LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
Degree Programme in Energy Technology

Risto Hyyryläinen

Economics of Power-to-Gas integration to wastewater treatment plant

Examiners: Professor Esa Vakkilainen
Professor Juha Kaikko

Instructor: Janne Keränen

ABSTRACT

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Economics of Power-to-Gas integration to wastewater treatment plant

Master's Thesis

2015

96 pages, 21 pictures, 12 tables, 6 figures and 2 appendices
Examiner: Esa Vakkilainen, Juha Kaikko
Instructor: Janne Keränen

Keywords: Power-to-Gas, wastewater treatment, biogas, synthetic natural gas, Neo-Carbon

Solar and wind power produce electricity irregularly. This irregular power production is problematic and therefore production can exceed the need. Thus sufficient energy storage solutions are needed. Currently there are some storages, such as flywheel, but they are quite short-term. Power-to-Gas (P2G) offers a solution to store energy as a synthetic natural gas. It also improves nation's energy self-sufficiency. Power-to-Gas can be integrated to an industrial or a municipal facility to reduce production costs.

In this master's thesis the integration of Power-to-Gas technologies to wastewater treatment as a part of the VTT's Neo-Carbon Energy project is studied. Power-to-Gas produces synthetic methane (SNG) from water and carbon dioxide with electricity. This SNG can be considered as stored energy. Basic wastewater treatment technologies and the production of biogas in the treatment plant are studied. The utilisation of biogas and SNG in heat and power production and in transportation is also studied. The integration of the P2G to wastewater treatment plant (WWTP) is examined mainly from economic view. First the mass flows of flowing materials are calculated and after that the economic impact based on the mass flows. The economic efficiency is evaluated with Net Present Value method. In this thesis it is also studied the overall profitability of the integration and the key economic factors.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT Energiajärjestelmät
Energiatekniikan koulutusohjelma

Risto Hyyryläinen

Taloudellinen tarkastelu Power-to-Gas integraatiossa jäteveden puhdistuslaitokseen
Diplomityö

2015

96 sivua, 21 kuvaa, 12 taulukkoa, 6 kuvaajaa ja 2 liitettä

Tarkastajat:	Professori Esa Vakkilainen
	Professori Juha Kaikko
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Hakusanat: Power-to-Gas, wastewater treatment, biogas, synthetic natural gas, Neo-Carbon

Aurinko- ja tuulivoima tuottavat sähköä epäsäännöllisesti. Tämä epäsäännöllinen tuotanto on ongelmallista ja välillä tuotanto voi ylittää energian tarpeen. Tällöin tarvitaan riittäviä vaihtoehtoja energian varastointiin. Tällä hetkellä energian varastointiin on olemassa joitain sovelluksia, kuten vauhtipyörä, mutta ne ovat kestoltaan melko lyhytaikaisia. Power-to-Gas tarjoaa vaihtoehdon varastoida energiaa kaasuksi. Se myös parantaa maan energia omavaraisuutta. Power-to-Gas voidaan integroida joko teollisiin tai kunnallisiin toimintoihin kustannuksien pienentämiseksi.

Tässä diplomityössä tutkitaan Power-to-Gas teknologian integroimista jäteveden puhdistamoon osana VTT:n Neo-Carbon Energy- projektia. Power-to-Gas tuottaa synteettistä metaania (SNG) vedestä ja hiilidioksidista sähkön avulla. Tämä tuotettu SNG voi oimia myös energiavarastona. Myös jäteveden puhdistusta ja sen ohessa tapahtuvaa biokaasun tuotantoa tutkitaan tässä työssä. Myös biokaasun ja SNG:n hyödyntämiseen perehdyttiin. Integraatiota tutkitaan pääsääntöisesti taloudelliselta kannalta. Ensiksi on laskettu virtaavien aineiden massavirrat ja niiden avulla taloudellisia arvoja ja vaikutusta. Taloudellisuutta on arvioitu nykyarvo-menetelmällä. Tässä työssä on tutkittu myös integraation yleistä tuottavuutta ja tärkeimpiä taloudellisia tekijöitä.

PREFACE

This Master’s Thesis was done for VTT during spring and summer 2015 in Jyväskylä. I’d like to thank VTT about this possibility to construct a study from this interesting topic. I’d like to thank my instructors and examiners. I’d like to also thank Lappeenranta University of Technology and especially the LUT School of Energy Systems about good and comprehensive education.

And of course I’d like to thank my family from the good support during my studies.

Risto Hyyryläinen
2.9.2015
Jyväskylä

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TABLE OF SYMBOLS

AEC	alkaline electrolyser cell	[-]
BOD	biochemical oxygen demand	[g/m^3]
bsCOD	influent soluble substrate concentration	[g/m^3]
CAPEX	capital expenditure	[€]
CH_4	methane	[-]
CH_3OH	methanol	[-]
$C_4H_7O_2N$	N-methylolacrylamide	[-]
CO	carbon monoxide	[-]
CO_2	carbon dioxide	[-]
D	discountable value	[€]
EBIT	earnings before interest and taxes	[€]
FCR	frequency containment reserve	[-]
FCR-D	frequency containment reserve for disturbances	[-]
FCR-N	frequency containment reserve for normal operation	[-]
q_m	mass flow	[kg/s]
H_2	hydrogen	[-]
H_2O	water	[-]
HNO_3	nitric acid	[-]
k	annual price development	[%]
I	investment	[€]
i	interest rate	[%]
LHV	lower heating value	[MJ/kg]
M	molar mass	[g/mol]
MLVSS	mixed liquor volatile suspended solids	[g/m^3]
m	mass	[kg]

N_2	nitrogen	[-]
NO_3^-	nitrate ion	[-]
NGV	natural gas vehicle	[-]
n	year	[-]
OH^-	hydroxide ion	[-]
$OPEX$	operational expenditure	[€]
P	power	[W]
PEM	Polymer Electrolyte Membrane electrolysis	[-]
SNG	synthetic natural gas	[-]
$SOEC$	Solid Oxide Electrolyte Cell	[-]
$WWTP$	wastewater treatment plant	[-]
η_e	efficiency	[%]

Sub- indexes

a	annual
e	electrolysis
el	electricity
H_2	hydrogen
O_2	oxygen

1. INTRODUCTION

The use of the renewable energy technology is increasing. EU has set its targets for year 2020, also known as 20-20-20-targets. These targets are: to reduce CO_2-emissions by 20% from 1990 levels, to increase the share of the renewables to 20% and to improve he energy efficiency by 20% (European Commission 2015). It is estimated that the use of the bioenergy rises from 1 344 Mtoe to 2002 Mtoe by the year 2040 (OECD/IEA 2014, 56). For example in Germany the renewable energy sources have become as the most significant energy sources in 2014. Germany produced in 2014 25,8% of its electricity power with solar-, wind- and hydropower. (Kokkonen 2014.) Germanys target for 2030 is that the share of the renewables is as high as 45% (Worldwatch Institute 2007).

Renewable energy sources like wind and sun produce energy with various intensity and to link this to energy consumption an energy storage is needed. Sun and wind power may cause short peaks to the electricity production and this may damage the electric grid. The electric grid needs to maintain the specific frequency and sudden variations to the electric load can cause variations the frequency. If the frequency is varies too much the whole electric grid may needed to be run down. To balance the energy production and demand the energy storage must be large enough. One option for long-term storage is to convert energy to gaseous or liquid form, which can be more easily controlled and transported. There are already numerous of different storage types for energy, like flywheel or different batteries, but these fit only for small scale and for relatively short time and are mainly used in small applications such as cell phones. For example a li-Ion battery has capacity up to 50 MW, but the charge lasts only for hours (Manuel 2014, 5), flywheel has also capacity up to 20 MW, but it can store energy only for minutes (Lehner 2014, 4). Larger industrial and municipal operations, such as factories or district heat production, require larger energy volumes and longer time periods, like from days to a year.

Power-to-Gas technology offers a solution to produce own synthetic natural gas (SNG) and to store energy into form of gas. The produced SNG can be stored in to gas tanks or distributed by using existing natural gas grids. SNG can be produced and used inside a nation and then it improves the energy self-sufficiency. SNG can also be stored and transported globally like traditional fuels. When SNG is produced with for example solar or wind power the gas is also green energy. Then Power-to-Gas has potential to affect globally to energy demand: SNG can be produced with renewable energy, for example with solar power in Sahara desert and transported with ships to Europe.

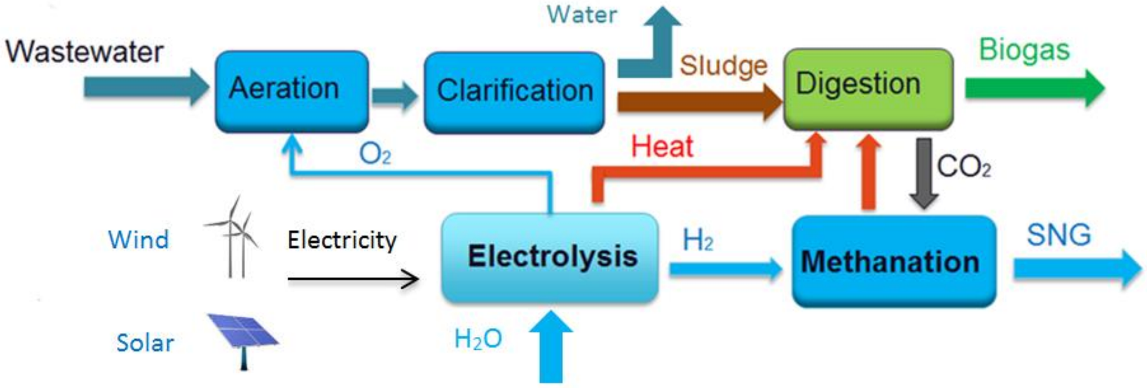
Power-to-Gas can be implemented as an independent unit or it can be integrated to some suitable process. VTT has project called Neo-Carbon Energy that studies the implementation of Power-to-Gas. Integration can help to reduce the investment and operational costs from Power-to-Gas technology and also operational costs from the integration object. Power-to-Gas technology is still quite expensive and relatively untested technology with fast development pace and therefore it can be better to integrate it. One potential integration option for Power-to-Gas is wastewater treatment. It is a compulsory process for modern day societies and it often requires large facilities that fit well for Power-to-Gas. Both Power- to-Gas and wastewater treatment can utilise each other's by-products and thus reduce their own production costs.

Biogas has become an alternative fuel option for transportation. It can be used in normal gas powered vehicles like natural gas. Biogas production has increased during recent years and special plants for its production are being built, for example in Germany it is predicted that there will be 61 new biogas plants built in 2015 (Biogas-allrounder 2014, 1-13). Biogas is produced from sewage sludge via digestion process and therefore biogas production is also waste treatment. Biogas can be used in transportation or in electricity and/or heat production.

Wastewater treatment is a process that consists of several steps. Although there are different types of treatment processes, the main steps are similar: mechanical separation, physic-chemical treatment and/or biological treatment. (Water.worldbank.org 2015.) Municipal treatment began at begin of the 20th century (Wiessmann et al. 2007, 1-19.). The technology used at water treatment are quite old, but there are several new technologies, such as the membrane technology, that may become more common in the future (Melin et al., 2006, 271-282.). Wastewater treatment consumes quite lot of energy, for example the Suomenoja plant in Finland: 0,42 kWh/m^3 (Kangas 2004, 11) and studies for electricity savings have been made. The main aim in wastewater treatment is to remove and reduce the level of hazardous compounds to accepted level and the desired level of water treatment varies from the use of the water (Water.worldbank.org 2015). In addition of producing clean water, wastewater treatment plants produce also biogas from sludge digestion (European IPPC Bureau 2014, 280). This digestion is a part of water treatment and biogas is collected and utilised at the plant or sold to gas grid. In the near future, there will be large investments in wastewater treatment markets. European and American WWTPs will require investments for maintenance and upgrades. In Asia the fast growing population sets demand for increasing number of WWTPs. (PPE 2012, 8-13.)

1.1 Aim and definitions of the thesis

In this master’s thesis an integration of Power-to-Gas to wastewater treatment plant (Picture 1) is studied as a part of VTTs Neo-Carbon Energy project. Wastewater treatment consumes oxygen and heat that are both by-products in Power-to-Gas technology. Power-to-Gas uses carbon dioxide that is received from wastewater treatment. Therefore the integration of these two technologies is interesting and studied more closely.



Picture 1: Power-to-Gas integration to WWTP

This thesis concentrates on the economic profitability. The profitability of the integration and the payback time of the integration are studied more closely. If the integration is found uneconomic, then it is studied what steps are needed to make it profitable. For example how much investments to Power-to-Gas are needed to be decreased in the future so that integration becomes profitable. Therefore it is important to find first the most important factors of the economics of the integration. These factors, such as the price of the final product can influence largely to the annual returns and therefore to the profitability. The aim of this study is to produce realistic data from the economics of the integration and a tool to estimate the economics. The level of the study is annual level, though some mentions to smaller timescales are also made and considered. Study is made for three locations: Finland, Germany and China to show the differences of economics in those countries.

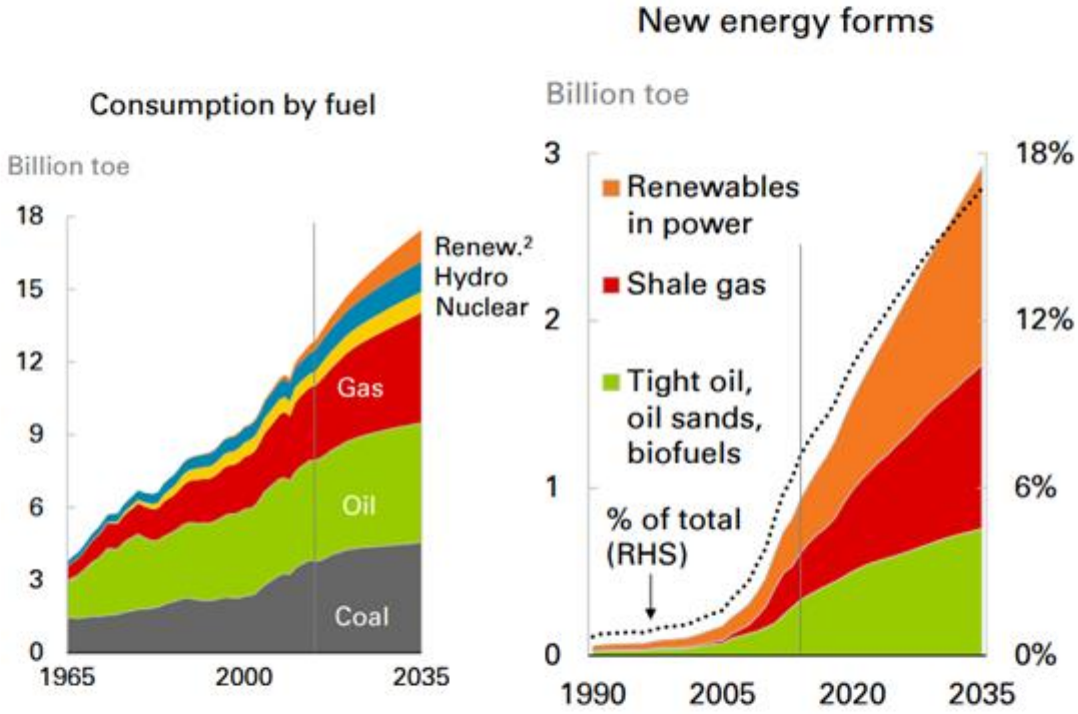
1.2 Structure of the study

First the utilisation of biogas and SNG, wastewater treatment and Power-to-Gas technology is studied. The focused utilisation option of biogas and SNG are in transportation, because the prices of these gases are highest in these areas. About the wastewater treatment the basic technologies are extensively studied, but also the future technology is introduced. Future technology can bring considerable savings to treatment costs that make them interesting. Also the biogas production in WWTPs is studied. Power-to-Gas technology is also introduced. In addition of technical description of wastewater treatment and Power-to-Gas, also the economics of these technologies are studied. After the literature part, the calculation part is presented where the profitability of the integration is studied. In the calculations the mass flows of the main product (SNG) and the by-products (oxygen, carbon dioxide and heat). With the mass flows the money streams are calculated of the integration with the prices found out in this thesis and from the money streams the annual returns and costs are estimated. Finally the profitability is studied with Net Present Value method.

