ and 0.26 DKK/kWh for natural gas and electricity respectively.

For this upscaled gas engine model, this means that the amount of money received for the sales of electricity have been lowered compared to the 2016 reference model. In the 2016 model, VCS Energy ApS earned subsidy 1 of 0.81 DKK/kWh, subsidy 2 of 0.336 DKK/kWh and subsidy 3 of 0.80 DKK/kWh, totaling 1.226 DKK/kWh of sold electricity. In the upscaled gas engine model, VCS Energy ApS earns subsidy 1 of 0.813 DKK/kWh, subsidy 2 which is set at the base value of 0.26 DKK/kWh and subsidy 3 is not included, as it has been out-phased in the future. Therefore, the total is 1.073 DKK/kWh of sold electricity.

This means that the revenues generated from the sales of heat and electricity then are 13,680,217 DKK and the expenses total 12,467,703 DKK. This gives VCS Energy ApS a profit of 1,212,514 DKK or 8.9%. The biogas price is then set, so that the desired profit of 4% is hit. The right price is found through iteration. The biogas price that makes VCS Energy ApS hit the 4%, is 2.46 DKK/Nm^3. This is the biogas price, which the biogas price achieved from the gas upgrade model can be compared to, to see the benefits of installing an upgrading plant.

5.5 Biogas and water prices with upgrading

In chapter 4, different upgrading possibilities are discussed and it is concluded that the preferable upgrading solution at ETP is by using membrane separation technology. A model of upgrading has, as mentioned, been made in EnergyPro. To find out if an upgrading solution is better than continuing with gas engines, it all comes down to if the residents who send their wastewater to ETP can save money. Many factors can have an effect on this and these will be discussed in the following subsections.

5.5.1 Change in biogas price with upgrading

The first thing to consider, is how does the biogas price change when using upgrading technology instead of gas engines. To investigate this, an analysis of costs and revenues with upgrading has been made.

Revenues and subsidies

As mentioned, VCS Energy ApS attempts to have a profit of 4%, which is the profit used to find their biogas buying price. When upgrading the biogas to biomethane, the majority of the earnings in VCS Energy ApS comes from selling the biomethane they produced through upgrading. Annually ETP produces almost 4.5 million Nm^3 of biogas with a methane percentage of 63 vol%. This amount of biogas contains an Energy amount of 28,000 MWh. When upgrading there is a small methane slip on less than 0.5% and a downtime on membrane separation plants of 2%, which means that, after upgrading the annual energy in the produced natural gas is on 27,200 MWh (Bioenergy Consult, 2015).

As the biomethane is produced from green energy, there are subsidies that can be received on the sold biomethane. These subsidies are mentioned in subsection 5.3.6. With the use of the natural gas price on 53.2 DKK/GJ and the subsidies, an estimation of the revenues from selling natural gas can be achieved. In one year, the revenues from selling natural gas at ETP adds up to 15,829,719 DKK, see appendix B, figure B.0.3.

Another revenue comes from selling the waste heat produced while upgrading. This waste heat can be sold back to VCS A/S, which they can use for space heating. The annual amount of heat is assumed to be 70 kW and gives a revenue of 114,043 DKK.

Costs

The costs for running an upgrading plant are also quite large. One cost is the electricity that needs to be bought for the plant to run. The electricity prices are found from the electricity prices in 2016 and as mentioned in section 5.3, the sales tax and electricity tax are reimbursed, which lowers the price a lot. As the plant uses approximately 130 kW, the annual cost becomes 424,431 DKK.

Another cost is the maintenance and operation of the plant. This includes service contracts, which can be agreed on with many manufacturers and the general operation of the plant, including fixing temporary problems. The plant does not need much operation as it is supposed to run all the time, while upgrading all the incoming biogas. Maintenance and operation is assumed to be an annual cost of 800,000 DKK.

While VCS Energy ApS will try to keep a more or less steady biogas price, the investment cost for the upgrading facility will have to be divided onto each year. As the investment cost is on approximately 8 million DKK and the lifetime is 20 years, the according amount of the investment in one year is 400,000 DKK. This amount is by looking at the first year in present value.

After receiving an offer from Hitachi Zosen Inova AG in Switzerland, the mentioned assumed costs have been compared to the ones calculated by Hitachi Zosen Inova AG, and they seem to approximately fit. The offer from Hitachi Zosen Inova AG can be seen in appendix E.

Before finding the biogas price, one more cost has to be added. This cost is not coming directly from installing the upgrading plant, but comes because the overhauling of the gas engines is not happening. As they invested in the gas engines the intention was to overhaul them after 10 years. Therefore to make the biogas price steady, the investment of 14 million DKK was not divided onto 10 years. Instead, the investment of 14 million DKK and the price of overhauling of 3.4 million DKK was divided onto 20 years. So, the first ten years they paid 8.7 million DKK which is half of 17.4 million DKK (the half of investment and overhauling), instead of paying the full 14 million DKK investment they would have paid, if they did not expect to overhaul the engines. Thus by choosing not to overhaul they are 5.3 million short. Thus, another cost of 5.3 million DKK in present value has to be included, as all the mentioned costs were in present value. By dividing this cost onto the lifetime of 20 years, it becomes 265,000 DKK annually.

Found biogas price

By using iteration on the biogas price, the price is found to be 2.99 DKK/GJ, which meets the profit of 4%.

5.5.2 Change in water price for the residents

As mentioned upgrading is the best solution, if it can lower the water price for the residents sending their wastewater to ETP. An increase in the biogas price means that VCS A/S receives more money from selling the biogas and as they have a monopoly this directly decreases the water price for the residents. On the other hand when upgrading there is an extra expense due to water heating. When using gas engines, VCS A/S, could buy heat directly from VCS Energy ApS. The price would reflect the heat selling price at the district heating grid on 51.13 DKK/GJ. With upgrading most of the heat has to be bought from the district heating grid at a much higher price. The calculations for this have been done in MATLAB and the script can be seen in appendix C.

Population Equivalent

A population equivalent (PE), is a unit used in waste water treatment. The unit is normally used to express the amount of waste water received at a treatment plant, and as it is population equivalents, it also incorporates waste water from industry. One PE equals 200 liters of used water a day, which means 73,000 liters a year (DCE, 2002). This fact has been used in the following calculations.

Effect of change in biogas price

At ETP they received wastewater load of 212,000 PE in 2016. But as VCS A/S has more water treatment plants than one, they also receive sludge from these. The two other plants they receive sludge from are Odense Northwest and Odense Northeast treatment plants. These plants had a load of 35,000 and 22,000 PE in 2016 respectively, see appendix D, figure D.0.6. To find how the water price changes, the extra earning from upgrading has to be divided onto the amount received at ETP and at the two other treatment plants. The extra earning is calculated as the difference between the gas prices with upgrading and with gas engines, multiplied with the biogas amount. The used biogas price with gas engines is the one found in the upscaling model:

$$(2.99\ \frac{DKK}{m^3} - 2.46\ \frac{DKK}{m^3}) \cdot 4,461,771 m^3 = 2,364,738\ DKK$$

As everything has been upscaled from the 2016 model, this upscaling also have to be done with the PE's. The upscaling is calculated to be 12%:

$$(212,000 + 35,000 + 22,000) PE \cdot 1.12 = 301,280 PE$$

Dividing it onto the received amount of PE's it gives a decrease in the water price of:

$$\frac{2,364,738 DKK}{301,280\ PE \cdot 73,000\ \frac{liter}{PE} \cdot 0.001 \frac{m^3}{liter}} = 0.1026\ \frac{DKK}{m^3}$$

This result is without taking the extra cost for heat into account.

Effect of change in heat price

The amount of heat VCS A/S will have to buy is 26,000 GJ annually (VandCenter Syd, 2014). The waste heat produced from the upgrading plant is assumed to be 70 kW, which means roughly an annual amount of 2200 GJ. This heat can be bought for 51.13 DKK/GJ. The rest of the heat needed is bought from the district heating grid, some for one price and the rest for another price, depending on if they have to pay VAT for the heat or not. The heat used for heating the digestion tanks is VAT-free, because VAT has already been paid by the residents getting their water cleansed (Skat). The amount of heat used for the digestion tanks is annually on 10,500 GJ, calculated from the information in appendix D figure D.0.1 and the heat price without VAT is 83 DKK/GJ. The rest of the heat used at ETP is for space heating and water heating. This heat is bought including VAT for 103.75 DKK/GJ and is an amount of 13,300 GJ.

The extra heat cost for VCS A/S when upgrading is found by subtracting the total heat cost when upgrading by the total heat cost when using gas engines. It gives an amount of 930,000 DKK. Dividing these onto the amount of PE's, gives an increase in water price by 0.0404 DKK/m^3. The calculations have been done in MATLAB, see appendix C.