The values of prices, investments and costs are chosen by using the literature sources and expert estimates. When the values are estimated it is considered that the values have to be as realistic as possible. The values used in this study are also similar through the Neo-Carbon Energy project and comparison to other succeeding cases of Neo-Carbon Energy project is thus possible. The profitability is now studied with Net Present Value method that calculates the annual cash flow with discounted values. In the calculations all the costs and returns are taken to account and studied. The economics of this integration depends largely on the production rate and the price of the SNG and the investment costs. In planning this integration the electricity price and investment costs pay the most important role.

In this integration study, three different cases are examined: Finland, China and Germany. All three cases have different input values like electricity prices, personnel costs, WWTP sizes etc. With different values the economics of the integration can be well examined and recognize the most important factors for the integration profitability. By studying these factors it can be later recognized their ideal value that the integration is profitable. The main product from this integration is the SNG, but Power-to-Gas has other values as well, such as increasing renewable energy production and energy self-sufficiency. SNG is chosen as main product, although Power-to-Gas produces hydrogen that can be upgraded to other products too.

2 UTILISATION OF BIOGAS AND SYNTHETIC NATURAL GAS



Picture 2: The shares of energy sources (BP 2015, 12, 20)

According to BP the share of the gaseous fuels is increasing in the near future (Picture 2). Therefore there also will be larger markets for bio-based gases and synthetic gases. Biogas is a gaseous fuel that is formed by microbe reactions in digestion reaction. Raw material is usually organic waste. Synthetic natural gas (SNG) is also a gaseous fuel, that is very similar to natural gas. SNG is produced from a carbon source, such as coal, oil or CO_2. Like natural gas, SNG consists mostly of methane. Biogas and synthetic natural gas can be used to heat and/or power production, mechanical energy or as a traffic fuel. Biogas and SNG can be burned like natural gas in boiler or in turbine. As a traffic fuel SNG and biogas can be used in cars, trucks or ships. Biogas contains usually others substances and it must be cleaned before it can be used in vehicles. (Motiva 2015, 10-11.)

Consumption of natural gas is expected to rise although the current recession has decreased the consumption levels. Natural gas is currently the third most used fuel measured as primary energy. The current global demand of 3,4 trillion cubic metres (tcm) is expected to rise to 5,4 tcm by 2040. Especially in China consumption has increased and China exceed EU as gas user in 2013. China prefers to use natural gas instead of coal to reduce its emissions. A major part, 40%, of Chinas growth in gas use comes from the transportation. In China the deployment of natural gas vehicles (NGV) is rapidly increasing and there are almost 3 million NGV’s on the Chinas road at the end of the 2013, in 2012 the figure was 1,48 million. Also the number of gas refuelling stations are increased, 1700 stations in 2013 alone.

In Europe the economic recession has decreased the overall gas consumption during recent years and gas consumption is expected to return in 2010 levels only in the early 2030’s. Also the increasing use of the renewables and coal in power generation has decreased the natural gas use. The use of the natural gas is expected to rise annually only by 0,6% in EU, while in China the growth is expected to be 5,2% per year. (OECD/IEA 2014, 57, 135 - 136, 138, 151.)

2.1 Electricity and heat production

The burning reaction of biogas is quite similar than of natural gas and SNG. The difference between these two gases is only the higher carbon dioxide level and lower energy content of biogas (Suomen Kaasuyhdistys 2013). The burning component in both gases is methane. In combined heat and power production (CHP) gases are burned in a traditional piston engine or in a turbine. In gas turbine air is compressed to high pressure and then burned with provided fuel in high temperature. Compression is made in compressor stage, where several axial or horizontal (rare) blades compress air. The fuel burns in separate chamber and the hot gases are lead to turbine stages, where fumes rotate turbine blades and turbine axel. Turbine produces electricity with a generator and the heat is received from a recovery boiler.

The basic principle in gas engine is the same as with normal piston engine: burning fuel moves piston down that moves the crankshaft. The shaft rotates generator’s axel, which produces electricity. Gas engines can be divided to compression- and spark ignition engine like normal petrol and diesel engine. In compression ignition piston makes a high pressure that ignites gas and air mixture. In spark ignition the separate spark ignites gas and air. The benefits of gas engine power plant are high electricity efficiency (approx. 45%) and short building period. (Bioenergiatieto.fi 2012.)

Gas is also used to produce mechanical energy. This method is commonly used at water treatment plants. Gas is burned in gas motor, but instead of electricity production, the power produced is used at aeration compressor. (Latvala 2009, 46.)

2.2 Transportation fuel

Globally, there are estimated over 17 million gas vehicles in the world (approx. 1,3% of all cars, motorcycles and mopeds), of which 1 million in Europe and 3 million in China. Italy has the largest number of gas vehicles in Europe, 800 000 vehicles, followed by Germany with 100 000 vehicles, Bulgaria over 60 000 and Sweden 40 000, in Finland there are almost 1000 vehicles. The total number of NGVs is expected to rise over 30 million in near future globally. (Rasi et al. 2012, 8, IANGV 2013.)

Gaseous fuels can relatively easily be used for transportation. Gas vehicles basic technology is quite similar to normal petrol or diesel cars. Gaseous fuel as a traffic fuel is old technology, already used in 1920’s. Gas engines have been rare in traffic, but during recent years when fuel prices have raised and emissions restrictions tightened, gas engines have become more common and during the same time also the distribution grid has grown. Traditional piston engines can run with gas with little modifications. The biggest difference between normal and gas vehicle is the fuel tank. Biogas vehicles are equipped with gas tanks where gas is in high pressure, 200 bars. The high pressure and gaseous fuel sets high demands for vehicles safety. The gas tank must not crack or broke in accident.

The SNG production began globally after the first energy crisis in 1970’s. SNG can be produced with numerous processes, such as fixed bed process. Many SNG production plants have been since built, like the Great Plains Synfuels Plant in USA producing 4,8 million m^3 per day. SNG production has been and still is under wide studies and many pilot plants have been built, such as the GoBiGas Phase 2 in Sweden producing SNG 800 GWh/a. (Kopyscinski et al., 2010, 1764-1779; Biofuelstp.eu 2015.) In 2007 there were globally 144 plants producing SNG via coal gasification. This number is equivalent to thermal capacity of 56 GW_{th}. (ETSAP 2010.)

Gas vehicles are of course more expensive than normal cars because of the extra technology required, such as gas tank and lower production volumes, but natural gas and biogas are supported with lighter taxation. Natural gas and biogas are more economic than normal fuels, but gas vehicles have extra annual taxation like diesel vehicles. This tax is smaller than with diesel cars. Gas filling stations are still quite rare, especially in Finland, so usually passenger cars are often bi-fuel vehicles that have a tank for both gas and traditional fuel. Busses and other larger commercial vehicles using gas can run only with natural gas or biogas.

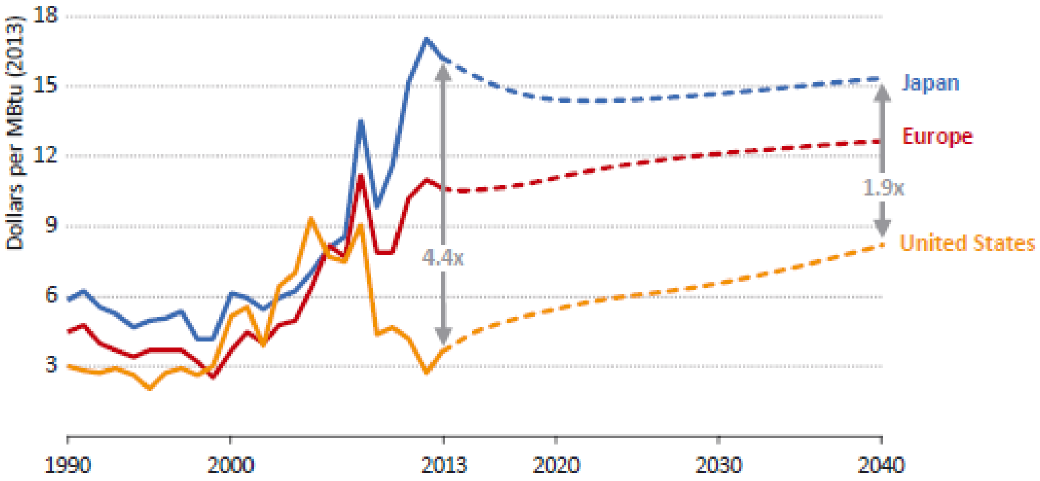
Biogas, like all biofuels, has considerably lower heat value when comparing to traditional fossil fuels, such as light fuel oil. The heat value for biogas is 14,4- 21,6 MJ/m^3, for normal petrol it is 42 MJ/m^3 (Alakangas 2000, 144, 155) and one cubic metre of methane equals to one litre diesel fuel. In practise the biogas bought from refuelling stations is a mixture of biogas and normal natural gas, so the real heat value is higher. Compared to traditional transportation fuels, biogas is very ecological, when it doesn’t produce nearly any CO_2-emissions and its production doesn’t require considerable amount of energy. (Latvala 2005, 16)

2.3 Price development of SNG and biogas

In this chapter the natural gas price development in recent years and future expectations is studied. Biogas and SNG prices are different than natural gas price, but these renewable gases don’t have large global price markets like fossil fuels. Biogas and SNG prices are linked to natural gas. Europe’s gas markets are well competed, that keeps the prices on average levels. Natural gas prices are linked to the oil prices and especially in southern

Europe. EU supports biogas and SNG production. According to Directive 98/70/EC proposal a fourfold calculation is allowed for gaseous transportation fuels that are produced from non-biological origins (Europa.eu 2012). This means that gases produced from non-biological components, such as electricity can have higher prices. In this integration case SNG has biological raw-materials, but it is mainly produced with electricity.

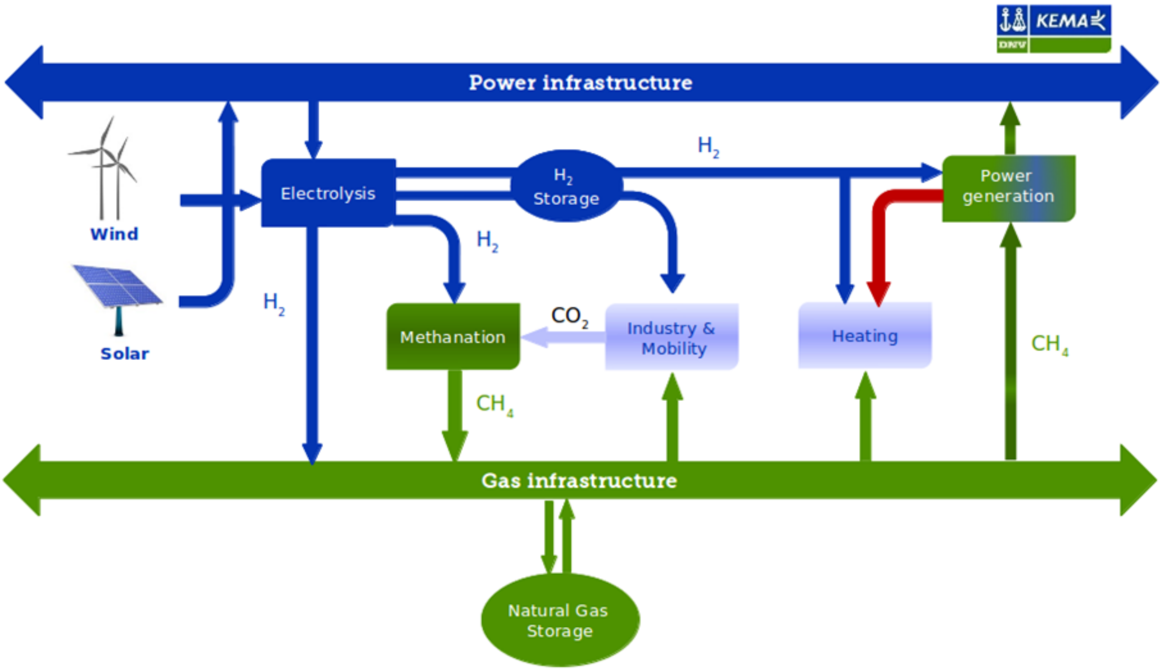
In Asia the gas markets are tight and natural gas is largely imported. The gas prices are higher because of the longer transportation distances. However in China prices are lower when China imports LNG and has access to imported pipeline gas from Turkmenistan and Russia. China has also its own domestic gas production. In the future the gas prices are expected to raise little. In Europe the price expectations are (Picture 3) 33 €/kWh for year 2020 and 35,1 €/kWh for 2040. (OECD/IEA 2014, 50 -51.)



Picture 3: Natural gas prices in recent years and future expectations (OECD/IEA 2014, 51)

3 POWER-TO-GAS TECHNOLOGIES

In Power-To-Gas concept (Picture 4) energy is converted to chemical form and most fitting for storage options are methane and hydrogen. Hydrogen is separated from water and this hydrogen is used to produce methane with carbon hydroxide. The main advantages of using these gases are the good volumetric density, existing infrastructure for transport and utilisation. Methane is very similar to natural gas that has been used in energy technology for long time (NaturalGas.org 2013), so all the infrastructure for methane is well known. Methane can be easily transported using natural gas pipes and –ships or used for heating at power plants, or be used as a transportation fuel in gas-powered vehicles like passenger cars or ships.



Picture 4: Power-to-Gas flow chart (NorthSeaPowertoGas 2015)

Electricity from solar power plant is used to produce hydrogen from water in electrolysis. Hydrogen is then used to produce methane with carbon dioxide in methanation process. Hydrogen itself can also be used in heat and power production, in traffic use or in chemical and metallurgical industries. The use of the hydrogen is still quite limited in vehicles and power plants, because hydrogen demands complex technology for safe use. Hydrogen is a very flammable and explosive gas that even corrodes metals. Therefore most of produced hydrogen would be synthesized to methane. The process requires carbon dioxide that has to be produced, or correctly, captured from air, or if Power-to-Gas is integrated in other industrial plants, CO_2 can be obtained from them.

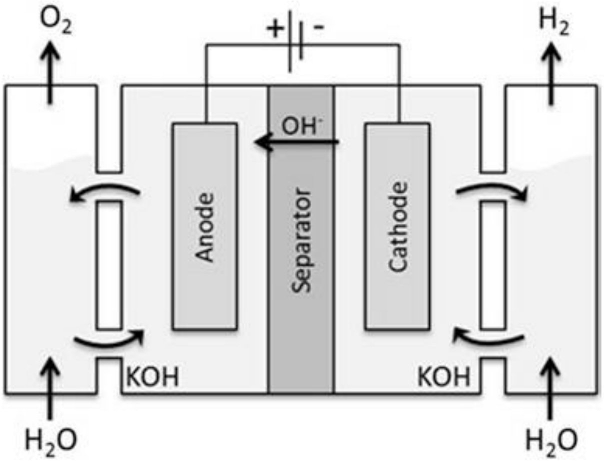
The overall efficiency of Power-To-Gas is inevitably reduced by the conversion processes. Electrolysis and methanation cause, like all technologies, some energy losses that decrease the overall efficiency of the process. The efficiencies for different paths in Power-to-Gas are shown in Table 1. (Lehner 2014, 10.)

Table 1: The efficiencies of Power-to-Gas methods (Lehner 2014, 10)

Path	Efficiency [%]	Boundary conditions
Electricity to gas		
Electricity to H_2	54 - 72	Including compression to 200 bar
Electricity to methane (SNG)	49 - 64	
Electricity to H_2	57 - 73	Including compression to 80 bar (feed in gas grid for transportation)
Electricity to methane (SNG)	50 - 64	
Electricity to H_2	64 - 77	Without compression
Electricity to methane (SNG)	51 - 65	
Electricity to gas to electricity		
Electricity - H2 - electricity	34 - 44	Conversion to electricity: 60 %. compression to 80 bar
Electricity - methane - electricity	30 -38	
Electricity to gas to combined heat and power (CHP)		
Electricity - H2 - CHP	48 - 62	40 % electricity and 45 % heat, compression to 80 bar
Electricity - methane - CHP	43 - 54	

3.1 Water electrolysis

Water electrolysis is a method to produce hydrogen and oxygen by dissociation of water with electricity. A water electrolyser converts electrical or thermal energy into chemical energy. The most common electrolysers are alkaline electrolyser (AEC), proton electrolyte membrane electrolyser (PEM) and solid oxide electrolyte electrolysis (SOEC). The most developed water electrolyser type is the alkaline electrolyser. An AEC (Picture 5) consists of two Ni-electrodes (anode and cathode) immersed in a 20…40% potassium hydroxide (KOH). KOH is used because it’s higher conductivity. The electrodes are commonly made of nickel or nickel plated steel. At cathode water is dissociated into hydrogen and hydroxide-ions, at anode hydroxide-ions are oxidized into water and oxygen. (Hydrogennet.dk 2015.)

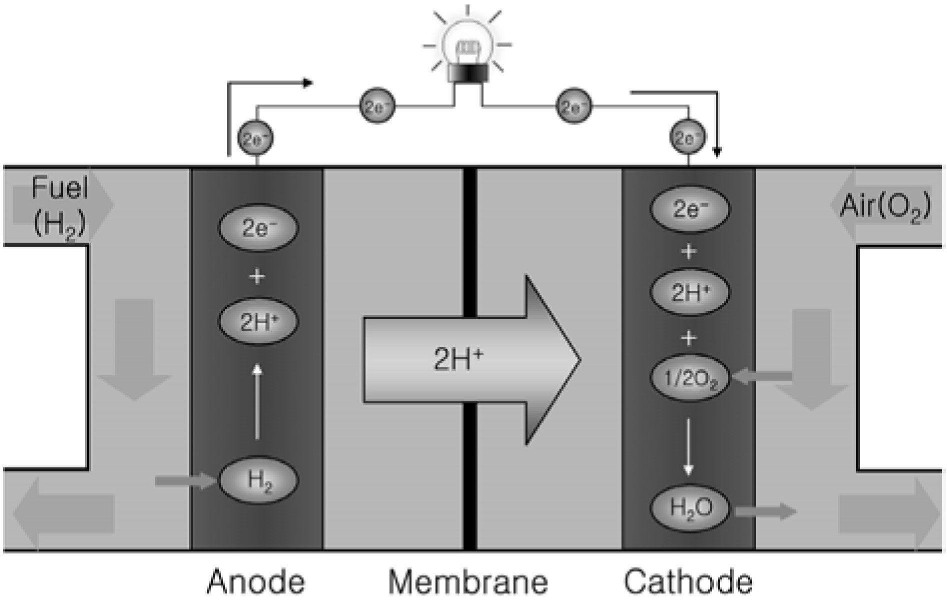


Picture 5: An AEC schematic (Lehner et al. 2014, 25)

Alkaline water electrolysis is a highly tested technology that is standard for large scale, industrial hydrogen production. The advantages are for example availability, quite low specific costs (euros per produced product) and proven durability. Two biggest disadvantages are low operating pressures and low current densities. Low current density demands larger system size and raises hydrogen production costs. The production capacity for AEC systems ranges from 1 to 760 scm H_2/h. Efficiency for AEC is 60-80%. The achieved hydrogen purity is at least 99,5%. AEC systems are most used electrolyser in large scale. (Lehner et al. 2014, 27-28.)

Another technology for water electrolysis is Polymer or Proton Electrolyte Membrane Electrolysis (PEMEC or PEM), where the liquid electrolyte is replaced with a solid polymer electrolyte. The polymer electrolyte has two major roles in the fuel cell: to separate the fuel and oxidant and transporting protons from anode to the cathode (Lee et al. 2006, 176.)

PEM technology is the second most important water electrolysis technology. PEM cell (Picture 6) consists of solid electrolyte that is a thin layer of proton conducting membrane and anode and cathode elements. The current densities in PEM cells are approximately 4 times higher than in AEC. The hydrogen production efficiency varies from 60 to 70% and hydrogen purity can be as high as 99,99%. PEM technology is currently used only in small scale, but it has been under intense research because of its key advantages, like high cell efficiencies and high current densities. PEM technology also provides highly flexible production with very fast start-up and shut-down times and it can operate with wide load range from 5 to 100%. However PEM cells are very complex and highly expensive and difficult to scale-up for larger production. Some PEM manufactures have still promised larger plants, even in MW-range. PEM technology is coming to industrial use in future and its main advantages make it very compatible to Power-to-Gas concept. (Lehner et al. 2014, 27-33.)



Picture 6: A PEM cell schematic (Lee et al. 2006, 176)

In SOEC a thin layer of oxygen is used as an electrolyte. SOEC cells use high temperatures from 700 to 1000 °C. This feature enables low overall energy demand, but causes also degradation problems in cell components. SOEC cells can reach the efficiency of 40 - 50%. Because of the high temperatures, SOEC cells require complex ceramic materials, such as yttrium oxide (Y_2O_3). (IEA/HIA 2015)

3.2 Methanation

Methanation is a gas-catalytic or biological process, where methane (SNG) is formed from hydrogen and carbon monoxide/ dioxide. The biological process is the anaerobic digestion that is also used to form biogas. Chemical methanation reaction is known for more than a hundred years and used to produce substitute natural gas (SNG). Another widely used technology is the gas purification. (Lehner et al. 2014, 41.) Bio-SNG is produced from biomass by gasification and its production can even reduce the carbon dioxide load. During the last steps of the production processes some of the biomasses carbon is removed as CO_2 that can be stored. (Meijden et al. 2009, 302.)

The chemical reaction for methanation is the Sabatier reaction: (Meijden et al. 2009, 308.)

$$CO_{2(g)} + 4H_{2(g)} \leftrightarrow CH_{4(g)} + 2H_2O_{(g)} \quad (1)$$

,where

CH_4=methane	[-]
CO_2= carbon dioxide	[-]
H_2=hydrogen	[-]
H_2O=water	[-]

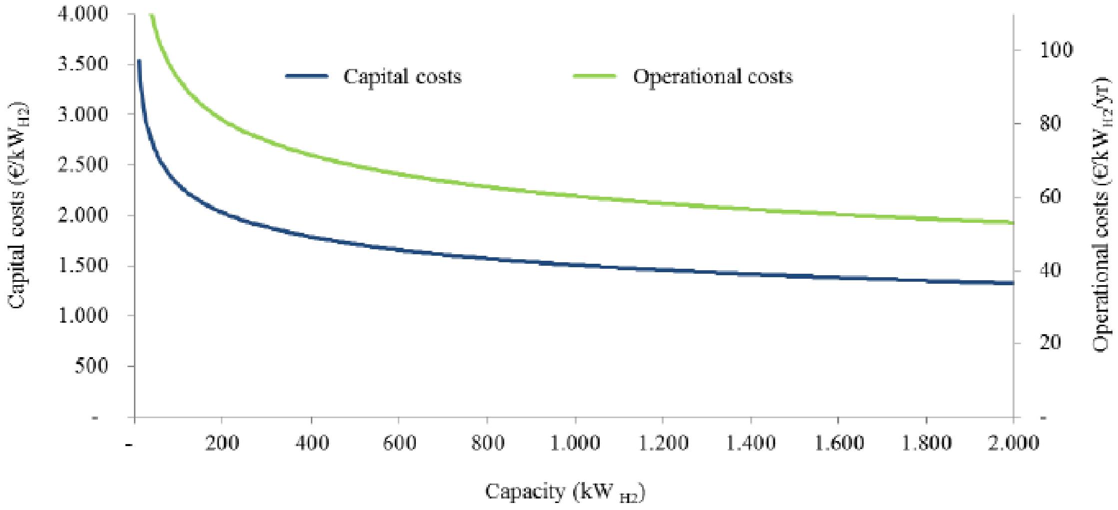
This reaction is strongly exothermic and the heat from this process can be later utilised. The produced gas contains in addition of methane also steam, carbon monoxide and unconverted educts. The reactions require catalyses for hydrogenation of CO_2 and widely used catalyses are Ni and silicabased catalysts. (Lehner et al. 2014, 42, Meijden et al. 2009, 308.)

Typical methanation process path is gasification, gas cleaning, conditioning and finally methanation and possible gas upgrading before feeding the gas into the grid. There are different process methods available that can be divided into 2-phase systems (fixed bed, fluidized bed, coated honeycombs) and 3-phase systems (bubble column). The main difference is the 3-phase systems liquid heat carrier is used to achieve an isothermal temperature profile. The methanation process requires huge amount of heat and the temperature regulation of the process is difficult and very important. (Lehner et al. 2014, 42-43.)

3.3 Costs of Power-to-Gas

The main costs from Power-to-Gas technology are the high investment costs. This technology requires complex appliances that are currently under development and not very widely used. Technologies in Power-to-Gas are still under improvements and it is estimated that the investment costs are decreasing in the future. The operational costs are relatively lower when the processes are highly automatized and prices of the raw materials are low. However, sudden equipment brake-downs may create high costs, because of the complex technology and flammable gases.

The capital and operational costs from the Power-to-Gas's main process, electrolysis can be evaluated with following chart (Picture 7). This is thus only for alkaline electrolyser.



Picture 7: Capital and operational cost for alkaline electrolysis (Grond et al. 2013, 22)

3.3.1 CAPEX of Power-to-Gas

Capital expenditures in Power-to-Gas technology consist mainly of costs from electrolysing, methanation, piping and gas storages. Electrolysers and methanation appliances are complex and expensive devices and gas transportation also requires sophisticated machines and tanks. Electrolysis process is therefore the largest investment cost in the Power-to-Gas followed by methanation process and the overall investment costs for Power-to-Gas are high.

It is expected that these investment costs are going decrease when technology improves. For example, with alkaline electrolysers a 0.4 % decrease of costs is expected annually through improved technology. Siemens has announced that its new generation PEM cells price can be reduced to under 2000 €/kW and with further improvements the costs can be well under 900 €/kW in a few years. Also the size of the electrolysers can be increased, Siemens third generation electrolyser are expected to achieve 100 MW class. (Siemens

2014.) At methanation process, a cost reduction is achieved only with larger capacities. In 2015, the investment cost for electrolyser (Table 2) vary between from 1100 to 1200 € per installed kW for alkaline electrolyser and from 1200 to 1940 €/kW for PEM. For the year 2030, the predicted costs for electrolysers are 370- 800 €/kW for alkaline and 250- 1270 €/kW for PEM. For SOEC the estimated price is 930 €/kW in 2020 (Mathiesen et al. 2013, 8). For methanation process the current costs are now 1000 €/kW$_{SNG}$ and estimations for future 650 €/kW$_{SNG}$ (Henning, Palzer 2015, 20).

Table 2: Cost reduction trend lines for alkaline and PEM electrolysers (Bertuccioli et al. 2014,13).

System cost(1)			**Today**	**2015**	**2020**	**2025**	**2030**
EUR/kW	Alkaline	Average	**1100**	**930**	**630**	**610**	**580**
		Range	1000-1200	760-1100	370-900	370-850	370-800
	PEM	Average	**2090**	**1570**	**1000**	**870**	**760**
		Range	1860-2320	1200-1940	700-1300	480-1270	250-1270

(1)incl. power supply, system control, gas drying (purity above 99,4%). Excl. grid connection, external compression, external purification and hydrogen storage

3.3.2 OPEX of Power-to-Gas

The operational costs of Power-to-Gas consist of electricity costs, personnel costs, raw material and maintenance costs. Power-to-Gas processes are operated by electricity, therefore the electricity costs are a quite large share of the overall operational costs. Raw materials, water and carbon dioxide are little cheaper.

Electrolysers require quite lot of electricity for hydrogen production, 4,3 - 5,5 kWh/scm H_2 (Lehner 2014, 26). Therefore electrolyse causes also the largest electricity costs in Power-to-Gas. When the price of the product, SNG is quite low, the Power-to-Gas can be only operated with low electricity prices. This is the basic idea in Power-to-Gas: to take advantage of the low electricity prices. The electricity price for industry in Finland is 72

€/MWh, 110 €/MWh in China and in Germany 152 €/MWh (Europa.eu 2015, OECD 2013, 133).

Price of water is quite low, the default price in Power-to-Gas is 1 € per ton as highest. Water costs are therefore low. The important raw material of methanation, carbon dioxide is however little more expensive, the default price is 100 €/t. However in this study the carbon dioxide price is determined by this case and the price is different and calculated later in this thesis. The price of CO_2 can vary by the method it is produced. In integration the carbon dioxide can be received from other processes and then the price can be considerably lower.

Maintenance costs can be little high because of the complex technology and the Power-to-Gas technology is still quite new and less tested in practise. This new technology can cause some unexpected maintenance costs and the maintenance and replacing old parts can be complex itself. Parts, for example in electrolysers can be difficult and slow to acquire that can cause disturbs to the gas production. Plant itself has only a few mechanical processes that decreases maintenance need and it is possible to operate with low number of personnel. However plant has several large pressure appliances that contain flammable gases that are needed to be inspected regularly by authorities. With these assumptions the personnel costs are estimated as from 80 000 to 280 000 €/a and the maintenance costs are estimated as 70 000 to 90 000 €/a. Large variation in personnel costs comes from different personnel costs in selected countries in this thesis.

4 WASTEWATER TREATMENT

The first WWTPs were built at 1890's. Later, at the beginning of the First World War, the activated sludge process was invented that improved the speed of the treatment process. (Wiessmann et al. 2007, 1-19.) Currently wastewater treatment is nearly a compulsory technology for a modern day society. In western countries there are WWTPs nearly every city and town, but in Asia and in Africa there is still struggle for fresh and cleaned water. Also there is a need for large investments for repairs, maintenance and replacement in western countries too. Many of the WWTPs in Europe and in USA are old and need investments. In developing countries there is a demand to build and expand the water systems. Both the developing countries and western countries have rapid increase in populations that increases the water consumption. Also the stringent legislation, such as the Urban waste water treatment -directive (UWWTD), for drinking water and sanitation sets demands for water treatment (Europa.eu 2015). The investment to water treatment and water industry was in 2010 425 billion dollars and it is estimated to be approximately 6 trillion dollars during the next 20 years. The largest investments are in South America and in Asia. The developing markets in water sector are for example: wastewater recycling and reuse, water conservation and water-efficient technologies. (PPE 2012, 8-13.)

There are two different ways to prevent and to treat wastewater. First way is to decrease or prevent wastewater production. These are process-integrated techniques, for example upgraded process techniques, water savings and pollution prevention. The second way is the wastewater treatment that is also called end-of-pipe treatment that consists of individual and/or central facilities. (European IPPC Bureau 2014, 27.) The requirements for drinking water are different, and often lower than for industrial water and therefore industrial water treatment can be more thorough, depending on the need, of course.

Environmental protection is shifting from end-of-pipe techniques to process-integrated techniques. Process-integrated techniques reduce or prevent the production of waste at the source. With these process improvements there is less demand for additional treatment measures, which decreases costs and raises economic efficiency when production increases. Despite of prevention of waste is becoming more significant, traditional waste water techniques will remain important ways to control emissions, especially when process-integrated techniques are not suitable for existing production. (European IPPC Bureau 2014, 27.)