Found change in water price

Subtracting the increase in water price due the change in heat price of 0.0404 DKK/m^3 from the decrease coming from the change in biogas price of 0.1026 DKK/m^3 gives a total decrease in the water price of 0.062 DKK/m^3 with the use of upgrading.

5.5.3 Evaluation of results

Investing in the upgrading facility will increase the revenues of VCS Energy ApS and therefore also make the biogas price raise from 2.46 DKK/m^3 to 2.99 DKK/m^3. This change in itself is a lot and definitely gives VCS A/S a larger revenue, but as upgrading also makes the heat cost for VCS A/S higher it does not tell the whole story. Therefore it is more relevant to look at how the water price for the residents changes, because the change in water price would include all costs and revenues. This was done by sharing the extra profit in VCS A/S onto the received amount of Population Equivalents, to see how much the water price would change for each volume amount. As mentioned in the subsection above the decrease in water price was found to be 0.062 DKK/m^3. This means that upgrading is more viable than using gas engines.

The water price at VCS A/S in 2017 is on 58.94 DKK/m^3, which obviously shows that the decrease is not large. The part of this price which concerns drain and cleansing of waste water in 2017 is 39.25 DKK/m^3.

Nevertheless, the models conclude that the best future solution regarding the water price for the residents is upgrading the biogas to biomethane. As the models have used many assumptions and the future of subsidies, taxes, revenues and costs are very uncertain, a sensitivity analysis have been made in section 5.7, to investigate what happens if some aspects are different.

5.6 Net Present Value, Equivalent Annual Annuity Approach and Payback Period

It is not only how the water price for the residents changes that can be relevant, when looking at the feasibility of upgrading the biogas at ETP. A Net Present Value (NPV) evaluation is equally relevant and this has been done for the VCS Energy ApS part of ETP, containing all revenues and costs for both upgrading and continuing with gas engines. It has been done with a biogas price set to the found biogas price of 2.46 DKK/m^3 in the upscaled gas engine model in section B.0.2. The reason for using the same biogas price is to make a better comparison of the two technologies and thus see which solution gets the higher NPV. Therefore it has been used in all NPV calculations. The NPV have been calculated in EnergyPro and the models used are modifications of the models explained in the previous sections.

5.6.1 Net Present Value of upgrading

A membrane separation unit is estimated to live 20 years, which is therefore the time period selected for the NPV. The real discount rate used for the calculations is on 4%, which is what Energistyrelsen recommends to use in energy projects (Energistyrelsen, 2013). Inflation is assumed to be 2% based on future estimations of the rate, which are approximately that (Knoema). By rewriting the Fisher equation into the following equation (Cooper and Andrew, 2012):

$$r_n = (1 + r_r) \cdot (1 + r_i) - 1 \tag{5.1}$$

it can be used to find the nominal discount rate. In the equation r_n is the nominal rate, r_r is the real rate and r_i is the inflation rate. The calculated nominal discount rate is:

$$(1 + 0.04) \cdot (1 + 0.02) - 1 = 0.0608$$

This number is rounded off and the used discount rate for the NPV's is 6.1%.

The costs for electricity and maintenance in the first year are calculated the same way as in the section 5.5. Regarding escalation the cost for electricity is set to follow the inflation as escalation factor, while maintenance and operation have a higher escalation factor of 3%, due to the assumed higher need for maintenance as the facility gets older.

The investment cost is still the same on 8 million DKK and the project is assumed to be depreciated linearly, which is done by EnergyPro.

The biogas price is as mentioned set to 2.46 DKK/m^3 and is set to have an escalation equal to the inflation rate.

To get an overall evaluation of the feasibility of the upgrading unit, the extra heat cost for VCS A/S also needs to be taken into account, even though it is not the same company. The reason for this is that extra expenses in any of the companies ends up being paid by the residents anyway. Therefore all payments that change in either VCS Energy ApS or VCS A/S, need to be taken into account. The extra expense for heat is, as calculated in subsection 5.5.2, on 930,000 DKK annually. This expense is also assumed to escalate according to the inflation rate.

The revenues for selling natural gas and the waste heat are calculated the same way as in section 5.5.1 and are also assumed to follow the inflation rate in their escalation.

The corporate tax has been set to be 22%, as it is in 2017 and is assumed to stay the same during the whole project period (SkatteInform).

The NPV of upgrading after 20 years, with a biogas price set to 2.46 DKK/m^3 is on 21,851,925 DKK. The main purpose of this amount is to use it for comparison with the NPV of the gas engines found in the next subsection. The results are evaluated together in subsection 5.6.5.

5.6.2 Net Present Value of gas engines

For the NPV of the gas engines the existing gas engines are assumed to be overhauled, which makes them last for 10 more years. After 10 years an investment in new gas engines is assumed.

To make the comparison with gas upgrading simpler, the chosen discount rate is again 6.1%, the biogas price is 2.46 DKK/m^3, the time period is 20 years and the inflation rate is set to 2 %.

The investment in the first year is on 3,400,000 DKK and is the overhauling of the two gas engines. The next investment is after 10 years and would in present value be 14,000,000 DKK for two new engines. As the second investment is after 10 years, the inflation rate has made it into an amount of 17,065,922 DKK in future value, which is used in the model.

Regarding the costs of the gas engines when making a NPV, they are quite much the same as explained in section 5.4. As the gas engines in this model are assumed to be replaced after 10 years, the escalation factor on maintenance and operation is only set to follow the inflation rate. The same counts for the rest of the costs. This includes biogas price and both NOx and methane tax. The corporate tax is again 22%.

The revenues from both electricity and heat are also calculated the same way as in section 5.4, with an escalation rate following the inflation.

The NPV after 20 years becomes 3,775,824 DKK. This will also be evaluated in subsection 5.6.5.

5.6.3 Equivalent Annual Annuity Approach

The two NPVs that have been made so far, are for a time period of 20 years, but this does not tell the whole story. As the gas engines can be overhauled for only 3,400,000 DKK and combined thereafter would be able to run for 10 years, this alone might be the best solution, as an investment in new engines is not needed. This will mean that two projects with different lifetimes would have to be compared and therefore NPV alone is not enough. Instead, after the NPVs of the projects have been found, the equivalent annual annuity (EAA) can be found, which can be compared instead. The EAA approach is a method normally used, when dealing with projects, that have different project periods. After finding the EAA, the project with the highest EAA is the most viable (Investopedia).

The NPV for only 10 years is done the same way is in subsection 5.6.2, except now the project period is 10 years and the high investment costs after 10 years are excluded. The escalation of the maintenance and operation costs is also put to 3%, instead of the 2% in the last subsection, because the gas engines only gets older during the 10 years.

The NPV becomes 6,404,347 DKK, but this value is not comparable. Instead the EAA can be calculated from:

$$EAA = \frac{r_n \cdot NPV}{(1 - (1 + r_n)^{-n})} \tag{5.2}$$

Where r is the discount rate and n is the number of years. The EAA for overhauled gas engines living 10 years, is found to be:

$$\frac{6.1\% \cdot 6,404,347DKK}{(1 - (1 + 6.1\%)^{-10})} = 874,272DKK$$

By calculating the EAA for upgrading, it becomes:

$$\frac{6.1\% \cdot 21,851,925DKK}{(1-(1+6.1\%)^{-20})} = 1,920,645DKK$$

Both results are evaluated in subsection 5.6.5

5.6.4 Payback Period

Overall it seems like upgrading is the better solution and when using the biogas price of the upscaled gas engine model, the NPV became 21,851,925 DKK. NPV is a very important tool, because it gives a result of how good an investment is in present value and therefore takes into account the time value of money. Nevertheless it is also interesting to see how fast a project can pay itself back monetarily. This is done by looking at the investment costs and the annual cash flows and thereafter finding out when the investment is paid back. This is done automatically by EnergyPro and a graph can be seen in appendix B figure B.0.7, which shows the time of equality between cash flows and the investment. The found payback time is 3 years and 5 months.

5.6.5 Evaluation of results

Calculating the Net Present Value with a biogas price set to what it is in the upscaled gas engine model is another way of investigating which solution is the best one.

The first two NPVs that were made were one for upgrading with a project period of 20 years, and one using gas engines with a project period of 20 years. The results for upgrading and gas engines were 21,851,925 DKK and 3,775,824 DKK respectively. It shows a huge difference in NPV over 20 years, between upgrading and continuing with gas engines, which clearly indicates the benefits of upgrading. It has to be mentioned though, that at the end of the gas engines NPV, they have only existed for 10 years. Which means they might be able to be overhauled cheaply, while the upgrading facility is expected to be entirely out of service at this time.

The second comparison that was made in this section is between, only overhauling the gas engines with a project period of 10 years and comparing that with the upgrading solution. As only overhauling the gas engines will give them a shorter lifetime, the NPV's where not enough and therefore EAA's were found as well.

With a NPV of 6,404,347 DKK, the EAA of overhauling the gas engines is 874,272 DKK. Compared to the EAA of upgrading on 1,920,645 DKK, it looks very low. As the NPV over 20 years is better with upgrading and the EAA of upgrading is better than the EAA of overhauling the gas engines, it once more seems like upgrading is the better solution.