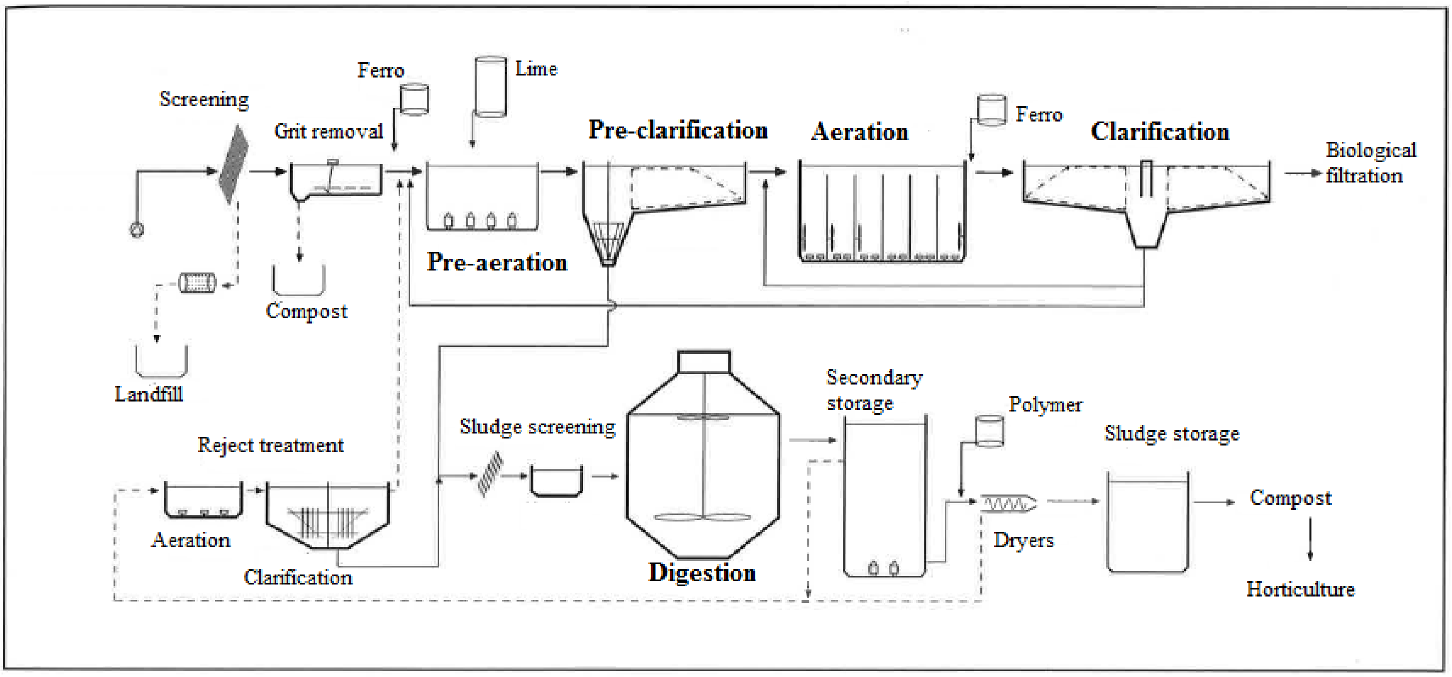
Process-integrated protection consists of different physical, chemical, biological and engineering techniques. These techniques are, for example improvement of plant technology, process control and reaction sequence, recycling of auxiliaries, immediate recycling of residues during the process, use of residues for energy generation. (European IPPC Bureau 2014, 27.)

Because it’s not always possible to prevent pollution at the process, there is a need for wastewater treatment. End-of-pipe techniques are used to treat produced wastewater. Wastewater treatment consists of different physical, chemical and biological treatments. During the process, all the solids, and usually harmful bacteria and heavy metals are removed to desired level. These techniques are for example aerobic treatment, biological removal of sulphur compounds, sand filters, retention ponds. (European IPPC Bureau 2014, 28-30.)

Waste water treatment facilities can be centralised or decentralised different ways, depending on the situation. Centralised WWTP is the common method for municipal water treatment. Decentralised waste water treatment is used often if there is a wide variation at the waste water properties.

4.1 Main water treatment processes at treatment plant

Waste water treatment is usually a combination of different treatment steps (Picture 8). The main steps are mechanical separation, physic-chemical treatment and/or biological treatment. WWTPs have different treatment techniques to treat wastewater. Among the fresh water, wastewater treatment produces also sludge and different gases, like methane and carbon dioxide.



Picture 8: Figure of Suomenoja WWTP (Kangas 2004, 11)

4.1.1 Mechanical separation

The first, and usually the final, treatment procedure for wastewater is the separation of suspended solids and immiscible liquids. Used separation techniques are screening, gravity separation, flotation and filtration. Primary treatment can reduce the BOD (biodegradable organics) by 20 to 30% and total suspended solids in water by 50 to 60%. At the beginning of the treatment process these techniques also protect the following treatment facilities against damage, clogging or fouling by the solids. These techniques are also used at the end of the treatment process to remove solids formed during the treatment. (Water.worldbank.org 2015.)

At first the biggest solids are removed, in municipal WWTP it is commonly used a simple screening, where water is lead through filter or screen. Larger solids stay on the filter and they removed with raked bars –system that transfers solids away from the water. After screening, there can be grit separator to remove sand and gravel. Grit separators are designed to protect other treatment installations and they are not installed because of environmental protection reasons. Grit chamber can be channel- shaped (Picture 9) or it can have horizontal flow, circular or aerated. Solids are removed by using gravity, an air-jet lift or compressed air. (European IPPC Bureau 2014, 177.)

Picture 9: Grit chamber in WWTP (T.L.M Engineers 2008)

Coagulation and flocculation are methods used to drive particles together and create a floc. In coagulation particles are charged with opposite charges. This causes particles to stick together. The coagulation is carried out by adding coagulant chemicals like ferric sulphate, aluminium chloride or sodium aluminate. Also a rapid mix is often needed in coagulation to achieve good efficiency. Without rapid mixing, floc particles disintegrate. In flocculation the particle size is increased. This is achieved by adding inorganic or organic polymers. After the floc has grown to the optimum size and strength, the waste water can be brought to sedimentation. (IWA Water Wiki 2010.)

Sedimentation or clarification is separation of suspended particles and floating material. Separation is made by gravitational settling. Sludge settles on the bottom of the large tank and floating material, such as oil and grease rise to the surface and they can be skimmed off. If particles are too small and light to be removed with gravitational forces, special chemicals are added like lime, ferric sulphate or cationic organic polymers. The chemicals cause emulsion entrapping, destabilisation of colloidal and/or drive particles into flocs. A sedimentator, or settler, can be a circular and open tank (Picture 10), hopper-bottom tank, or lamina or tube settler. Sedimentators are equipped with different techniques for rapid water mixing needed in chemical separation. The main target of clarification is to produce homogenous liquid that can be treated biologically. Sedimentation has its limits too, for example sedimentation is unsuitable for too fine material and stable emulsions and created floc can disturb the disposing of the sludge. Sedimentations advantages are its simplicity to install and its removal efficiency can be increased with chemicals. (European IPPC Bureau 2014, 181 -185, Neutralac.com.)

Picture 10: A circular sedimentation tank (City of Lincoln)

In flotation solid or liquid particles are separated from waste water by fine gas (usually air) bubbles. Flotation is an option for sedimentation and used if sedimentation is not available or it would be less efficient. The gas accumulates particles at the water surface, where they are collected. The floatation process can be boosted by adding flocculant additives like activated silica, aluminium and ferric salts and various organic polymers. The function of these chemicals bases on coagulation, flocculation and creating a surface or structure that absorbs gas bubbles. (European IPPC Bureau 2014, 186-187.)

There are three floatation methods, the main difference of these methods being the way the gas is added: electro-flotation (EF), vacuum flotation, induced gas/air flotation (IGF, IAF) and dissolved gas/air flotation (DGF, DAF). Compared to sedimentation, flotation has lower capital costs, high separation efficiency and higher dry matter content. But flotation has higher operational costs and high potential for odour release. (European IPPC Bureau 2014, 186-189, Rubio et al. 2002, 142-143.)

4.1.2 Soluble non-biodegradable particles

After removing the solids, waste water is either segregated into a biodegradable and a non-biodegradable part, or the contaminants causing the non-biodegradability can be separated. The non-biodegradable compounds (eq. heavy metals, salts) are treated, for example, with following operations: precipitation, crystallisation, chemical reactions (chemical oxidation, chemical reduction, and chemical hydrolysis), absorption, ion exchange, evaporation. (European IPPC Bureau 2014, 174-175.)

Chemical precipitation is a method to form particulates that can be later separated later from the treated water with sedimentation or filtration for example. Precipitation is used mainly to separate metals and other inorganics, suspended solids, fats, oils, greases and other organic substances. Precipitation is carried out with chemicals and assisted with coagulants that are commonly long-chain polymers. Commonly used precipitation chemicals are lime (calcium oxide), dolomite, sodium hydroxide, sodium carbonate and some others. These chemicals are often mixed with flocculants to support the separation. Precipitation is used in many industrial plants. (EPA 2008.)

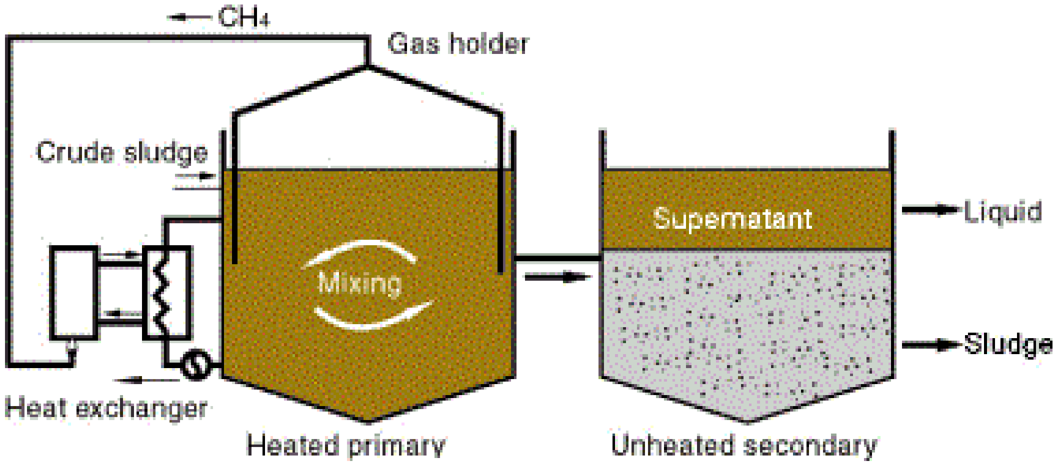
Crystallisation is similar process than precipitation. Separation is made using seed material like sand or minerals that form a precipitate in a fluidised-bed process in a pellet reactor system. Treated waste water is fed to circulating stream. Seed material grows and moves towards the reactor bottom. The velocity of waste water maintains the fluidised bed that provides a very big crystallisation surface (5 000-10 000 m^2/m^3). Large surface enables fast and controlled system that crystallises nearly all the anion or metal particles on the pellets. Crystallisation is used mainly to remove heavy metals from waste water, but also to treat fluoride, phosphate and sulphate. Crystallisation is a nearly waste-free process and doesn’t produce sludge. (European IPPC Bureau 2014, 214-218.)

Ion exchange is used in wastewater treatment to change harmful ionic particles with suitable ions. There are two types of ion exchangers: anion and cation exchangers. Ion exchanger consists of strong and weak cationic or anionic functional groups and a system to regenerate the resin. Ion exchanger is sensitive system for disturbances. Cationic and anionic units require regular recovery, flush, with high concentration solution. Ion exchanging includes actual ion exchange operation, backwash stage, regeneration stage, displacement with slow water flow and fast rinse. (WasteWaterSystem.net 2013)

4.1.3 Soluble biodegradable particles

Major parts of waste water are often biodegradable waste water that is treated with techniques based on biological processes. The two main processes are anaerobic treatment (anaerobic digestion) and aerobic treatment (aerobic digestion). There is also the biological nitrification/ denitrification. (European IPPC Bureau 2014, 174.) These processes treat the solid content of the wastewater, also known as the sludge.

In anaerobic treatment or digestion microorganisms convert the biological content to sludge and gaseous substances, the most important being the methane (**Picture 11**). The raw sludge that is collected from previous treatment stages is mixed in heated tank. The bacteria operation produces solid sludge that can be later utilised and gases. Anaerobic treatment can be divided into mesophilic and thermophilic digestion depending of the digestion temperature. Anaerobic treatment is processed in airtight stirred tank reactor. The most widely used reactor types are: anaerobic contact reactor, upflow anaerobic sludge blanket (UASB), fixed-bed reactor and expanded-bed reactor. (European IPPC Bureau 2014, 280, QM Environmental Services Ltd 2010.) The anaerobic digestion is later studied more closely in this thesis.



Picture 11: Anaerobic digestion process. (UNEP)

In aerobic treatment the organic components of waste water are converted into CO_2, water or other metabolites and biomass. The conversion is made by injecting air, pure oxygen or oxygen radicals to the solid waste, sludge. The oxygen radicals are a new method called advanced oxygen process (AOP). Commonly used biological treatment techniques are: complete mix activated sludge process (CMAS), membrane bioreactor process, trickling or percolating filter process, the expanded-bed process and fixed-bed biofilter process. CMAS –process is the most widely used aerobic treatment method and commonly used with chemical industry. The aeration in CMAS is done in the aeration chamber, which can be a traditional flat tank or a tower. The produced activated sludge mixture is sent to a clarification tank, where the sludge is brought back to the aeration tank. The membrane bioreactor process is a combination of biological, activated sludge treatment and membrane separation. In this process the clarification tank is replaced with a membrane bioreactor that is more compact. In the trickling filter process a highly permeable filter is used that trickles the wastewater. (European IPPC Bureau 2014, 289-290.)

An aerobic digestion can be divided into two phases. At the first phase, called activated-sludge process, the primary sludge provides food supply for microorganisms that causes rapid increase of bacteria population. The bacteria use efficiently oxygen and organic waste and after some days oxygen uptake rate declines and food supplies decreases. After this, bacteria are forced to use internal storage products as energy sources. When bacteria's food supplies become depleted, the growth of bacteria population decreases and stabilizes. The second phase of aerobic digestion is continuation for first phase. The most important reaction at this phase is the oxidation and treatment of cellular constituents with lysis and auto-oxidation. (Adams et al. 1999, 350-351.)

Nitrogen is removed from waste water by special biological treatment called denitrification. In this process nitrate (NO_3^-) is conversed to nitrogen gas, nitric oxide or nitrous oxide. Nitrate is converted into nitrogen gas by microorganisms operation in presence of organic matter (wastewater) (Selba.org.). Methanol is a chemical used in denitrification. Methanol removes nitrogen from wastewater via complex reactions and bacteria operations. The overall formula is (Claus and Gunther 1985, 379):

$$50.5\, CH_3OH + 3HNO_3 + 46.2NO_3^- \rightarrow 3C_4H_7O_2N + 38.5CO_2 + 23.1N_2 + 46.2OH^- + 68.9\, H_2O \qquad (2)$$

,where

CH_3OH= methanol [-]
HNO_3= nitric acid [-]
NO_3^-= nitrate ion [-]
$C_4H_7O_2N$= N-methylolacrylamide [-]
N_2= nitrogen [-]
OH^-= hydroxide ion [-]

Denitrification and nitrification causes most of the WWTP's nitrous oxide (N_2O) gas emissions. N_2O is a very harmful greenhouse gas; its effects are 200-300 times greater than those of CO_2. Therefore an extra carbon source and other treatments are used during denitrification to control and reduce N_2O emissions. (Park et al. 2000, 247.)

Nearly all waste water treatment techniques produce solids during the process, for example from sedimentation or filtration. These solids can be further recycled, disposed or treated (digestion) on site. Sludge is a common product in WWTP and can be used eq. in agriculture. If sludge isn’t digested it is further treated with following treatments: thickening and dewatering, stabilisation and conditioning or composting. (European IPPC Bureau 2014, 175-176, UNEP.)

Sludge thickening and dewatering are methods to increase the solid content of sludge and decrease water content. Sludge is then easier to handle for further treatment when its volume is smaller. Often used techniques are gravity settling, centrifugal thickening, gravity belt and rotary drum. (European IPPC Bureau 2014, 325-328.)

The techniques for sludge stabilisation are chemical and thermal stabilisation, aerobic and anaerobic digestion and dual sludge stabilisation. Stabilisation reduces amount of odorous constituents, quantity of biodegradable sludge solids, pathogens, potential for putrefaction and improves dewatering. The main reason for stabilisation is to reduce odorous emissions. The purpose of sludge conditioning is to improve the system conditions for thickening and/or sludge dewatering. Conditioning techniques are chemical conditioning with for example ferric chloride, lime or organic polymers, thermal conditioning by heating the sludge in a pressure system from 60 to 80 °C (low temperature conditioning) or from 180 to 230 °C (high thermal conditioning). (European IPPC Bureau 2014, 331-333.)

4.2 Future technology

Advanced oxidation processes (AOP) are treatment methods that use high reactivity hydroxyl radicals (-OH) to treat biologic contaminants. These radicals react quickly with pollutants and dissolve them into smaller particles. Radicals are produced in the site with ozone, hydrogen peroxide (H_2O_2), UV-light or titanium oxide (TiO_2). AOP processes are for example: Fenton processes (H_2O_2), photoassisted Fenton processes (UV-light), photocatalysis (TiO_2). (Andreozzi et al. 1999, 52-54.) AOP consume fewer chemicals than traditional treatment processes and can also be more effective in treatment. Hydroxyl radicals treat nearly all the organic content of waste. However, AOP technology is expensive and has high operation costs. AOP technology is at present used in some WWTPs, but it still needs large research to be more implemented. (Felizen 2015.)

Membrane bioreactors (MBRs) are a combination of activated sludge process and membrane filtration. MBR are operated like activated sludge process, but it doesn't require secondary clarification. The membrane material separates wastewater from sludge. Membrane can be either submerged or external. Also complete nitrification and denitrification as well as phosphorous removal can be operated in MBR. Membrane technology is more efficient and enables smaller reactor volume in wastewater treatment than traditional activated sludge process, but it is also more expensive and it's more sensitive for pressure, temperature and pH-levels. MBR also requires air or oxygen. First membrane bioreactors in Europe are built in 90's and currently MBR are used in some municipal wastewater treatment plants. (Melin et al., 2006, 271-282.)

Nanotechnology means using very small particles, smaller than 100 nm. Nanomaterials, like Carbon nanotubes or Nano-Ag can have good features that make them ideal for wastewater treatment, such as high specific surface area or superparamagnetism. The current and potential applications of nanotechnology in both water and wastewater treatments are adsorption, membranes, photocatalysis, disinfection and microbial control and sensing and monitoring. Nanotechnology is a promising improvement to wastewater treatment, but currently nanomaterials have to be more studied. Some features, like long-term efficacy or health risks are still quite unknown when nanomaterials are used mostly only in laboratory conditions. Nanomaterials are also still quite expensive, although the cost-effectiveness can be solved by retaining and reusing nanomaterials. Despite of the current disadvantages, some nanomaterials are in pilot testing or even in commercial use. (Qu et al. 2012, 3931-3946.)

Natural wastewater treatment systems offer low-cost alternatives for municipal treatment plants. Natural treatment systems can be wetlands, constructed wetlands (CW) (Picture 12), lagoons or other natural systems. Natural treatment system consists of specific plants and bacteria that are capable to treat wastewater. Natural wastewater treatment doesn't require building sewerage systems for single houses and it offers are natural solution with aesthetic features for wastewater treatment. However it requires large area and the treatment efficiency may not be as high as in WWTP and natural treatment is considered as secondary or tertiary treatment stage. (Ayaz, Akça 2001, 189-195.)

Picture 12: Constructed Wetland Park in Hong Kong (Environment Hong Kong 1986-2011)

4.3 Biogas production at water treatment plant

Biogas is produced at WWTPs via anaerobic digestion where sludge from wastewater is digested in anaerobic conditions. There are two main types of digestion: mesophilic and thermophilic digestions which vary from the digestion temperature. Digestion is also a treatment stage in waste water treatment and therefore nearly compulsory for WWTP. The most widely used digestion techniques are mesophilic (temperature 35...37°C) and thermophilic (temperature 50…55°C) digestions (Virta 2011, 11).

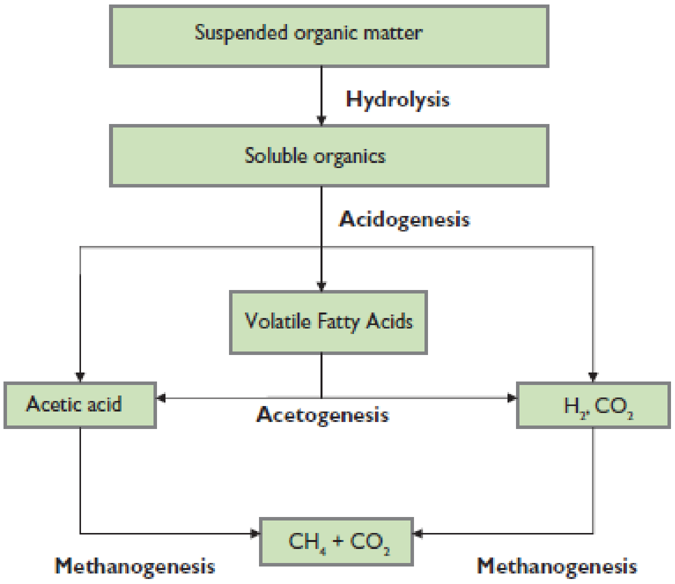
4.3.1 Anaerobic digestion

Anaerobic digestion is an anaerobic biological process, where part of the sludge’s organic compounds is transferred to biogas, which mainly consists of methane, carbon dioxide and small amount of nitrogen and hydrogen sulphide. Digestion can be divided into hydrolysis, acidogenesis (form of acid) and methanogenesis (form of methane) (Picture 13). (Kangas et al. 2011, 17.)

The hydrolyse stage is where organic substance decomposes into smaller dissolved particles. Hydrolysive bacteria transform particles in to more simple form that other bacteria can treat at later stages. Hydrolyse can be enhanced with different pre-treatment stages, where the dry-substance content is increased. It is also possible to separate hydrogen after hydrolysis, if the process uses two-phased digestion. (Virta, 2011, 11.)

In acidogenesis special acetogenic bacteria form acetic acid, hydrogen, carbon dioxide and acetates. The process uses substances formed during previous stages. (Virta 2011, 11.) During acidogenesis propiate and butyrate are formed that later disintegrated into hydrogen and acetic acid. (Latvala 2005, 29.)

Methanogenesis is a stage where methane is formed by bacteria. Methane is formed in two ways. The first method, acetoclastic methanogenesis, where 70 % of the methane is formed, is when bacteria form methane from acetate. In the second method, hydrogenotrophic methanogenesis, bacteria form methane from carbon dioxide and hydrogen. Although, the second method doesn’t produce so much methane, it is still important process for the digestion, because it removes hydrogen that can disturb bacteria. The high concentration of hydrogen causes bacteria to form acid instead of acetates. (Virta, 2011, 11.)



Picture 13: Different processes in digestion (Kangas et al. 2011, 17).

Digestion process can also be boosted by various methods. The most common is homogenising the sludge by crunching the sludge to homogenous mass. This can be made by using mechanical force or ultrasound. (Latvala 2005, 6.)

Organic waste can be treated either by composting or by digestion. Digestion produces more energy and the end-product is biogas that is easier to use. Digestion itself can be done in one or in several reactors. Reactors can be divided that first reactor has optimized conditions for hydrolyse and acidogenesis. This kind of system is called two-phase reactor system that provides more biogas than one reactor. Reactor is a tank or a vessel, where the anaerobic process happens. The most common process is wet-process, where the dry-particle content is approx. 10 -13%. (Kiviluoma- Leskelä 2010, 45.)

The most common biogas reactor in Finland is a single-phased, full mixture, mesophilic and continuous wet-process. The organic waste is regularly fed to the reactor. (Latvala 2005, 6.)

4.3.2 Mesophilic and thermophilic digestions

The mesophilic digestion is more common technique, because the process is currently easier to control. In thermophilic digestion reactions happen faster than in mesophilic, so it produces more biogas from same volume of sludge. Thermophilic process requires more energy to heating (higher temperature), but the retention time is shorter and the higher temperature eliminates more harmful bacteria which makes the sludge after the process more hygienic. Thermophilic method is currently used at least by two treatment plant in Finland (Vaasa and Satakierto). (Kangas et al. 2011, 6.)

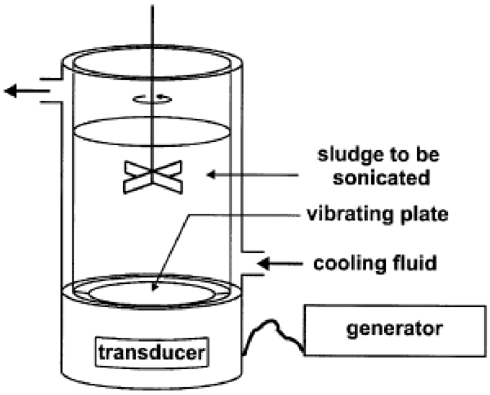
Digesters can be divided into conventional (mesophilic) and high-rate (thermophilic) digesters. These two methods vary in detention time and in loading rates. High-rate digesters have shorter detention time, but larger loading rate. Conventional digesters are loaded from 13 to 45 kg per 300 m^3 per day. Common detention times are 30 to 60 days. Conventional digesters consist of series of digesters. The primary digesters are heated from 30 to 35 °C. Primary digesters are commonly followed by one or more secondary, unheated digesters. Primary digester doesn’t have mixing unless the secondary digesters are unmixed. (Adams et al. 1999, 357.)

High-rate digesters (thermophilic digestion) are loaded from 45 to 225 kg per 300 m^3 per day, detention times being from 10 to 20 days. High-rate digesters are heated from 50 to 55 °C. High-rate units can operate in series or there can be also unheated, conventional series after them. High-rate digesters are equipped with mixing and gas re-circulation. Estimated gas production is 7,4 m^3 per 1 kg sludge treated. (Adams et al. 1999, 357.)

4.3.3 Digestion improvement with pre-treatments

Anaerobic digestion is a slow process and slow rate means lower biogas production. Digestion process can be however improved and biogas production increased. The hydrolyse phase is identified to be the rate-limiting phase. Therefore different mechanical, thermal or chemical pre-treatments can improve anaerobic digestion. (Tiehm et al. 2000, 2003.)

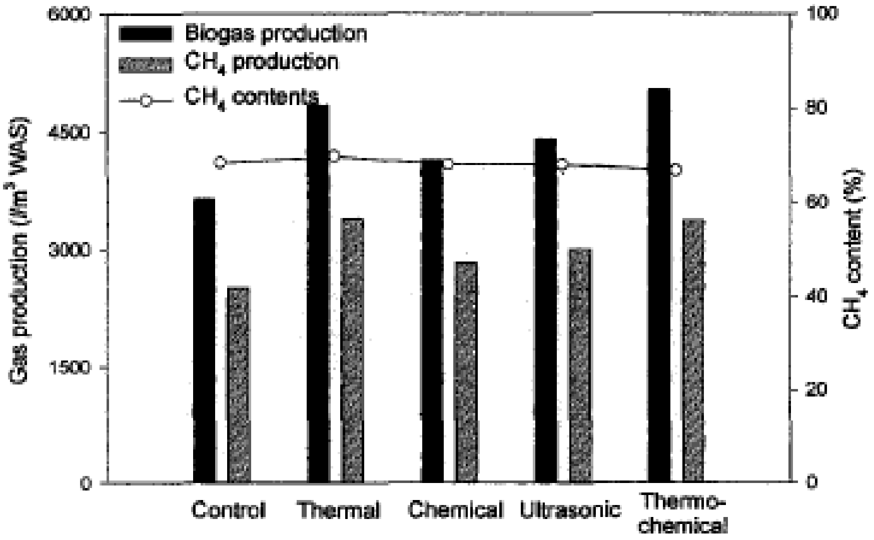
Digestion and therefore biogas production can be boosted with ultrasound. Ultrasound treatment (Picture 14) during digestion process increases digestion and biogas production. At water treatment plant at Wupa Abuja in Nigeria, experiments showed that ultrasound in digestion increased biogas production by 13%. (Onyenobi et al., 2013.) Ultrasound disintegrates microbial cells by causing periodical compression and rarefaction of the medium in the liquid. Ultrasound waves create growing bubbles that collapse rapidly. Too extreme pressure and temperature (circa 5000K and several hundred atmospheres) during ultrasound treatment can lead to form of very reactive hydroxyl radicals. Ultrasound is the most effective at low ultrasound frequencies (200 kHz and below). (Tiehm et al. 2000, 2003-2005.)



Picture 14: An ultrasound reactor (Tiehm et al. 2000, 2005.)

Sludge thickening increases organic substrate concentration that supports larger bacteria colonies and that produces more biogas. The thickening can be done by eq. feeding chemicals, such as ferric chloride during digestion process. Ferric chloride can increase the production up to 30%. Thickening can also be done with gravitation in separate installations, but this method has higher operational costs. (Hons 2011, 33-34.)

Thermochemical pre-treatment is a combination of several treatments. At these pre-treatments thermal energy is brought along with ultrasound and chemicals to sludge that altogether increase bacteria activity. Thermal treatment is heating the sludge at eq. 120 °C for half an hour and NaOH is widely used in chemical treatment. Together these treatments reduce significantly particle size and increase the level of soluble protein. Higher protein level improves anaerobic digestion and biogas production. Thermochemical pre-treatment increases biogas production up to 38%. Gas production volatilities with different pre-treatments are shown in Picture 15. (Kim et al. 2003, 271-274.)



Picture 15: Gas production with different pre-treatments (Kim et al., 2003, 274.)

4.3.4 Biogas enrichment

Produced raw biogas contains in addition of methane useless gases that must be removed (**Table 3**). This enrichment makes biogas more productive and safer. Hydrogen sulphide can cause corrosion, which can cause serious damage to equipment and installations. Water must be also removed because of the accumulation risk in the pipe lines. Carbon dioxide is eliminated from biogas, which increases the heat value. (Osorio and Torres, 2009.)

Table 3: Biogas and natural gas comparison (Suomen Kaasuyhdistys, Guangyou 2014)

Compound	Treated biogas	Natural gas FIN, Russia import	Natural gas GER, Goldenstedt	Natural gas (CHI)
Methane [%]	60-70	98	88	65-99.97
Ethane [%]	0	0.8	1	0.01-25
Carbon dioxide [%]	30-40	0.1	0.8	5-20
Nitrogen [%]	0.2	0.9	10	5-25
Higher heating value [MJ/kg]	14.4-21.6	55.3	50-55.3	50-55.3
Lower heating value [kWh/Nm^3]	6.5	10	9-10	9-10

Biogas can be enriched by several ways: pressure swing absorption (PSA), physical or chemical absorption, use of organic solvents, cryogenic separation and membrane purification. The most common used technologies are the water scrubbing and the PSA. (Osorio, and Torres, 2009.)

Water scrubbing is based on the higher solubility of carbon dioxide in water than methane, especially at lower temperatures. Water scrubbing is the most common technique for biogas upgrading and there are many manufacturers providing with wide range of water scrubbers. There are two different water scrubbing methods used to upgrading biogas, single pass absorption and regenerative absorption. In single pass absorption water is used only once and that is a typical installation at a waste water treatment plant. In regenerative absorption water is recycled by removing the carbon dioxide with air counter flow. Water is then cooled to achieve the large difference in solubility between CO_2 and CH_4. (Petersen and Wellinger 2009, 10.)

One variation to water scrubbing is organic physical scrubbing. Instead of absorbing carbon dioxide in to water, in this variation an organic solvent, such as polyethylene glycol is used. The rate of absorption is higher with polyethylene glycol and it is possible to remove also oxygen, nitrogen and sulphide. Polyethylene glycol solution is regenerated by pressuring and/or heating. (Petersen and Wellinger 2009, 11.)

In PSA carbon dioxide is separated by absorption on zeolites or activated carbon. Zeolites or carbon are used as absorption materials to capture carbon dioxide. Hydrogen sulphide poisons the absorption material and therefore it has to be removed before PSA -process (Jönsson, 2003). In this method the column is reloaded by pressure drop or "swing". During the pressure drops a slight volume of biogas is also absorbed, but it can be returned. (Petersen and Wellinger 2009, 9.) Different biogas upgrading methods are compared in **Table 4**

Table 4: Comparison of biogas upgrading methods (Petersen and Wellinger 2009, 14)

	PSA	**Water scrubbing**	**Organic physical scrubbing**	**Chemical scrubbing**
Pre-cleaning needed	Yes	No	No	Yes
Operating pressure [bar]	4 -7	4 -7	4 -7	No pressure
Methane loss	< 3-10%	< 2%	2-4%	<0,1%
Methane content in upgraded biogas	>96%	>97%	>96%	>99%
Electricity consumption [kWh/Nm^3]	0,25	<0,25	0,24 -0,33	<0,15
Heating requirement [°C]	No	No	55 -80	160

4.4 Global demand of wastewater treatment

As mentioned before, wastewater treatment requires large investments during next decades both in western and developing countries. In the EU and in USA the investments are needed for repairs, maintenance and replacements, in Southern America and in Asia the investments are to expand and build the treatment systems.

In Europe the largest biological WWTP markets are currently in France, followed by UK and Germany. The market is in moderate growth, market size was 1,5 billion dollars in 2008 and expectations for year 2015 are 2,2 billion dollars. In EU the investments are concentrated in upgrading and maintaining the existing WWTPs, but in the more developed market counties, such as in Germany, the aim is also to develop more advanced and efficient treatment systems. The key drivers for European WWTP markets are the implementation of the UWWTD (Urban Wastewater Treatment Directive) and IPPC (Industrial Pollution Prevention and Control Directive) directives. (Frost & Sullivan 2009, 12-17.)