This section also shows that there is a payback period of only 3 years and 5 months, when using upgrading with a biogas price equal to the one, when using gas engines. This verifies the viability of upgrading. But before any conclusions can be done, the sensitivity on different factors have to be investigated, which is done in the following section.

5.7 Sensitivity analysis

When discussing future projects there are always many factors that might not stay the same in the future and these are hard to take into account. Nevertheless investigating what happens when some aspects are different is smart to analyze and that is why sensitivity analysis on some factors have been made.

5.7.1 Sensitivity analysis on subsidies

When making a sensitivity analysis the first thing that comes to mind is subsidies. These might change a lot during the upcoming years and therefore are very relevant to investigate. Therefore the models to find the gas prices have been made once more, this time where all subsidies have been removed.

In the gas engine model, the selling price for the electricity produced from the gas engines is set to follow the known spot prices of 2016. This makes the biogas price fall to 0.478 DKK/m^3. This is used in the MATLAB model that can be seen in appendix C and is used to see how the water price will change with no subsidies. From the MATLAB model the achieved result is an increase in water price of 0.384 DKK/m^3.

Comparing it with upgrading, all the subsidies are also removed and only the natural gas selling price of 53.2 DKK/GJ remains. The biogas price is found to be 0.723 DKK/m^3 and is also inserted in the MATLAB model in appendix C. Even though the biogas price is a lot higher than the one of the gas engines, the change in water price becomes very similar, due to the extra heat cost when upgrading. This extra heat cost is the same as explained in section 5.5.2. The change in water price found from the MATLAB model is an increase of 0.376 DKK/m^3, almost the same as for gas engines with no subsidies.

As the changes that would happen in water prices are almost the same, when subsidies are removed from both electricity and natural gas, it shows, that even in this case the upgrading solution is viable.

In the case that subsidies are only removed from natural gas, then upgrading would definitely not be a viable solution, as there would be an increase in the water price of 0.376 DKK/m^3.

5.7.2 Sensitivity analysis on natural gas price

The price of natural gas is not a fixed amount. The price of natural gas fluctuates based on supply and demand, and will continue to fluctuate in the future as it has done in the past and this is rather important for the economics of an upgrading plant compared to gas engines.

As previously explained in 5.3 and 5.4.2, subsidy 2 on natural gas and subsidy 3 on electricity produced on biogas fluctuate with the natural gas price. When the price of natural gas is low, the subsidy is large and when the natural gas price is high, the subsidy is small.

The subsidy was created so that when the price of natural gas is 53.2 DKK/GJ, subsidy 2 on natural gas is 26 DKK/GJ and subsidy 3 on electricity is 0.26 DKK/kWh, and neither the biogas upgrading technology nor the gas engine technology is subsidized advantageously. However, the more the price of natural gas deviates from the base value of 53.2 DKK/GJ, the more the subsidies will be advantageous to one technology compared to the other.

To show how this advantage shifts when the natural gas price changed, the models of both the upscaled model with gas engines as well as with biogas upgrading have been altered. In the first example, the price of natural gas is set at 79.2 DKK/GJ. This takes both subsidy 2 on natural gas and subsidy 3 on electricity down to zero. For both the gas engines and the biogas upgrading the new price of the biogas is found to hit the 4% profit, and the savings on water for the consumers is found. It is found, that when the subsidies are at their lowest and has engines are used, the water consumers have to pay an extra 0.114 DKK/m^3 for water compared to the base model. As the natural gas price has increased the same as the subsidy has been lowered, the savings on water are still the same as previously found. This saving was found to be 0.062 DKK/m^3. This shows, that when the price of natural gas is high, biogas upgrading provides a change in the price of water which is 0.176 DKK/m^3 better than that of the gas engines.

In order for the subsidies to hit zero, the price of natural gas was risen by 26 DKK/GJ compared to the base value. This same change is made negatively, to show the opposite effect. The price of natural gas is set to 27.2

DKK/GJ, taking subsidy 2 on natural gas to 52 DKK/GJ and the subsidy 3 on electricity to 0.52 DKK/kWh. Once again the new price of biogas is found, as well as the savings on water for the consumers. The savings due to the gas engines end up being 0.114 DKK/m^3. This is the same result as previously but with opposite sign, naturally because the subsidy also has been changed the same amount as before but with opposite sign. Again, as the subsidy has increased by the same amount as the price of natural gas has lowered, the savings on water due to biogas upgrading are still 0.062 DKK/m^3. This shows, that when the price of natural gas is low, the gas engines provide a change in water price which is 0.052 DKK/m^3 better than that of the biogas upgrading.

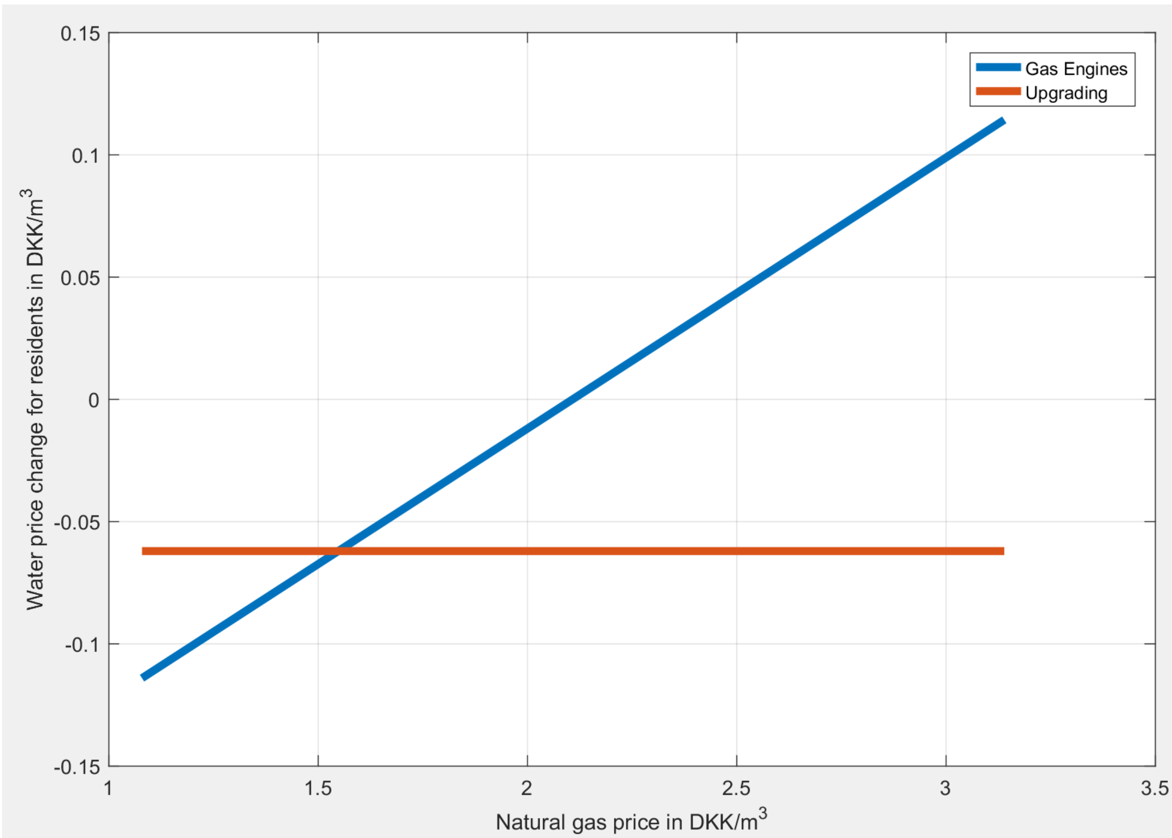

Figure 5.7.4: Change in price on water due to the gas engines and biogas upgrading as a function of the natural gas price

In figure 5.7.4, the change in water gas price due to natural gas price has been depicted graphically. It can be seen, that at a natural gas price of 1.5488 DKK/m^3, or 39.08 DKK/GJ the technologies are equally good. Should the price of natural gas fall below this value, then the gas engines are subsidized advantageously and should the price of natural gas increase, then the biogas upgrading is subsidized advantageously.

A discussion on the future of natural gas and its price in Denmark will be done in section 6.2.

Chapter 6

Discussion and topics for future investigation

6.1 Discussion of the results

The goal of the project was to investigate the feasibility of biogas upgrading at Ejby Mølle Wastewater Treatment Plant. This has been done by first creating a model used to simulate the production of electricity and heat on gas engines which are currently being used, and comparing the results to a model simulating the upgrading of the biogas. It is found, that the users of water can save 0.062 DKK/m^3 if an upgrading facility is installed instead of new gas engines in the future. This is under the assumption, that the subsidies stay the way they are today and that the price of natural gas is 53.2 DKK/GJ.