4.4.1 Finland

In Finland, over 80% of population lives at centralized sewer and water treatment district. The level of treatment is quite high: on average, 97% of organic particles, 96% of phosphorus and 56% of nitrogen is treated from waste water. Finland has quite strict regulations for water treatment and as a result of this even the tap water is drinkable. There are over 540 water treatment plants in Finland that treat more than 50 households waste. (Vesilaitosyhdistys, 2015.) The production of biogas in Finland began in 1962, when the first digestion plants were built at water treatment plants in Mikkeli and Tampere (Kiviluoma- Leskelä 2010, 22).

As an example of recent investments the Helsinki's regional environmental services (HSY) have announced to build a new water treatment plant at Blominmäki in Espoo. New WWTP will be partly underground and it replaces old Suomenoja plant. The population of Helsinki region is growing and Suomenoja plants is insufficient to treat growing water consumption. It is estimated that plant will treat 150 000 m^3 of waste water per day. (HSY, 2015.) Blominmäki WWTP will be having a digestion reactor. The produced biogas is used for heating and/or electricity production. (Espoon Vesi, 2008.)

4.4.2 China

Nearly one fourth of the world's population lives on eastern and southern Asia. However, the region contains only a fraction of fresh water needed. Because of the rapid development in food producing, the demand for clean water is increasing. China has had difficulties with its fresh water resources over three decades. Approximately 300 of Chinas megacities have insufficient water resources and over 100 cities are confronting a severe lack of water in the near future. Nearly 40% of Chinas most important rivers water has polluted so badly that the water cannot be used in any way (Turkki, 2013).

In 2012 China invested 14 billion yuan (2,1 billion €) in wastewater treatment and the total investment in wastewater treatment and recycling is expected to rise to 430 billion yuan (64,2 billion €) during the five-year plan. In February 2014 Chinas Ministry of Environmental Protection announced that China will spend 2 trillion yuan (298, 5 billion €) to prevent water pollution. (Hu et al. 2014.)

China has started several large investments to secure its fresh water resources. The most famous is the massive Three Gorges Dam at the Yangtze River in Yiling District. The production of clean water and water treatment has become a great business: Beijing alone is investing 269 billion euros to renew its water infrastructure (Turkki, 2013). Several foreign companies are bringing or offering their modern applications to Chinas markets. For example Finnish Envor Protech Oy delivered a biogas production plant to Kunming, 19th largest city in China. The plant treats sludge from regions eight largest and newest wastewater treatment plant. Plants capacity is 182 500 tons of dried sludge that is two times the sludge produces at Helsinki region (Talouselämä, 2015). Another good example of the size of Chinas WWTPs is for example the Xiaohongmen WWTP in Beijing, started in 2007 and capacity 600 000 m3 per day. Plant has 6 digesters and it uses the biogas to heat and power production (WABAG, 2009).

In the biogas sector, China has rapidly expanded its production: biogas production started in the 1970’s when development of household biogas digesters began, in 2009 there were 322 large-scale biogas plants and over 50 000 medium and small plants (Jiang et al., 2011).

4.4.3 Germany

Germany has rich fresh water sources. In 2010 approximately 33,1 billion m^3 of water was used in Germany. There are nearly 10 000 wastewater treatment plants and annual volume of treated wastewater is 10,1 billion m^3. The treatment efficiency in Germany WWTPs is also rather good: in 2005 the reduction in nutrient loads was 90 % for phosphorous and

81% for nitrogen. The EU Urban Waste Water Treatment Directive demands a 75% reduction. There are large WWTPs in Germany, such as the Hamburg plant and these large plants also consume a lot of electricity. The overall annual electricity consumption of WWTPs in Germany is around 3200 GWh that is roughly equivalent to the modern coal power-plants annual production. (Umwalt Bundesamt 2014)

The German biological wastewater treatment systems market is estimated to be 300 million euros in 2015. The UWWTD-directive has largely effected to the German markets at least in industrial sector. Germany is also replacing its older wastewater technology with advanced membrane technology. (Frost & Sullivan 2009, 35)

4.5 Costs of wastewater treatment plant

The costs in waste water treatment come from the investment costs and operating costs. WWTPs are large facilities with large machines raise the investment costs. The technology itself is quite old-fashioned and well tested. However the investment costs can be several hundreds of millions depending on the size of the plant. The operating costs consist of waste, chemical, electricity and personnel costs.

4.5.1 CAPEX of wastewater treatment plant

The capital costs of wastewater treatment plant are quite large and they vary depending on the plant size and selected treatment stages. Buildings and water facilities are often quite large and made of concrete and they require large areas. Therefore building costs consist of traditional costs such as excavation of building foundations, compaction of the soil and concrete consumption and building itself. During the designing stage, a WWTP usually needs an environmental permission to operate. Environmental laws are country specific and therefore costs from operation vary.

Plant often requires large facilities and machines. Although the treatment phases itself are traditionally quite simple and doesn’t need so sophisticated appliance, they still require large equipment, like motors and pumps, and tanks for large water masses. Of course wastewater treatment also requires normal industrial I/O-appliances. The estimated costs for WTTP construction is 1,5 €/m^3 for plant treating 1,4 million m^3 of waste per year. (CCWPC.org 2010.) The overall investment costs are then approximately 2,1 million €. Equipment and installation costs can be more evaluated with following definitions (Haandel and Lubbe 2007, 458): civil construction 23-29%, mechanical construction 21 to 27%, equipment and installation 10 to 16%, piping 2 to 5%, instrumentation and controls 2 to 5% of all investment costs. In addition for these costs, the start-up of the plant requires following costs: lab equipment and etc., first fills of chemicals, filter materials and hiring and training employees. These all together are quite a small cost, 1 to 3% of all investment costs. There are always additional costs such as design and engineering, project and construction management and miscellaneous costs which can be quite high costs: all together 10 to 20% of total investment. (Haandel and Lubbe 2007, 459.)

Anaerobic digestion at WWTP requires its special treatment facilities. A digester is commonly a simple large tank with few appliances to mix sludge and collect biogas. In addition of the digester itself, the produced raw biogas needs appliances for its enhancement for transportation use. These are little more complex and more expensive. If WWTP produces biogas and uses it itself, there often are a separate gas engine and a boiler. The prize of anaerobic digester depends on its size, for average (Haandel and Lubbe 2007, 459) the prize varies 300 to 700 \$/m^3, based on prize level in 2006.

4.5.2 OPEX of wastewater treatment plant

The operational cost of wastewater treatment consists of electricity cost, personnel costs, maintenance costs, sludge disposal costs and other material costs such as chemical costs. Wastewater treatment processes consume heat and electricity. Heat is mainly used in digestion phase and to heat the buildings. The most expensive process is the aeration where large pumps are used to mix the air or oxygen to water. For example in Hamburg WWTP in Germany there are four 1000 kW blowers in the bubble aeration system (Laurich 2014).

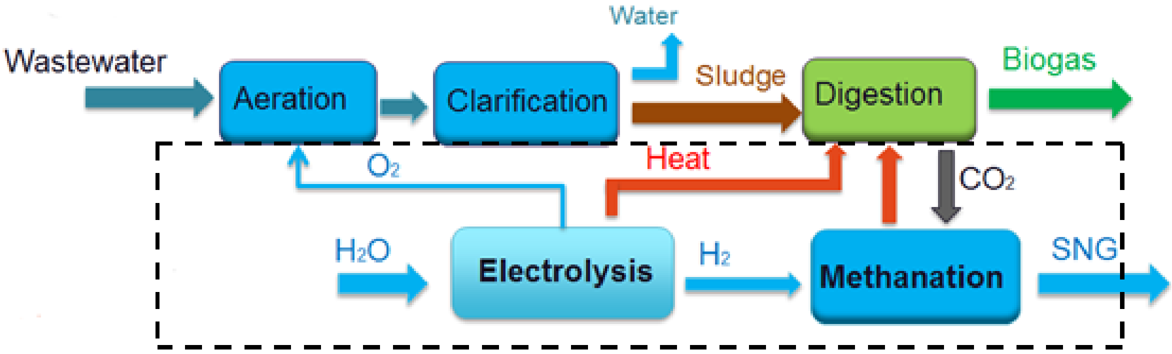
Also in Germany WWTPs are the largest single municipal energy consumers (Husmann 2009, 4).. Some plants also produce oxygen from the air that increases the costs.

Costs from energy are 14 to 21% of the total costs, depending of the plant size (Hernandez-Sancho, Sala-Garrido 2008, 221). Treatment processes also consume different chemicals, like ozone or sodium carbonate. Chemical costs depend on the selected treatment methods and selected chemicals. Different wastewater treatment methods consume different volumes and types of chemicals.

Of course all the maintenance works and normal operator work cause operational costs. These personnel costs are a considerably large cost, depending of course the number of the personnel (=plant size) and maintenance need. Personnel costs range from 40 to 55% being the largest costs in water treatment. The share of the maintenance costs is 8 to 12%. (Hernandez-Sancho, Sala-Garrido 2008, 221.) The estimated O&M costs for plant treating 1,4 million m^3 of wastewater per year are 0,2 €/m^3 (280 000 € per year) (CCWPC.org 2010). The personnel costs depend of course on country the plant is located. For example in Finland the salaries and other personnel costs are little higher than in China. Wastewater treatment also produces sludge. Waste costs vary from 3 to 18%, this share is larger with larger plants. There are also other costs that are between 9 and 17%. (Hernandez-Sancho, Sala-Garrido 2008, 221.)

5 INTEGRATION POSSIBILITIES OF POWER-TO-GAS TECHNOLOGIES TO WASTEWATER TREATMENT

Power-to-Gas technology provides many products and by-products that are beneficial to other industrial or municipal applications. Power-to-Gas technology is possible to integrate to industrial or municipal wastewater treatment plant. In the Picture 16 is shown the mass streams between WWTP and Power-to-Gas and the area that is now studied. Now the economics are studied from Power-to-Gas point of view and wastewater treatment economics are left outside of the examination. Wastewater treatment plant can utilise oxygen, ozone, heat and methanol produced in Power-to-Gas processes. Wastewater treatment often needs ozone that can be produced from the oxygen with electricity. Heat flow from methanation and electrolysis can be utilised in digestion phase to warm the sludge. WWTPs also use methanol that can be produced from the hydrogen and carbon dioxide in Power-to-Gas. Also the carbon hydroxide formed in the digestion phase can be used in methanation or in methanol production. The integration of these technologies also sets certain demands for the produced by-products and technologies.



Picture 16: Overview of the integration, the area limited by dashed line is studied now in economic calculations

This kind of integration of Power-to-Gas to WWTP is planned to build in Avedore, Copenhagen. Avedore wastewater treatment plant is an average sized municipal plant that treats 25-30 million m^3 of wastewater annually (Spildevandscenter Avedore 2013). There a 1 MW alkaline electrolyser will be used. The integration will be same as in this study: Hydrogen is produced in electrolysis and with raw biogas or carbon dioxide the hydrogen is refined to methane. Methane is fed to gas grid. Oxygen from Power-to-Gas is used at WWTP in active sludge processes and the heat is used for heating and sludge pre-heating. There will be also frequency control regulation services by Power-to-Gas. The current project budget is 6,7 million euros and project is scheduled to be finished on December 2015. Project receives funding support of 55%. The Biocat project will be a demonstration plant where the integration can be studied in practise. (BiocatProject 2014.) The Biocat will bring important data from practical aspects of integrating Power-to-Gas to WWTP and can act as a reference plant for future integrations.

The integration must be economically profitable too, so Power-to-Gas must not be an extra cost to wastewater treatment. Investment costs from Power-to-Gas technology are needed to be covered with by-products, SNG production or WWTP's increased biogas production during a reasonable long time period. This requires that the by-products and the transportation fuels (SNG and biogas) must be produced as with low costs as possible.

The potential WWTPs for this integration are needed to be specific type. Wastewater treatment can use either air, pure oxygen or advanced oxygen processes in aeration. Now it is focused only on plants that use pure oxygen. Oxygen is a valuable by-product from Power-to-Gas and it is needed to be efficiently utilised. Power-to-Gas can be integrated to plants using also air and advanced processes. The use of pure oxygen has been adapted from 70's and currently there are several hundreds of WWTPs using pure oxygen. Key potentials of this integration as mentioned before in this thesis are listed below:

- Already hundreds of WWTPs using pure oxygen in aeration
- Incoming investments to WWTPs, 300 billion € in China alone
- Increase of use natural gas/biogas/SNG in transportation, the number NGVs is expected to rise in 30 million in near future

5.1 Benefits, technology demand

Power-to-Gas technology can provide several benefits to wastewater treatment. Wastewater treatment requires heat and electricity to its various processes. Heat is used primarily to warm sludge in digestion that digestion bacteria would have the best operating conditions. In addition, various types of chemicals are used, such as ozone and methanol. Some of these chemicals are more complex and must be brought from specific factory, but the other, like ozone, can or must be produced on the site. By integrating Power-to-Gas to wastewater treatment, the by-products from both technologies can be utilized and demand for bringing, for example energy decreases. The oxygen and methanol produced can reduce the demand of those substances in wastewater treatment process. Ozone can be produced from the oxygen gas and it can be used in wastewater treatment processes or the oxygen can be used directly in aeration. The hot water from methanation and electrolyse can be led to the digestion phase and it can be used to warm the sludge, which decreases the heat demand. Extra heat can also be used in other water treatment phases as well.

Also by-products from wastewater treatment can be utilized in Power-to-Gas. Carbon dioxide that is formed during the digestion can be used in methanation and in methanol production. This will decrease the demand for bringing carbon dioxide outside of the system. When this CO_2 is utilized the digestion phase receives energy from Power-to-Gas and brings carbon dioxide to it. This leads to a situation where either the methanation is designed by the CO_2 feed from the digestion or the digestion is designed by the heat feed from the Power-to-Gas. Then it has to be evaluated that which one of processes is more important for whole integration.

The size of the Power-to-Gas plant has to be optimized that the by-products from both technologies can be efficiently utilised. For example, hydrogen production from electrolysis determines the methane production and therefore large share of the annual incomes. Larger gas production leads also to larger CO_2 demand.

5.1.1 Ozone synthesis

Traditionally chlorination has been a widely used method to water treatment. This method can, however produce toxic by-products and that is why better solutions have been examined. Ozone is one of the AOPs that are studied to improve wastewater treatment. Ozone has been regarded as one of the best options for chlorine. Ozone has strong oxidizing capability and fast decomposition rate. (Chang and Wu 2008, 241.)

The basics of ozone production has been known for over a century and today there are many hundreds of WWTPs using ozone and the ozone production is growing. Ozone production is, however expensive. (Chalmers et al. 1995, 1249.)

There are several ways to produce ozone, such as UV photolysis, electrolysis, plasma excitation but the most used method for ozone production is dielectric barrier discharge reactor (DBD) (Chang and Wu 2008, 241.). In DBD method a dielectric material is placed between the discharge gap and one of the discharge electrodes. Alternating current (AC) is feed to system and it generates gas discharges. When the potential across the gap reaches the breakdown voltage, a large number of microdischarges is formed and spread over discharge gap. There an electric field dissolves oxygen molecules (O_2) into oxygen-ions (O). A single oxygen-ion detaches into intact oxygen molecule and forms an ozone molecule (O_3). (Chang and Wu 2008, 241-242.)

Large electric field strength in dielectric barrier discharges requires large amounts of energy, up to 10eV. This amount of energy can however also produce electronic excitation, ionization and gas radicals. The major factors of ozone production are frequency and voltage level, configuration of the reactor, gas flowing velocity and composition of the gas stream. Gas flowing rate indicates that how long the gas stream stays in the reactor. High voltage and slower gas flow rate improve ozone production, but also increase the energy demand. (Chang and Wu 2008, 247-253.)

In water treatment ozone is transferred into treated water with different devices such as stirred-tank reactor with diffuser. The most popular is the counter-current sparged column. In water treatment ozone is used as a disinfectant and as an oxidant. Ozone is an unstable gas and the distance between the ozone generation and its end-use has to be quite short. It is even so unstable that in large treatment systems it dissolves before treating the water. Another disadvantage is that ozone reacts with natural organic substances and produces by-products that are biodegradable. These substances cause biological growth and limit the treatment efficiency of the ozone. (Glaze 1987, 224-227.)