In order to investigate the vulnerability of the results to changes in either the price of natural gas or the subsidies, a sensitivity analysis on each factor has been conducted.

The sensitivity analysis on the subsidies show that if the subsidies on electricity produced on biogas are removed, then the price of water will increase by 0.384 DKK/m^3 and if the subsidies on the biomethane produced by gas upgrading are removed, the price of water will increase by 0.376 DKK/m^3. Both of these price increases are compared to the scenario with gas engines with subsidies.

The sensitivity analysis on the natural gas price shows that if the natural gas price is low and therefore the subsidies on the electricity produced on biogas large, then the gas engines will give a saving for the consumers of water of 0.114 DKK/m^3. And if the natural gas price is high, and therefore the subsidies on the electricity produced small, then the consumers of water will see an increase in the price of 0.114 DKK/m^3. The savings for the consumers of water due to biogas upgrading stay constant at 0.062 DKK/m^3. This means that the savings for the consumers due to the gas engines fluctuate between a saving of 0.052 DKK/m^3 and an extra expense of 0.176 DKK/m^3 compared to the biogas upgrading. The natural gas price at which the savings for the consumers are equal are at 1.5488 DKK/m^3 or 39.08 DKK/GJ.

Furthermore, net present value and equivalent annual annuity approach calculations have been made for both of the future scenarios with gas engines as well as the scenario with biogas upgrading. This is still done under the assumption that the subsidies stay the way they are today and that the price of natural gas is 53.2 DKK/GJ. The net present value of upgrading becomes 21,851,925 DKK, much higher than the net present value over 20 years for gas engines on 3,775,824 DKK. But the equivalent annual annuity calculated from the gas engines over 10 years on 874,272 DKK is not that far from the one of upgrading on 1,920,645 DKK. With changes in the natural gas price, this could tip in favor of overhauling the gas engines and have them for 10 more years.

Should the subsidies be removed, then the economics of either solution would naturally become worse, but it would still be more beneficial to use one of the solutions, rather than not using the biogas at all. As shown by the sensitivity analysis on the natural gas price though, then the optimal choice of solution changes as the price of natural gas is changed. The price at which gas engines and biogas upgrading is equally good was found to be at 1.5488 DKK/m^3. In the past eight years the price has been quite a bit higher than this, topping at 3.47 DKK/m^3 in 2011. The price has been dropping since 2011 though, and in 2016 the price was at average 1.64 DKK/m^3, meaning the natural gas price today is close to the value that makes the two solutions equally good. It is therefore important to have a great understanding of the future role of natural gas in the Danish energy system and if the price of natural gas will continue falling or rise back up, before choosing which solution to implement. This is further discussed in section 6.2.

6.2 The future of natural gas in Denmark

As shown by the sensitivity analysis on the price of natural gas in subsection 5.7.2, the price of natural gas is very important to consider when choosing which technology to invest in. Therefore, having a good idea of what will happen with the price of natural gas in the future is important.

As mentioned in chapter 1 Denmarks goal is to become fossil fuel free by 2050. The use of natural gas in Denmark began in the mid 80's and reached its apex in 2003 and 2006 at 192 PJ. But since then, the use of natural gas has dropped down to 138 PJ in 2013, and this development does not seem to change. There are several factors that have been causing the use of natural gas in Denmark to drop, and the use will drop further prior to the deadline of being fossil fuel free in 2050 (Dansk Energi, 2015).

The first point is that the danish electricity demand to a larger and larger extent is being met by renewable sources such as wind- and solar-power, as well as hydro-power from Norway. The increasing availability of electricity and the stagnating consumption means, that the decentralized CHP plants primarily running on natural gas no longer have the same amount of operation hours as previously. Enhancing this effect is the fact, that the base subsidy for decentral CHP plants which went into effect in 1998 is reaching the end of its 20 year lifetime. Furthermore, with the industrial sector receiving support for the use of renewable energy as well as the expansion of district heating in both the industrial and residential sector, process heat and residential heating by natural gas is slowly becoming less favorable, lowering the need for natural gas. And in the market, the reduced demand for natural gas means a lower price making it unlikely that the price will rise in the future.

The out-phasing of natural gas has several consequences for the future of renewable gases such as upgraded biogas. The main consequence is the effect that the lower amounts of natural gas being transported around will have on the Danish natural gas grid. Dansk Energi, an industry- and interest group, expects the demand for natural gas in Denmark to fall to roughly 43.3 PJ by 2035. The reduction in the amount of gas in the grid by 150 PJ compared to its peak may bring consequences to the economy, expansion and functionality of the grid. It is still unknown if the large investments made on renewable gases will pay of, but maintaining the grid is crucial for the vision of using renewable gases as a part of the future Danish energy system.

There are some points that draw in favor of maintaining the Danish natural gas grid until the technologies for renewable gases have matured though. One of the main points is that all of the natural gas imported by Sweden is transported in transit through Denmark. In 2011, this amount was roughly 50 PJ. There are uncertainties on how this amount will change in the future, but the Swedish ambitions in regards to biogas and the use of liquefied natural gas in the transport sector are factors that point in the direction of continued gas-transit of Swedish imports through Denmark.

Another point is the need for reserves in the Danish energy system. With renewables such as solar and wind power taking up the majority of electricity production in Denmark, the electricity grid is also more prone to instability. This calls for reserves being at hand, which at large can be covered by decentral CHP plants that run on natural gas. Additionally, in the future fuel cells can be used to regulate the frequency in the electrical grid whilst producing hydrogen, which can either be sent to the natural gas grid or be used in biogas upgrading in the methanation process.

Even with maintenance of the natural gas grid for future use though, the amount of gas in the grid will be lower than today thus most likely increasing the costs for e.g. distribution for the few who use it.

As a concluding remark, it is important to keep an eye on the gas system and the politicians' intent for it in the future, as large changes will happen within the next 20 years. When speaking of the subsidies on natural gas and how subsidy 2 changes in accordance to the natural gas price specifically, it is important to keep and eye on the development of these subsidies in the future. Biogas upgrading currently receives the bulk of its profits through subsidies and most likely will continue to do so for many years, until the technology has matured.

6.2.1 Subsidies on natural gas

Currently, the subsidies favor biogas upgrading when the price of natural gas is high, and the subsidies favor gas engines when the price of natural gas is low. As the future of natural gas in the Danish energy system is rather uncertain though, so is the future form of the subsidies. The current subsidies have no expiration date due to Danish law, but the approval of governmental support by the European Union which was given in 2013 only last for 10 years. Therefore, the current subsidies are up for revision in 2023, where anything can happen (Energistyrelsen).

Chapter 7

Conclusion

The three most tested and used biogas upgrading technologies have been evaluated in regards to the circumstances at Ejby Mølle Wastewater Treatment Plant, and it was found that biogas upgrading using the membrane separation technology is the most suitable choice for the plant. Based on this technology, several models have been made in order to calculate the future economics of the plant in different scenarios. The results show, that in most cases biogas upgrading by membrane separation is the better solution compared to gas engines. This includes models, where the change in water price for the residents are found at a natural gas price of 53.2 DKK/GJ or 2.11 DKK/m^3, which the ministry of energy, supply and climate has set as the base price of natural gas. Here the water price is decreased by 0.062 DKK/m^3, by installing a biogas upgrading facility instead of gas engines. It also includes models where the net present value of installing an upgrading facility is compared to the net present value of gas engines. The net present value of upgrading over 20 years ends up being 21,851,925 DKK compared to 3,775,824 DKK for gas engines. When comparing the net present value of upgrading over 20 years, with the net present value of gas engines over 10 years, an equivalent annual annuity was found. It gave an amount of 874,272 DKK for gas engines and 1,920,645 DKK for upgrading, which again is in favor of upgrading.

In the current subsidization form, the gas engines which are currently being used, are only better when the natural gas price is lower than 1.5488 DKK/m^3. The price of natural gas has been dropping for the past five years though, and was in 2016 1.64 DKK/m^3 which is very close to the value that makes gas engines and biogas upgrading equally good. It is therefore very important to conduct further investigation into the future of natural gas in Denmark in order to have the best idea of, whether biogas upgrading will stay viable in the future or not.

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Appendix A

The problem proposal

The lifetime of the gas engine at Ejby Mølle Wastewater Treatment Plant is coming to an end in roughly five years. Therefore a plan for how the biogas is to be utilized in the future is needed.

This study investigates the possibility of upgrading the biogas to natural gas and selling it to the natural gas grid. This includes a review of the various technologies, that can be used for upgrading. Furthermore it includes considerations in regards to operating the whole plant, such as possibilities of using process heat internally at the plant. The economy of upgrading is compared to the economy of installing new gas engines when the lifetime of the old ones comes to an end and the achieved results are investigated in a sensitivity analysis.

Appendix B

EnergyPro results

This section includes results from the different EnergyPro models. Underneath is the income statement of the 2016 reference model:

Income Statement from January 1, 2016 to December 31, 2016

(All amounts in kr.)

Revenues								
SoldElectricity	:	9.213,3 MWh	at	1.226,0*	=	11.295.461		
Sold Heat Grid	:	4.625,9 MWh	at	184,0*	=	851.166		
Sold Heatinternally	:	7.219,7 MWh	at	184,0*	=	1.328.429		
Total Revenues								**13.475.056**
Operating Expenditures								
Maintenance and Operation Servi	:				=	682.000		
Biogas Price	:	4.039.072,6Nm^3	at	2,31*	=	9.330.257		
NOx tax	:				=	91.500		
Methane tax	:				=	110.000		
Fixed costs for boilers	:				=	27.000		
Ejby Mølle staff Hours	:				=	400.000		
Total Operating Expenditures								**10.640.757**
Depreciations								
New Gas Engine							870.000	
Total Depreciations								**870.000**
Operation Income								**1.964.299**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**1.964.299**
Tax payments								
Corporate Tax							432.146	
Total Tax payments								**432.146**
Result Of The Year								**1.532.153**

Figure B.0.1: *Income statement of 2016 model*

The income statement below is the income statement of the upscaled model:

Income Statement from January 1, 2022 to December 31, 2022

(All amounts in kr.)

Revenues								
SoldElectricity	:	10.499,0 MWh	at	1.073,0*	=	11.265.443		
Sold Heat	:	5.923,8 MWh	at	184,0*	=	1.089.973		
Sold Heatinternally	:	7.200,0 MWh	at	184,0*	=	1.324.800		
Total Revenues								**13.680.217**
Operating Expenditures								
Maintenance and Operation Servi	:				=	682.000		
Biogas Price	:	4.444.027,6Nm^3	at	2,46*	=	10.932.308		
NOx tax	:				=	102.000		
Methane tax	:				=	121.000		
Fixed costs for boilers	:				=	27.000		
Ejby Mølle staff Hours	:				=	400.000		
Total Operating Expenditures								**12.264.308**
Depreciations								
New Gas Engine							870.000	
Total Depreciations								**870.000**
Operation Income								**545.909**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**545.909**
Tax payments								
Corporate Tax							120.100	
Total Tax payments								**120.100**
Result Of The Year								**425.809**

Figure B.0.2: *Income statement of upscaled model*

The income statement below is the income statement of upgrading:

Income Statement from January 1, 2022 to December 31, 2022

(All amounts in kr.)

Revenues								
Sales of Natural Gas								
Total sale of Natural Gas	:	27.199,7 MWh	at	577,8*	=	15.715.987		
Sales of Natural Gas Total							**15.715.987**	
Heat Sold	:	618,1 MWh	at	184,0*	=	113.732		
Total Revenues								**15.829.719**
Operating Expenditures								
Electricity Cost	:				=	424.431		
Maintenance and Operation	:				=	800.000		
Biogas Price	:	4.449.523,8Nm^3	at	2,99*	=	13.304.076		
Extra cost due to not overhauling	:				=	265.000		
Total Operating Expenditures								**14.793.507**
Depreciations								
Upgradingfacility							400.000	
Total Depreciations								**400.000**
Operation Income								**636.211**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**636.211**
Tax payments								
Corporate Tax							139.967	
Total Tax payments								**139.967**
Result Of The Year								**496.245**

Figure B.0.3: Income statement of upgrading

Underneath are the three calculated NPV's. The first one is the NPV of upgrading, the second is the NPV of the gas engines over 20 years and the last one is the NPV of gas engines over 10 years.

Investment Key Figures

Net Present Value of		
Net cash from operation and investments	:	28.423.297 kr.
Tax payments	:	-6.571.372 kr.
Financialpayments	:	0 kr.
All Payments	:	21.851.925 kr.
(at a nominal rate of: 6,1% p.a.)		

Figure B.0.4: Net present value of upgrading over 20 years

Investment Key Figures

Net Present Value of		
Net cash from operation and investments	:	6.534.382 kr.
Tax payments	:	-2.758.558 kr.
Financialpayments	:	0 kr.
All Payments	:	3.775.824 kr.
(at a nominal rate of: 6,1% p.a.)		

Figure B.0.5: Net present value of gas engines over 20 years

Investment Key Figures

Net Present Value of		
Net cash from operation and investments	:	8.169.126 kr.
Tax payments	:	-1.764.779 kr.
Financialpayments	:	0 kr.
All Payments	:	6.404.347 kr.
(at a nominal rate of: 6,1% p.a.)		

Figure B.0.6: Net present value of gas engines over 10 years

Underneath is a graphical representation of the Payback Period with upgrading, if the biogas price is kept the same as in the upscaled model:

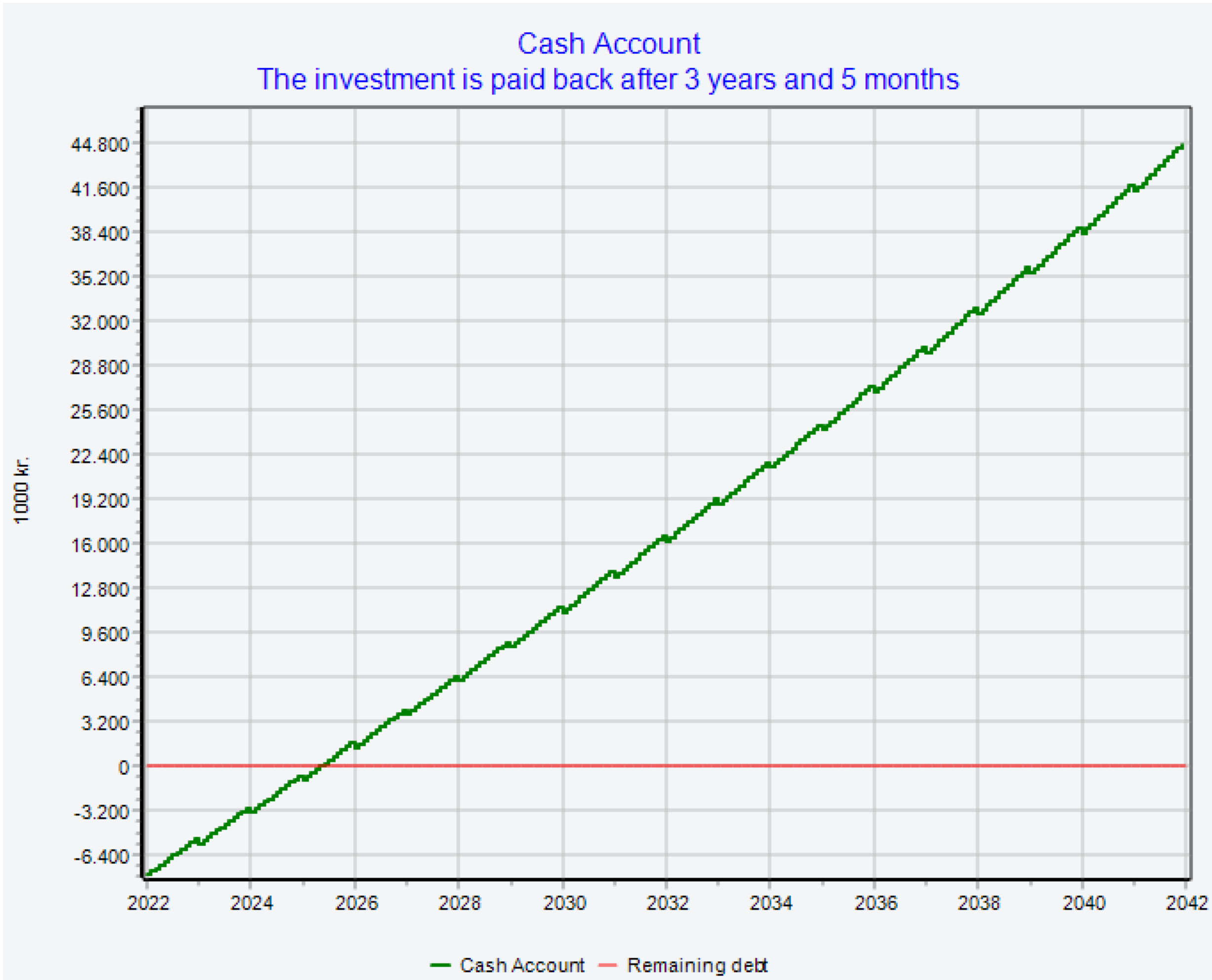

Figure B.0.7: *Graphical representation of payback period*

The income statement below is from upgrading with no subsidies:

Income Statement from January 1, 2022 to December 31, 2022

(All amounts in kr.)