As an oxidant ozone oxidizes many harmful toxicants, such as manganese and phenolic materials. Ozone also improves the filtration of raw water and therefore replaces the demand for other chemicals. (Glaze 1987, 226.)

5.1.2 Oxygen in aeration

The produced oxygen can also be used directly in aeration at WWTP. Aeration is a part of the activated sludge process that is widely used in wastewater treatment. Oxygen from electrolysis can replace the oxygen or air used in aeration. If WWTP has previously used only air, the oxygen feed can improve its treatment efficiency. The air and oxygen demand in aeration is quite large: a plant treating sewage waste from 60 000 persons can use air roughly 130 kg per hour (Water & Wastewater Engineering 2015).

5.1.3 Methanol production

Methanol can be produced from different carbon-hydrogen materials, such as natural gas, coal or wood. The most economical method is the production from natural gas. Biogas can also be used, but typically it is required to add hydrogen to biogas before it is suitable. Methanol can also be produced from other carbon-based gases too, like from carbon hydroxide. The hydrogenation of carbon hydroxide to methanol is: (Jessop et al. 1995, 264.)

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \tag{3}$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{4}$$

$$CO + 2H_2 \rightarrow CH_3OH \tag{5}$$

,where

CH_3OH= methanol [-]

The reaction itself is done in 50-100 bar pressure and in 220- 300 °C temperature. Carbon hydroxide is quite a stable molecule, so its reactions require different catalysts, like zinc oxide or copper oxide. (Tuuttila 2010, 13.) In addition of methanol, the hydrogenation of carbon dioxide also produces carbon monoxide and water. These by-products act as inhibitors during the reaction and decrease methanol production rate. Water and CO are formed with reactions 3 and 4 and via the reverse reaction 4 water reacts with CO and produce CO_2 and H_2. This can be avoided by feeding also CO to the reaction. The extra carbon monoxide forms methanol with hydrogen and only a small volume of water is formed and therefore the overall process is not disturbed. (Saito et al. 1995, 313-314.)

5.1.4 Frequency control

Maintaining the specific frequency is vital for electricity grids. The frequency can be interrupted by sudden changes in loads or in production. These can cause problems for grid and the frequency must be controlled. Frequency can be controlled with emergency resources that are power plants or energy storages. These power sources must be fast to start and large enough (Pahkala 2006, 20.). Power-to-Gas- technology can be used as a frequency control reserve with its energy storages. However then part of the power of the plant is reserved for frequency control and cannot be used for gas production.

The frequency control is nowadays business that can bring considerable returns. Different power producers can offer to buy or sell electricity to balance aberrances in the frequency. Frequency control markets vary in different countries and there might be shared grids between nations, like in Scandinavia. (Pahkala 2006, 39-40.)

In the joint Nordic system that includes Finland, Sweden, Norway and East Denmark countries have frequency maintaining reserves for joint use. The Frequency Containment Reserve for Normal operation (FCR-N) includes 600 MW of reserve for frequency regulation. There is also reserve for disturbances (FCR-D) that includes a reserve of 1200 MW in normal state (Fingrid 2015). FCR-N is now used in calculations in this thesis.

5.1.5 Integration types

The integration of Power-to-Gas and wastewater treatment means that they have to be connected with pipes or via gas storages. So, in theory these two technologies can be on the same site, in WWTP site, or the distance between them is long and the by-products are changed with trucks and storages. Both of these integration types have their advantages and disadvantages that are studied.

5.1.6 Integration on-site

When the Power-to-Gas is brought to WWTP-site, they can be linked with pipes and the transport distances are short. If the electrolysis and methanation appliances are small enough they might even fit to same premises with wastewater treatment installations. This would lower the investment costs when there is no need to build extra buildings. However, gas technology often requires large tanks and pipes, so the Power-to-Gas appliances would probably need own buildings. The installations of electrolysis, methanation and ozone synthesis are quite compact when compared to WWTP installations, so the needed extra buildings would be thus relatively small. In addition, WWTPs are often located on remote areas with little distance to urban locations, so the additional costs of the new buildings for Power-to-gas would be relatively low. The location of the ozone synthesis is critical, because ozone is very unstable and its production must be near to the wastewater treatment, or like it is in practise in the treatment processes.

In addition of the appliances itself, the Power-to-Gas integration requires pipes and tanks for the gas and the steam. WWTPs produce biogas by digestion and it has to be upgraded before use in transportation. This biogas is different than the synthetic methane produced in Power-to-Gas, so both gases require own pipelines and appliances, but at least the final storage tank can be shared. Use of the hydrogen requires its own special pipelines and tanks. The boiling point for hydrogen is very low, -253 °C, so its liquefaction requires cryotechnology and high pressures.

The possible methanol production would require its own special facility and pipelines. Methanol production can replace methanation or these technologies can be both utilized.

When wastewater treatment and Power-to-Gas are on the same site, the same personnel can operate both facilities and also take care about the maintenance. This will reduce personnel and maintenance costs, although the WWTP personnel must be first trained to use and maintain Power-to-Gas technology. Also when Power-to-Gas is brought to WWTP, the utilisation rate of the WWTP must not also be interrupted from the Power-to-Gas. The feed of fresh water from the plant is the most important factor and integration must not decrease the wastewater treatment reliability.

5.1.7 Integration with long distances

The integration may also be done with long distance between WWTP and Power-to-Gas. This enables to utilize benefits from WWTPs, where it's impossible to build Power-to-Gas. Also a one Power-to-Gas unit could change by-products with several WWTPs that are too small to operate with Power-to-Gas alone. Especially in Finland many municipal wastewater treatment plants are often quite small, but linking multiple units together, the integration could be profitable.

Longer distances would mean of course long transportation of heat, oxygen and carbon dioxide. If the distance is for example hundreds of kilometres, gases would be needed to transport with trucks or even with ships and extra storages are also needed. Long pipelines would simply be too expensive. Ozone production must still be done in WWTP, so oxygen should be transported, as the carbon dioxide from digestion. Storing and transporting these gases would cause some loses and of course extra costs. In addition, both installations would require backup storages, if there are problems and delays in the transportation. The installations itself would be quite similar than with integration with smaller distance, thus more storage space and facilities for transportation, e.g. loading and unloading are needed. The advantages and disadvantages from both integration methods are listed in Table 5.

Table 5: Comparison of integration on site and with long distances

	Integration on site	**Integration with long distances**
Advantages	-Short transportation distances -Shared personnel	-Possible to utilise several WWTPs -Possible to utilise also smaller WWTPs
Disadvantages	-Utilises only one WWTP	-Extra transportation costs -Extra storages -Requires extra personnel

5.2 Utilisation of by-products

The by-products from the Power-to-Gas and wastewater treatment must be properly utilised to achieve proper benefits from the integration. The utilisation of by-products is the main idea of the integration and it must be functional. By-products, carbon hydroxide, heat, ozone/oxygen and methanol must be suitable for utilisation and the utilisation rate must be as high as possible.

The use of the by-products sets demands of their purity and specifications. Normally, when some of these by-products aren't utilised and simply dumped there is no need to control their values. Now, for example the carbon dioxide must be pure enough to be suitable in the methanation or in the methanol production. Extra pollutants in the by-products may cause e.g. equipment brake-downs, corrosion or poor performance. The values of the by-products must be now measured and controlled, which may require extra measuring devices and treatment appliances. This causes of course extra investment and personnel costs.

In addition of the purity of the by-products, the production rate of them must be controlled. If, for example the carbon dioxide feed from the digester suddenly stops, the methanation or the methanol production is interrupted and may be stopped too. This kind of events can be however avoided with storages and back-up systems, but the primary target is to the design the processes to work well together.

In the integration there are economic factors as well. The price and value of the by-products can affect to the utilisation rate. If, for example the electricity price rises significantly, it increases the costs of electrolysis and the whole Power-to-Gas phase. This will also raise the price of the ozone, heat and methane that can become too expensive to be economically utilised.

5.2.1 Utilisation of oxygen

Whereas WTTPs can use air, pure oxygen or oxygen radicals, the Power-to-Gas is can only be integrated to plant that uses pure oxygen. The oxygen is valuable for Power-to-Gas and it is needed to be utilised efficiently. If WWTP uses only air or oxygen radicals it doesn’t need the pure oxygen. However the plants using only air can be upgraded to use pure oxygen. This is mainly for plants using air feed. The oxygen is roughly four times more efficient in aeration than the air. The oxygen feed can upgrade the treatment efficiency and it requires less space. In Korean chemical plant the oxygen improved the aeration by 10% and it required 40% less the aeration system (Gurney, Gases 2013).

The saves from the space is not important in low-populated countries like Finland, but in Germany and China the wastewater treatment plants can be built in dense populated cities where the land can very valuable. For example in Beijing the average land price was 63 380 yuan, 9 460 €/m^2 in 2014 (Reuters 2014). If it estimated that oxygen requires 40% less space and there are now 6 circular aeration tanks (r= 10m) the savings from land area would be:

$$Savings = 0{,}4 \cdot 6 \cdot (\pi \cdot (10m)^2) \cdot 9460\ \frac{€}{m^2} = 7\ 164\ 000€$$

5.2.2 Utilisation of heat

The heat produced in electrolysis and in methanation process, can be utilised in digestion to warm the incoming sludge. Digestion requires heating to anaerobic reactions and this heat demand can be decreased or perhaps covered with the heat from methanation and electrolysis. Methanation produces hot steam and electrolysis hot water that can be mixed and led via pipes to the digester.

The temperatures in the digestion are fairly low, from 30°C to 55°C, depending on the process type, and therefore the key factor for the heat demand is the level of the mass flow of the sludge. The faster the sludge is warmed and digested the faster the biogas is formed. Of course there are other factors that influence to biogas production too, but the heat feed is one of the main factors.

5.2.3 Utilisation of methanol

In wastewater treatment methanol is used in denitrification, in other words to remove nitrogen from the wastewater. Denitrification bacteria work in anaerobic conditions and require an outer carbon source. Carbon from the wastewater itself can be used, but it is often really difficult, because all the soluble organic content is removed before denitrification and therefore an outer treatment chemical is used. (Kinnunen 2013, 19.)

Methanol consumption causes some costs for WWTP, for example in Suomenoja WWTP the annual methanol consumption is 1900 tons annually (Kangas 2004, 11). With 300 €/t methanol price the costs are 570 000 €. The methanol is cheaper in Europe but in China little more expensive, 400-420 €/ton (OrbiChem 2013).

In Denmark it was studied methanol production from biogas with SOEC electrolyser. In these studies it was discovered that a methanol plant with production of 38 tons per day the price for methanol was with SOEC 388-420 €/ton. It was also examined the production costs without SOEC and then the costs were 310-400 €/ton. (Pedersen and Schultz 2012, 69-71, 91.) These prices are a higher than market prices Europe. In China the average methanol price is nearly the same as these prices as highest.

5.2.4 Utilisation of carbon dioxide and biogas

Carbon dioxide is formed during the digestion phase and this by-product can be utilised in Power-to-Gas, during the methanation or in methanol production. Carbon dioxide is formed in digestion that produces raw biogas. Carbon dioxide can be left in biogas if biogas is simply burned at the plant. If biogas is used for transportation the carbon dioxide must be separated. Carbon dioxide is removed via, for example water scrubbing or PSA. Raw biogas can be also used directly in the methanation. Then the carbon is used for methanation and the biogas is upgraded to SNG. When using the raw biogas the sulphur must be removed.

Pressurised CO_2 is led to the methanation or the methanol process. In both processes CO_2 reacts with hydrogen produced in electrolysis. The amount of produced CO_2 depends on speed of the digestion process.

The price of the carbon dioxide in this integration is determined by the method used. The default case is that without the Power-to-Gas technology WWTP doesn’t separate the CO_2 and uses the raw biogas for electricity production and heating. In Power-to-Gas integration there are now two cases: 1) CO_2 is separated and led to Power-to-Gas and biogas is used at WWTP to heat and electricity production and 2) all the raw biogas is used in Power-to-Gas and WWTP covers the biogas production with natural gas.

The costs from CO2 separation from biogas depends on the method used. PSA costs 0,40 € per m^3 of raw biogas, chemical scrubbing 0,17 € per m^3 of raw biogas and water scrubbing 0,13 € per m^3 of raw biogas (VALORGAS 2011, 14-17)

6 ECONOMICS OF PRODUCING SYNTHETIC NATURAL GAS AT WATER TREATMENT PLANTS

In this chapter the economics of the integration are studied. The main factors of costs, such as investments and returns, like SNG sales are studied. The economics of producing transportation fuel at WWTP depends mainly on, like other industrial productions, the price of the final product in the market, raw material and production costs. Now in this integration two technologies have been considered together. Wastewater treatment is a compulsory process that causes costs for municipalities and it is now examined how Power-to-Gas technology can lower these costs with synthetic gas production. Therefore the investment and operational costs from Power-to-Gas must be low enough to achieve proper net profit with decent repayment period. Power-to-Gas shall not be therefore cause an extra cost for wastewater treatment. The utilisation of the by-products from both of the technologies lowers the payback time, which was one of the motivators of the study.

Annual- and investment costs and also annual incomes depend on the size of the plant. The larger and more expensive is the plant, the larger is the annual gas production and incomes. The size of the Power-to-Gas processes has to be optimised that they are feasible in practise and economically profitable, like for example the raw material consumption must be realistic.

Power-to-Gas has also other than economic values. Power-to-Gas can improve the energy self-sufficiency with SNG production. Power-to-Gas helps the deployment of renewable energy technology by improving the utilisation rate of them. One major limiting factor for example for solar power and wind power is the irregular electricity production of them. By creating a system for energy storage the produced electricity from renewable energy can be stored and therefore be better utilised when needed. This allows to build more renewable energy and to reduce non-renewable CO_2-emissions.

Currently approximately 21,6% (18 TWh) electricity used in Finland is brought from abroad (Energiateollisuus 2015). European Union’s one major targets in energy sector is to decrease its dependence of Russians energy and Finland is part of the EU. The European

Commission in May 2014 put forward an EU Energy Security Strategy, which main objective is find ways to increase EU’s energy security. (European Commission 2014, 15.) By adding the energy self-sufficiency it is possible to ensure the basic functions of society during a crisis.

6.1 Cost factors of gas production

The main cost factors of producing synthetic gas in waste water treatment plants are investment costs and the production costs and hours. Power-to-Gas-technology requires quite high investments that raise the annual fixed costs. The production costs (electricity+ raw material) and annual hours affect to the annual variable costs. Electrolysis and methanation require considerable amount electricity and variations of electricity price affects the production costs. Electricity prices vary considerably during days, week and months. Power-to-Gas technology consumes a lot of electricity and the electricity price determines whether the process is profitable to operate. This leads to situations where Power-to-Gas is very profitable with low electricity prices or unprofitable with high electricity prices. This variation between different electricity prices causes that Power-to-Gas is economical to be operated during specific periods. The lower operating hours also decrease the annual SNG production that will decreases the returns.

The investment cost of Power-to-Gas is quite high that raises the annual fixed costs. The high number of equipment brake-downs and need for maintenance lowers the gas production and also increases maintenance costs in industry. Power-to-Gas technology is highly complex and brake-downs of its appliances require special expertise and parts that may not be very cheap. In addition of expensive electrolyse and methanation appliances, gases like hydrogen and methane require several secondary systems, storages and pipes that increases the investment costs. The storing of gases, such as methane and hydrogen require large amount of electricity first to liquefaction and storing itself. Therefore the operating style of the Power-to-Gas plant affects to the electricity consumption and gas production costs.

The price of raw materials, water and CO_2, affects to the production costs. However, the default price for water is fairly low, 1 €/ton, and its share of the overall costs is lower. Carbon dioxide is more expensive, 40 €/ton, but it can be collected from the integration, in this case from the digestion, that reduces the need for buying carbon dioxide. (NeoCarbon 2015.) The effects of cost factors are later studied in Discussion (Chapter 8).

6.1.1 Delivery of SNG and biogas

Biogas and SNG can be delivered with natural gas grid or by trucks to refuelling stations. The best option depends on the distance. The cheapest option is a steel container for distances less than 35 -40 km, for longer distances, more economical option is a carbon fibre container. Gas pipe is expensive and is more profitable than truck transport only at short distances or with high volumes. (Rasi et al. 2012, 29.)