Revenues								
Sales of Natural Gas								
Total sale of Natural Gas	:	27.199,7 MWh	at	191,52*	=	5.209.287		
Sales of Natural Gas Total							**5.209.287**	
Heat Sold	:	618,1 MWh	at	184,0*	=	113.732		
Total Revenues								**5.323.019**
Operating Expenditures								
Electricity Cost	:				=	424.431		
Maintenance and Operation	:				=	800.000		
Biogas Price	:	4.449.523,8Nm^3	at	0,723*	=	3.217.006		
Extra cost due to not overhauling	:				=	265.000		
Total Operating Expenditures								**4.706.437**
Depreciations								
Upgradingfacility							400.000	
Total Depreciations								**400.000**
Operation Income								**216.582**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**216.582**
Tax payments								
Corporate Tax							47.648	
Total Tax payments								**47.648**
Result Of The Year								**168.934**

Figure B.0.8: *Income statement of upgrading with no subsidies*

The income statement below is from gas engines with no subsidies:

Income Statement from January 1, 2022 to December 31, 2022

(All amounts in kr.)

Revenues								
SoldElectricity	:				=	2.090.357		
Sold Heat	:	5.923,8 MWh	at	184,0*	=	1.089.973		
Sold Heatinternally	:	7.200,0 MWh	at	184,0*	=	1.324.800		
Total Revenues								**4.505.131**
Operating Expenditures								
Maintenance and Operation Servi	:				=	682.000		
Biogas Price	:	4.444.027,6Nm^3	at	0,478*	=	2.124.245		
NOx tax	:				=	102.000		
Methane tax	:				=	121.000		
Fixed costs for boilers	:				=	27.000		
Ejby Mølle staff Hours	:				=	400.000		
Total Operating Expenditures								**3.456.245**
Depreciations								
New Gas Engine							870.000	
Total Depreciations								**870.000**
Operation Income								**178.886**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**178.886**
Tax payments								
Corporate Tax							39.355	
Total Tax payments								**39.355**
Result Of The Year								**139.531**

Figure B.0.9: *Income statement of gas engines with no subsidies*

The income statement below is for gas engines with a high natural gas price:

Income Statement from januar 1, 2022 to december 31, 2022

(All amounts in kr.)

Revenues								
SoldElectricity	:	10.499,0 MWh	at	813,0*	=	8.535.699		
Sold Heat	:	5.923,8 MWh	at	184,0*	=	1.089.973		
Sold Heatinternally	:	7.200,0 MWh	at	184,0*	=	1.324.800		
Total Revenues								**10.950.473**
Operating Expenditures								
Maintenance and Operation Servi	:				=	682.000		
Biogas Price	:	4.444.027,6Nm^3	at	1,87*	=	8.310.332		
NOx tax	:				=	102.000		
Methanetax	:				=	121.000		
Fixed costs for boilers	:				=	27.000		
Ejby Mølle staff Hours	:				=	400.000		
Total Operating Expenditures								**9.642.332**
Depreciations								
New Gas Engine							870.000	
Total Depreciations								**870.000**
Operation Income								**438.141**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**438.141**
Tax payments								
Corporate Tax							96.391	
Total Tax payments								**96.391**
Result Of The Year								**341.750**

Figure B.0.10: *Income statement of gas engines with high natural gas price*

The income statement below is for gas engines with a low natural gas price:

Income Statement from January 1, 2022 to December 31, 2022

(All amounts in kr.)

Revenues								
SoldElectricity	:	10.499,0 MWh	at	1.333,0*	=	13.995.187		
Sold Heat	:	5.923,8 MWh	at	184,0*	=	1.089.973		
Sold Heatinternally	:	7.200,0 MWh	at	184,0*	=	1.324.800		
Total Revenues								**16.409.961**
Operating Expenditures								
Maintenance and Operation Servi	:				=	682.000		
Biogas Price	:	4.444.027,6Nm^3	at	3,05*	=	13.554.284		
NOx tax	:				=	102.000		
Methanetax	:				=	121.000		
Fixed costs for boilers	:				=	27.000		
Ejby Mølle staff Hours	:				=	400.000		
Total Operating Expenditures								**14.886.284**
Depreciations								
New Gas Engine							870.000	
Total Depreciations								**870.000**
Operation Income								**653.677**
Financial Expenditures								
Interest on Cash Account							0	
Total Financial Expenditures								**0**
Result Of The Year (before tax)								**653.677**
Tax payments								
Corporate Tax							143.809	
Total Tax payments								**143.809**
Result Of The Year								**509.868**

Figure B.0.11: Income statement of gas engines with a low natural gas price

Appendix C

MATLAB model

The MATLAB script starts with calculating the difference in water prices between upgrading and using gas engines. It also calculates the difference in water prices when using no subsidies, for both upgrading and gas engines. Then it calculates the change in water price when using gas engines, at different natural gas prices. It ends up plotting figure 5.7.4 and calculating the natural gas price where gas engines and upgrading have the same effect on the water price.

```matlab
%% Finding Biogas Price For Residents With Upgrading
clear, clc, close all

BPrice=2.99;                        % Price for the biogas found in EnergyPro
BPriceEng=2.46;                     % Price as it is for gas engines
DifPrice=BPrice-BPriceEng;          % The difference in biogas prices
BProduction=4461771;                % Amount of biogas produced annually
ExtraEarning=BProduction*DifPrice;  % The extra earning that VCS A/S gets due to upgrading

ETP_PE=225000;                      % Number of Person Equivalents going to ETP
NE_PE=35000;                        % Number of Person Equivalents from NE
NW_PE=22000;                        % Number of Person Equivalents from NW
TOTAL_PE=(ETP_PE+NE_PE+NW_PE)*1.12; % Total number of PE's with upscaling
Dayli_PE=200;                       % Number of liters one person uses a day
Annual_PE=Dayli_PE*365;             % Number of liters one person uses a year
ETP_total=Annual_PE*TOTAL_PE/1000;  % Number of m^3 used by residents connected to ETP

HeatConsumption=26000;              % The total heat consumption at ETP
HeatFromUpgrading=70*8760/1000*3.6; % Waste Heat from the upgrading plant that can be used
HeatWithVAT=10500;                  % The amount of heat VCS A/S has to pay VAT for, without
subtracting upg. heat
HeatWithVAT_Upgrading=HeatWithVAT-...
HeatFromUpgrading;                  % The heat VCS A/S has to pay VAT for
HeatWithoutVAT=HeatConsumption-...
    HeatWithVAT;                    % The heat VCS as do not have to pay VAT for
HeatPriceVAT=103.75;                % Heat price with VAT
HeatPriceNoVAT=83.00;               % Heat price without VAT
HeatPriceMarket=51.13;              % Heat price directly from VCS Energy (Market Price)
PaymentVAT=HeatPriceVAT*HeatWithVAT_Upgrading;  % The payment with VAT
PaymentNoVAT=HeatPriceNoVAT*HeatWithoutVAT;     % The payment without VAT
PaymentUp=HeatPriceMarket*HeatFromUpgrading;    % The payment for heat from upgrading
PaymentTotal=PaymentVAT+PaymentNoVAT+PaymentUp; % The total payment for heat at VCS A/S, when using
upgrading tech

PaymentWithGasEng=HeatConsumption*...
    HeatPriceMarket;                            % The total payment for heat at VCS A/S, with gas
engines
PaymentDif=PaymentTotal-PaymentWithGasEng       % The difference in payment for heat with upgrading and
with gas engines

PayPerRes=PaymentDif/ETP_total;                 % The extra payment for heat divided on each m^3


SavingsForResidents=ExtraEarning/ETP_total-PayPerRes % The savings for the residents in kr/m^3




% Water price change with no subsidies for gas engines


BPriceEngNoSub=0.478;                        % Price for the biogas found in EnergyPro
DifPriceNoSub=BPriceEngNoSub-BPriceEng;      % The difference in biogas prices
ExtraCost=BProduction*DifPriceNoSub;         % The extra cost that VCS A/S gets with no subsidies



ExtraExpForResidents=ExtraCost/ETP_total     % The extra cost for the residents in kr/m^3

% Water price change with no subsidies for upgrading

BPriceUpgNoSub=0.723;                           % Price for the biogas found in EnergyPro
DifPriceUpgNoSub=BPriceUpgNoSub-BPriceEng;      % The difference in biogas prices
ExtraCostUpg=BProduction*DifPriceUpgNoSub;      % The extra cost that VCS A/S gets with upgrading and
no subsidies

ExtraExpForResidentsUpg=ExtraCostUpg/ETP_total-PayPerRes % The extra cost for the residents in kr/m^3
```

```
% Water price change using gas engines, with high natural gas price


BPriceEngHighNaturalGas=1.87;                          % Price for the biogas found in EnergyPro
DifPriceHighNG=BPriceEngHighNaturalGas-BPriceEng;      % The difference in biogas prices
ExtraCost2=BProduction*DifPriceHighNG;                 % The extra cost that VCS A/S gets with high NG
price

ExtraExpForResidents2=ExtraCost2/ETP_total             % The extra cost for the residents in kr/m^3


% Water price change using gas engines, with low natural gas price


BPriceEngLowNaturalGas=3.05;                          % Price for the biogas found in EnergyPro
DifPriceLowNG=BPriceEngLowNaturalGas-BPriceEng;       % The difference in biogas prices
ExtraSaving2=BProduction*DifPriceLowNG;               % The extra saving that VCS A/S gets with low NG
price

ExtraSavingForResidents2=ExtraSaving2/ETP_total       % The extra saving for the residents in kr/m^3


% Making figure of change in water price, with different natural gas prices

NGLOW=1.08;                                           % The low NG price used
NGHIGH=3.14;                                          % The high NG price used
figure('MenuBar', 'none','rend',...                   % Making a figure with the appropriate size
    'painters','pos',[10 10 900 600]);
plot([NGLOW, NGHIGH,],[-ExtraSavingForResidents2,...  % Plotting the gas engines curve
    -ExtraExpForResidents2],'Linewidth',4);
hold on
plot([NGLOW, NGHIGH,],[-SavingsForResidents,...       % Plotting the upgrading curve
    -SavingsForResidents],'Linewidth',4);
grid on
xlabel('Natural gas price in DKK/m^3');
ylabel('Water price change for residents in DKK/m^3');
legend('Gas Engines', 'Upgrading');


Dif1=NGHIGH-NGLOW;                                    % Calculations to find the crossing point
Dif2=ExtraSavingForResidents2-ExtraExpForResidents2;
Dif3=ExtraSavingForResidents2-SavingsForResidents;
Share=Dif3/Dif2;
CrossingPoint=NGLOW+Dif1*Share
```

Appendix D

Mail correspondences

This section includes the most relevant e-mail correspondences with Ib Pedersen from VandCenter Syd. The e-mail below is used to calculated the needed amount of heat for the digestion tank:

Ib Pedersen <ip@vandcenter.dk>

Til: Rune Kvols Rasmussen; Cc: Rune Dal Andersen;

30-03-2017

0677_001.pdf
105 KB

Hent

Hej Rune og Rune

Godt at høre fra jer
Seneste biogasanalyse er vedlagt.
Varmeforbrug til opvarmning af rådnetanke er 333 kW (gennemsnit over 2016, forbruget afhænger af belastning og temperatur på det ind-pumpede slam og udetemperaturen).
Jeg er ikke bekendt med at der er en aftale med Unilever... Er det Fjernvarme Fyn som har lavet den?
Vi levere alt vores overskudsvarme til Fjernvarme Fyn.

Med venlig hilsen
Ib Pedersen
Teamleder, Drift af renseanlæg

VandCenterSyd
DIT VAND · VORES ELEMENT

+45 29 69 24 43
ip@vandcenter.dk
www.vandcenter.dk
Mød vores kunderådgivning på Facebook

Figure D.0.1: E-mail regarding heat for digestion tanks

The e-mail below contains information on the internal heat price:

Ib Pedersen <ip@vandcenter.dk>
Til: Rune Kvols Rasmussen;
19-04-2017

Hej Rune

Intern varme afregnes til 49,96 som salg.
Prisen på varme er steget fra 49,96 til 51,13 er jeg lige blevet opmærksom på.

Med venlig hilsen
Ib Pedersen
Teamleder, Drift af renseanlæg

VandCenterSyd
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Figure D.0.2: *E-mail regarding the internal heat price*

The e-mail below contains information on operation and maintenance costs for gas engines at ETP:

Ib Pedersen <ip@vandcenter.dk>

Til: Rune Kvols Rasmussen;

24-04-2017

Hej

Det er nok nemmest at holde fokus på Gasmotor 1, da vi har en serviceaftale på den:

Investering, opstilling: kr. 7.000.000

Drift. Kr. 45,17 kr./h

Levetidsforlængelse fra 60.000h til 120.000h : kr. 1.700.000

Hertil kommer stører vedligehold på ca. 700.000 kr./60.000h og vores egne timer.

Håber det er præcist nok, ellers skal vi have fat i budgettet.

Med venlig hilsen

Ib Pedersen

Teamleder, Drift af renseanlæg

VandCenterSyd

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Figure D.0.3: E-mail regarding operation and maintenance costs

The e-mail below shows where the 4% profit in the models comes from:

Hej Rune

Det er en anbefaling fra revisionen. Lovgivning ?

Med venlig hilsen
Ib Pedersen
Teamleder, Drift af renseanlæg

VandCenterSyd
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ip@vandcenter.dk
www.vandcenter.dk
Mød vores kunderådgivning på Facebook

Rune Kvols Rasmussen
Til: Ib Pedersen <ip@vandcenter.dk>;
03-05-2017

Hej Ib
Tak for svaret.

Du nævnte at i må have et overskud på 4% i energiselskabet. Ved du hvor i har de 4% fra? Er det tager ud af lovgivning eller noget i selv har valgt?

Venlig hilsen
Rune Kvols Rasmussen

Figure D.0.4: *E-mail regarding 4% profit*

The e-mail below contains data on the biogas and its production:

Ib Pedersen <ip@vandcenter.dk>
Til: Rune Kvols Rasmussen;
08-03-2017

Hej Rune

Se svar herunder

Med venlig hilsen
Ib Pedersen
Teamleder, Drift af renseanlæg

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Fra: Rune Kvols Rasmussen [mailto:ruras14@student.sdu.dk]
Sendt: 8. marts 2017 12:45
Til: Ib Pedersen <ip@vandcenter.dk>
Emne: SV: Varmpumpe ved Ejby Mølle

Hej Ib,

Efter at have snakket mulighederne igennem, lyder det som om det mest relevante og spændende er at kigge på muligheden for opgradering til naturgas, med fokus på økonomien i det.

Vi har lavet en problemformulering som følgende:

The lifetime of the gas engine plant at Ejby Mølle Wastewater Treatment Plant is coming to an end in roughly five years. Therefore a plan for how the biogas is to be used in the future is needed.
This study investigates the possibility of upgrading the biogas to natural gas, and selling that gas to the natural gas grid. The remaining lifetime of the gas engine will be kept for peak load supply and a heat pump will be installed to provide heat for the gas production.
This scenario will be compared to the scenario of installing a new gas engine at the end of the old ones lifetime.

Har du mulighed for at give os følgende data at komme igang på?:
- Hvilken process benyttes til biogasproduktionen (type af bakterier osv.) og hvad er opvarmningsmetoden til anlægget? Har i eventuelt et datablad? Mesofile bakterier ved 37°C, et trin i 4 stk. parallelle tanke på hver 2800 m³, udrådning af Primærslam + biofilterslam + aktivslam. Opholdstid mellem 21 og 31 døgn afhængig af belastningen på renseanlægget. Indfødning mellem 360 og 410 m³ i døgnet med ca. 7 % Tørstof. Tørstof indhold i tankene er ca. 4%.
Opvarmning kommer fra CHP på 1.700 kW el./ 2.200 kW varme.

- Data på mængden af biogasproduktion 4.500.000 m³n biogas. Metan indhold 63%

Se evt. vedr. proces i "Spildevandsteknik af Leif Winther, Mogens Henze, Jens Jørgen Linde og H. Thorkild Jensen, kap 9.8 Slamstabilisering" eller liggende.
NGF Nature Energy driver flere biogasanlæg med opgradering, de kunne måske også inspirere jer vedr. opgraderingsteknologien?

Figure D.0.5: *E-mail regarding biogas production*

The e-mail below contains data on the received amount of sludge in Population Equivalents at ETP:

Ib Pedersen <ip@vandcenter.dk>

Svar til alle

Til: Rune Kvols Rasmussen;

08-05-2017

Inbox

Hej Rune

Her er belastningstallene 2016 for de 3 renseanlæg som biogasanlægget behandler slam fra:
EM: 212.000 PE
NV: 35.000 PE
NØ: 22.000 PE

Med venlig hilsen
Ib Pedersen
Teamleder, Drift af renseanlæg

VandCenterSyd
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ip@vandcenter.dk
www.vandcenter.dk
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Figure D.0.6: *E-mail regarding number of population equivalents at ETP*

Appendix E

Received offer from Hitachi Zosen Inova AG

The pdf underneath, was received from Hitachi Zosen Inova AG on the 4th of May 2017. As the data was received late, it was mainly used for comparing cost prices. In the data file Hitachi Zosen Inova AG has made a comparison of upgrading with membrane separation technology and upgrading with amine technology:

Preliminary costs analysis
for a biogas upgrading unit

Type 500-M

Membrane upgrading system - 500 Nm³/h biogas // 318 Nm³/h biomethane

Comparison with

Type Special size

Amine scrubbing system 500 Nm³/h biogas // 318 Nm³/h biomethane

Company: **Rune Dal Andersen**

Contact person:	Jan Ludeloff
Phone:	+49 (0) 4281 9876 132
E-Mail:	jan.ludeloff@hz.inova.com

Date: 04.05.2017

Hitachi Zosen INOVA

Rune Dal Andersen	Date:	04.05.2017	
Hourly capacity of upgrading plant in m³/h biogas		500	500
Upgrading technology		Membrane	Amine
Stages Membranes		3-stage	-

Base data		
Operating hours of upgrading system	8.500	Hours of operation
Methane content of biogas	63	Vol-%
Higher calorific value (HCV)	6,26	kWh/Nm³
Lower calorific value (LCV)	6,98	kWh/Nm³
Wobbe Index - Wi biomethane	51,63	MJ/Nm³
Purchase price of biogas for upgrading	0,00	cts per kWh
Exchange rate	1,0	€/€

Investment costs in €*			
Upgrading system		**1.143.000 €**	**1.391.000 €**
Desulphurization		not considered	not considered
Initial filling activated carbon		not considered	not considered
Biogas compressor		Adicomp - VG132-16EG INV OF Ex; 16 bar; 770 Nm³/h	not required
HMI over 24'' Touch Panel PC		incl.	incl.
Piping (within HZI-system boundary)		incl.	incl.
Flare: N/A		not considered	not considered
Adsorption dryer (ADDR)		not required	incl.
Planning & engineering		incl.	incl.
Assembly (Shop & onsite)		incl.	incl.
Lifting equipment	approx.	5.000 €	5.000 €
Transportation	approx.	15.000 €	15.000 €
Foundations upgrading plant	approx.	2.000 €	2.000 €
Expert assessment	approx.	8.000 €	8.000 €
Approval planning	approx.	15.000 €	15.000 €
Civil works	approx.	10.000 €	10.000 €
Supply infrastructure water/power/telecommunication	approx.	15.000 €	15.000 €
Geotechnical survey	approx.	2.000 €	2.000 €
Site equipment & related expenditure	approx.	5.000 €	5.000 €
Optional equipment - necessary if not provided on site			
Biogas blower skid (BBS)		incl.	incl.
Cooling dryer skid (CDS)		incl.	incl.
VOC-cleaning for siloxanes and terpenes		not considered	not considered
Natural gas fueled boiler system incl. system integration		not required	not included
Off-gas Treatment		not required	not required
Volume flow rate measurement rawgas		incl.	incl.
Volume flow rate measurement Biomethane		incl.	incl.
Compressor for air supply		incl.	incl.
Distribution of biomethane to flare (mono fuel) (up to 10 m Pipe lenght)		not considered	not considered
Distribution of biomethan incl. refeed into biogas plant (up to 10 m Pipe lenght)		incl.	incl.
Outlet pressure control biomethane			
Post-compression biomethane		not required	not required
Pressure regulator unit for biomethane		not included	not required
Optional equipment			
Operational data collecting		incl.	incl.
Remote access (Fortinet)		incl.	incl.
Heat recovery		incl.	incl.
Total costs		**1.143.000 €**	**1.391.000 €**
Depreciation period	20,00 years	57.200 €	69.600 €
Interest rate	5,00 % in the first year	57.200 €	69.600 €

* Design according to EU / German technical codes

Hitachi Zosen INOVA

Consumables				
Quantities	Activated carbon **	t / a	not considered	not considered
	Amine solution MDEA	€ /a	- -	- -
	Replenishment PIP	€ /a	- -	- -
	Amine solution CCS	€ /a	- -	7.300 €
Total			**0 €**	**7.300 €**

** Assumption: 89 ppm

Methane balance		
Technology specific methane loss	0,4%	0,1%
Overall methane loss in kWh per year	113.499	26.626
Increased expense of biogas resulting from methane loss	**0 €**	**0 €**

Electricity consumption				
Electricity consumption amine scrubbing	0,07	kWh/Nm³ biogas		35 kWel
Electricity consumption peripherals	0,02	kWh/Nm³ biogas		10 kWel
Electricity consumption membrane upgrading	0,26	kWh/Nm³ biogas	130 kWel	
Electricity consumption peripherals	0,01	kWh/Nm³ biogas	5 kWel	
Electricity consumption biogas blower	0,02	kWh/Nm³ biogas	10 kWel	10 kWel
Cooling dryer skid (CDS)	0,01	kWh/Nm³ biogas	5 kWel	5 kWel
Specific consumption per Nm³ biogas in kWh			0,30	0,12
Specific consumption per Nm³ biomethane in kWh			0,47	0,19
Electricity costs ***:	7,90	€-Ct. / kWh -// € / Nm³ Biom.:	0,04	0,01
Total costs for electricty per year			**100.700 €**	**40.300 €**

*** Price assumption may increase when using renewable energy

Heat demand for regeneration			
Heat demand in kW			300
Efficiency of heat generation			0,87
Heat purchase costs	in cent per kWh	N/A	4,2
Total		**N/A**	**123.400 €**

Heat Extraction - revenue situation			
Full load hours per year		8.500	8500
Heat extraction	in kWh per hour	74	60
Cost savings	in cent per kWh	4,2	4,2
	€-Ct./Nm³ biogas	0,62	0,51
Total revenues from heat per year		**26.486 €**	**21.471 €**

Operation and maintenenace of upgrading plant					
Labour for plant supervision / basic maintenance	0,50	Man-hours per day at	47 €	8.600 €	8.600 €
Annual compressor maintenance costs per year				12.500 €	not required
Annual membrane management costs per year				12.140 €	not required
Annual maintenance costs (membrane system) per year *****				26.000 €	
Annual maintenance costs (amine system) per year *****					28.000 €
Annual costs of additional wear and spare parts				11.400 €	10.400 €
Total annual maintenance costs				**70.600 €**	**47.000 €**

***** Scope of service: HZI Basic

Total annual cost		
Depreciation upgrading plant	57.200 €	69.600 €
Interest	57.200 €	69.600 €
Consumables	0 €	7.300 €
Methane loss	0 €	0 €
Total cost for electricity	100.700 €	40.300 €
Total cost for heat	N/A	123.400 €
Maintenance costs	70.600 €	47.000 €
Costs for maintenance of heat generation unit	N/A	0 €
Total costs	285.700 €	357.200 €
Total revenue from heat	26.486 €	21.471 €
Total costs	**259.200 €**	**335.700 €**

Total costs in Euro cent per production unit		
Useable energy in kWh, HHV (Biogas - methane loss)	29.549.600	29.636.470
per kWh, higher calorific value (HCV)	**0,88**	**1,13**
per kWh, lower calorific value (LCV)	0,98	1,26
Proportionate per kWh, HCV		
Depreciation upgrading plant	0,19	0,23
Interest	0,19	0,23
Consumables	0,00	0,02
Methane loss	0,00	0,00
Total cost for electricity	0,34	0,14
Total cost for heat	N/A	0,42
Maintenance costs	0,24	0,16
Total costs for grid injection unit	N/A	N/A
Costs for maintenance of heat generation unit	N/A	0,00
Total revenue from heat	-0,09	-0,07

Gas upgrading costs		
per year	259.200 €	335.700 €
Costs in €-ct / kWh, Hs,n gross calorific value	**0,88 ct./kWh**	**1,13 ct./kWh**

Appendix F

Biogas composition analysis

Underneath is a data sheet on the measured biogas composition at ETP:

eurofins

Vores ref. 218328-151-142

Analyse af biogas

Rekvirent:	Odense Vandselskab A/S Vandværksvej 7 5000 Odense C Ib Pedersen Driftsleder Ejby Mølle Rensningsanlæg	Sags nr. 218328-151-142
Prøvemateriale:	22. april 2009 af Eurofins Miljø A/S Biogas fra Ejby Mølle Rensningsanlæg	
Analysemetode: Analysemetoder er beskrevet på side 3		

Resultater

Komponent	**Ejby Mølle Rensningsanlæg***	**Enhed**
Methan	63	vol%
Kuldioxid	37	vol%
Nitrogen	0,20	vol%
Ilt	< 0,1	vol%
Svovlbrinte	89	ppm
Ammoniak	< 0,2**	mg/m^3
Siliciumforbindelser, **målt**		mg/m^3
Tetramethylsilan	-	
Hexamethylsilanol	-	
Hexamethyldisiloxan	-	
Hexamethylcyclotrisiloxan	0,035	
Octamethyltrisiloxan	0,095	
Octamethylcyclotetrasiloxan	1,2	
Decamethyltetrasiloxan	0,33	
Decamethylcyclopentasiloxan	7,6	
Sum af Siliciumforbindelser, **beregnet**	9,3	mg/m^3
Sum Silicium, **beregnet**	3,5	mg/m^3

*: gennemsnit af 2 målinger
**: kun én måling foretaget
- ikke påvist

Galten, den 20. maj 2009 – SB

Eurofins Miljø A/S
Smedeskovvej 38, 8464 Galten

Søren Brødsgaard
civilingeniør

Alfred Larsen
miljøtekniker

Figure F.0.1: Composition of biogas at ETP