Pipe investment depends on the terrain and the length of the pipe. In cities and in urban areas gas pipe is more expensive to build than in sparsely build areas. Total investment cost for short distances, less than 10km, are between 500 €/m and 600 €/m and for longer distances between 350 €/m and 450 €/m. (Rasi et al. 2012, 29.) The Finnish natural gas grid is concentrated mainly in South-Finland. Also the gas refuelling stations can therefore be built on the grid. There are currently no visions of expanding the existing gas grid.

Gaseous fuels are stored in gasholder at the production site. Gasholder is a hemisphere, sometimes rounded by metal frame, sized typically approx. 100- 1000m^3. (Motiva, jätevesilietteen anaerobinen käsittely ja biokaasun hyötykäyttö, 10-12.)

6.2 Income and profit expectations

Incomes of producing synthetic natural gas at WWTP are highly dependent from the gas prices on the market when assumed that sale prices are comparative to these market prices. Gas prices vary between different countries, because of different taxation and production costs. The incomes from SNG are highest when it is sold for transportation and therefore it is now considered that all the SNG is sold for transportation use. Renewable transportation fuels receive supports, for example from EU and transportation fuels are in common more expensive than fuels used in basic energy production. Then now the SNG price is a lot higher than the average industrial natural gas price. The price can be based on the Finnish price model, where the transportation biogas is more expensive (5 - 10%) than the natural gas sold at petrol stations (Gasum 2014).

The oxygen and heat incomes can be little smaller than SNG sales, but they bring extra returns to the integration that are now evaluated. The heat price is calculated from the natural gas price. It is estimated that WWTPs uses primary its biogas to heat production. This biogas covers 10% of the heat demand in WWTP; the rest is produced with natural gas. Integration receives returns also from FCR-N services that can be considerable factor in the profitability. FCR-N use provides steady incomes, but it also reduces annual gas production when part of the power of the plant is reserved for frequency regulation.

The profit expectations are highest when the production costs are as low as possible and the price of the product as high as possible. In Power-to-Gas the largest costs are the investment and electricity costs. However, for the product itself, methane, there are steady markets and the demand for new, renewable energy source is only increasing.

Because of the high investment costs and electricity consumption, the profit expectations of Power-to-Gas are relatively average. The incomes from methane production alone can be inefficient compared to annual costs of the project. However this integration has various valuable by-products (oxygen, heat, FCR-N) that can bring considerable returns.

High costs during the first years can cause large amount of negative cash flow that can be later difficult to fulfil with the returns. Therefore it is essential to study the most important cost factors and find the methods to decrease these costs.

7 BUSINESS OPPORTUNITIES

Now it is examined how economical the integration of Power-to-Gas technologies to wastewater treatment plant would be. The economics of the Power-to-Gas is calculated by examining the repayment period with the Net Present Value method (NPV). In the Net Value Method the annual returns are discounted to net value to present time. The NPV method is the most widely used in investment calculations and it allows comparing annual costs and returns. The investment and operational costs are estimated with the best available data. In calculations, the annual returns are calculated via annual sales and prices. The annual profits are calculated by discounting the fixed annual costs, variable costs and annual investments from the returns.

The integration can be implemented by several ways, for example the by-products from Power-to-Gas can be utilised with different methods and therefore different business cases are examined. The most profitable case foreseen is then selected. An important factor is the price of the oxygen produced in Power-to-Gas. Aeration is the most expensive process in WWTP and it requires a lot of electricity for oxygen production or air supply. When some of this aeration costs can be covered with oxygen feed from integration and therefore it brings extra value for Power-to-Gas economy. The heat from Power-to-Gas is now used to replace heating in digestion process. Integration also provides FCR-N services.

In the calculations WWTP and Power-to-Gas are separated and examined individually that the impact of the Power-to-Gas integration is better exposed. The investment costs of WWTP are high and wastewater treatment isn’t a profitable business alone, so the calculations are more focused on Power-to-Gas. In the end the benefits and from Power-to-Gas are combined to WWTPs costs and the profitability of integration is examined.

7.1 Case study approach

The calculations are divided into technical and economical parts. The technical part calculates the amounts of products and raw material and electricity consumption with given inputs. The outputs of technical part (7.1.2) are then used in the economical part (7.1.3). The final outcomes of the calculations are the economic statistics and the paragraphs. The WWTP in which Power-to-Gas is integrated is determined next. The values and figures for this reference plant are based on Finnish WWTP.

7.1.1 Reference WWTP and integrated Power-to-Gas plant

The reference WWTP, in which Power-to-Gas-technology is integrated, is now described. This reference plant is used in Finnish case and little modified for Germany and China cases. The basic structure of the plant (treatment processes) is same in every cases. This helps to compare cases better.

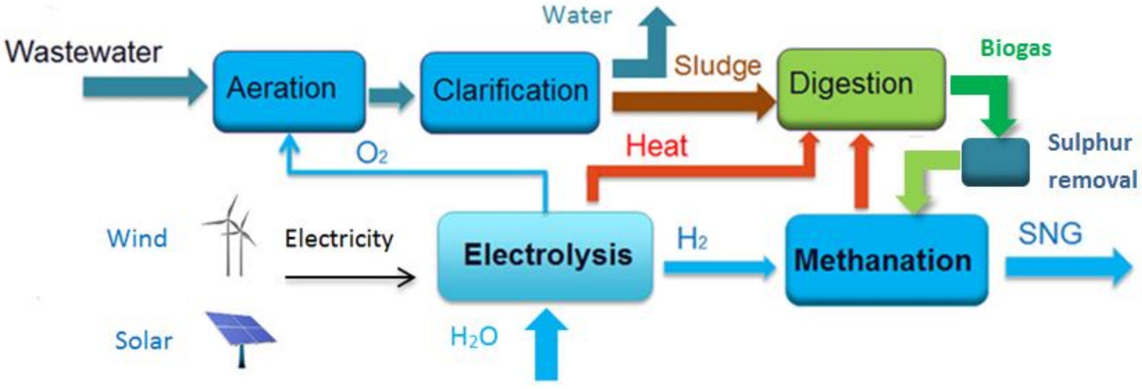
The annual treated wastewater flow is 35 400 000 m^3. Plant uses pure oxygen in aeration process and it has a digester that produces biogas. Heat demand in digestion is 5000 MWh annually. Oxygen need is calculated in every case with wastewater flow. The content of the wastewater flow is now estimated as constant and same in ever cases. This means that wastewater consumes the same amount of oxygen and produces same amount of biogas constantly. In practise different cities can have different wastewater contents and the content can also vary during a day. The main specifications of the wastewater are: influent soluble substrate concentration (bsCOD): 192 BOD g/m^3, Mixed liquor Volatile Suspended Solids (MLVSS): 2500 g/m^3(Lenntech.com).

The reference WWTP produces biogas 425 Nm^3/h. This is annually 3 400 000 Nm^3 of biogas. With this biogas WWTP covers 100% of its heating demand. Methanation in Power-to-Gas needs a carbon source and now it can use the raw biogas or carbon dioxide separated from biogas. If the carbon dioxide is separated from the raw biogas the costs are 0,13- 0,40 €/Nm^3 depending on the separation method. If the cheapest method is used, 0,13 €/Nm^3, water scrubbing, the annual costs is:

$$CO_2 - separation\ costs = 0{,}13\ \frac{€}{Nm^3} \cdot 3\,400\,000\ Nm^3 = 442\,000\ €$$

If WWTP doesn't separate the CO_2 from biogas and biogas is led to Power-to-Gas, WWTP needs to buy extra natural gas to produce heat. However the heat produced in Power-to-Gas can be now used to cover WWTPs heating. When using the raw biogas in methanation the sulphur must be first removed. The required level of sulphur is 1<ppm (Hannula 2015). In methanation the carbon dioxide is used as carbon source and the methane content in biogas remains and comes out from methanation as SNG. Now it is selected the activated carbon desulphurization process Siloxa. The sulphur removal costs are now: investment costs: 70 300 € and operational costs annually 35 500 € (Allegue Hinge 2014, 29). Integration also receives more returns when more SNG is produced.

The costs from sulphur removal are clearly smaller than in CO_2 -removal, so the sulphur removal is now selected. The integrated Power-to-Gas plant is similar (electrolyse + methanation) in all three cases. Plant has alkaline electrolyser that produces hydrogen for methanation. Oxygen is used at WWTP in aeration. SNG, heat and oxygen productions depend on the annual production hours that are different in each case, so the production rates are evaluated later in the calculations. Also the size of the Power-to-Gas plant is now determined by the oxygen demand of the WWTP. The heat produced in Power-to-Gas is now used in WWTP to cover the biogas production. Therefore there are no returns from heat. Now the selected integration method is shown in Picture 17.



Picture 17: The selected Power-to-Gas- integration method

It is also considered that WWTP had own electricity production from the biogas. Now it is considered that this produced electricity is replaced by buying electricity with 60 €/MWh price (transfer fees). The amount of electricity is now considered as 50 % of the heat demand in digester. These costs are added to annual variable costs. The key assumptions for the integration are:

- WWTP previously used oxygen in aeration
- P2G-plant size based on WWTP oxygen requirement
- WWTP previously fulfilled its heat demand with biogas production
- In integration biogas is upgraded to SNG

7.1.2 Technical part

The Power-to-Gas technology is in the calculations divided into its main processes: electrolyses and methanation and ozone synthesis. The electrolyses calculations are simple mass balance calculations with lower heating values and molar masses. The produced power of hydrogen is calculated with electrolysis efficiency and input electricity:

$$P_{H2} = P_{el} \cdot \eta_e \tag{6}$$

, where

P_{el}= electricity power	[W]
P_{H2}= hydrogen power	[W]
η_e= electrolysis efficiency	[%]

For example with 10 MW electrical power and 62% electrolysis efficiency:

$$P_{H2} = 10MW \cdot 0{,}62 = 6{,}2\ MW$$

The mass flow of hydrogen is calculated with the power and lower heating value of hydrogen:

$$q_{m,H2} = \frac{P_{H2}}{LHV_{H2}} \tag{7}$$

, where

LHV= lower heating value	[MJ/kg]
q_{mH2}= mass flow hydrogen	[kg/s]

For example with 6,2 MW hydrogen power the mass flow is:

$$q_{m,H2} = \frac{6{,}2MW}{119{,}56\ MJ/kg} = 0{,}052kg/s$$

The mass flow of oxygen is calculated with molar masses:

$$\frac{q_{m,O2}}{M_{O2}} = \frac{q_{m,H2}}{M_{H2}} \tag{8}$$

, where

M_{O2}= oxygen molar mass [g/mol]

M_{H2}= hydrogen molar mass [g/mol]

q_{mO2}= oxygen mass flow [kg/s]

When the equation is multiplied by M_{O2}, the final equation is:

$$q_{m,O2} = \frac{q_{m,H2} \cdot M_{O2}}{M_{H2}} \tag{9}$$

With 0,052 kg/s hydrogen mass flow the oxygen mass flow is:

$$q_{m,O2} = \frac{0{,}052kg/s \cdot 2 \cdot 16\ g/mol}{2 \cdot 1{,}008\ g/mol} = 0{,}412\ kg/s$$

The mass flow for carbon dioxide is calculated with the equation 9 using now hydrogen mass flow and molar masses of carbon dioxide and hydrogen. The equation is:

$$q_{m,CO2} = \frac{q_{m,H2} \cdot M_{CO2}}{M_{H2}} \tag{10}$$

, where

M_{CO2}= carbon dioxide molar mass [g/mol]

qm_{CO2}= carbon dioxide mass flow [kg/s]

Now the molar mass of hydrogen is multiplied with 8 when every carbon dioxide mole requires 4 moles hydrogen. With 0,052 kg/s of hydrogen mass flow the carbon dioxide demand is:

$$q_{m,CO2} = \frac{0{,}052\ kg/s \cdot 44{,}01\ g/mol}{4 \cdot 2 \cdot 1{,}008\ g/mol} = 0{,}28\ kg/s$$

When the mass flow of hydrogen, carbon dioxide and oxygen are calculated, the produced methane from methanation can be calculated. Methane mass flow is calculated using the same equation as with oxygen (9) with carbon hydroxide mass flow and molar mass:

$$q_{m,CH4} = \frac{q_{m,CO2} \cdot M_{CH4}}{M_{CO2}} \tag{11}$$

, where

M_{CH4}= methane molar mass [g/mol]

M_{CO2}= carbon dioxide molar mass [g/mol]

q_{mCH4}= methane mass flow [kg/s]

With 0, 28 kg/s of carbon dioxide mass flow the methane mass flow is:

$$q_{m,CH4} = \frac{0{,}28 kg/s \cdot 16{,}04 g/mol}{(12{,}01 + 2 \cdot 16{,}00) g/mol} = 0{,}10\ kg/s$$

The utilisation of produced oxygen in electrolysis is an important factor in the integration. The oxygen can be used without further improvements at WWTP in aeration or it can be transferred to ozone. When used in aeration, the oxygen doesn’t require extra appliances and it can replace the oxygen or air used at WWTP. The ozone on other hand needs special appliances to its production. This increases the investment costs and the use of the pure oxygen can be economically better.

7.1.3 Economic part

The output data from technical calculations is used in economic part to evaluate the overall profitability of the integration. The economic calculations are standard investment calculations using Net Present Value method (NPV) where the profitability is evaluated by the profits and repayment period. Annual price developments and interest rates of investments are considered in the calculations and their values are shown in Table 7. The annual price development is now used only for electricity and SNG prices.

The investments of the integration are estimated with existing studies and evaluations. The investments of Power-to-Gas are high, particularly expensive is the electrolyses. The invested capital is divided into land area, equipment, buildings, working capital and to other investments. Land area costs are quite small, when plant is estimated to be built close to WWTP and no large excavation is needed.

Equipment of Power-to-Gas is the largest investment. The technology used in electrolysis and methanation require complex appliances and numerous secondary systems, such as gas storages. Costs from buildings and working capital can be considered as normal for industrial plants, thus the working capital can be little higher because of the complex processes. Other investments include budgeted extra costs that usually appear in large investments.

Variable costs consist of annual raw material, electricity and logistics costs. The variable costs depend on the country selected for integration. The prices of the raw materials, carbon hydrogen and water are quite low and the carbon hydrogen can be received from WWTP. The received carbon from digestion is now considered to be free and if Power-to-Gas requires more carbon dioxide that WWTP produces, the remaining volume is bought outside. The largest share of variable costs is the electricity cost, because Power-to-Gas processes consume a lot of electricity. The electricity price is calculated from the Spot-prices acquired from separate calculation made for Power-to-Gas project. The overall electricity price consists of Spot-price, taxes and transfer price. Taxes and transfer prices are estimated for every country using different sources. In reality the electricity price varies hourly, but now is used constant prices, because payback time is examined on an annual basis and therefore hourly changes in electricity price cannot be used.

Variable costs are calculated using current prices and calculated consumptions. The water consumption is calculated by adding the mass flows of oxygen and hydrogen together. The water mass flow is low and therefore the water costs are also low. The annual development percentage is also considered in variable costs.

The fixed annual costs include all the costs that aren’t related to the production rate, such as personnel costs. Fixed costs include investment, personnel, maintenance, land area, working capital costs. The discounted investment costs with specific period at present time are calculated. The personnel costs are evaluated at each country by using data that received from reliable statistics. The maintenance costs are now evaluated with default Power-to-Gas prices. These personnel and maintenance costs can be considered as constant every year, although in reality there might be unexpected maintenance costs. These extra costs are thus considered in the other costs.

The annual returns of Power-to-Gas consist of the incomes from selling SNG and by-products and frequency control regulation (FCR) services. The annual SNG sales are now estimated as constant. The annual SNG price development and interest rate percentages are chosen. First the Power-to-Gas is examined alone and by-products are sold outside using market prices. Then the economics of Power-to-Gas itself can be better studied. In the integration the benefits from the by-products would be seem only in reduced raw material consumptions. After all returns and costs are evaluated and calculated their value is discounted to present time and profitability can be estimated. The discounted values are calculated with following equation:

$$Net\ Present\ Value = D \cdot \frac{(1+k)^n}{(1+i)^n} \tag{12}$$

, where

D= discountable value [€]

k= annual price development [%]

With 4 million € discountable value, 0,5 % annual price development, 5 % interest rate and 5 years the net present value is:

$$NPV = 4\ 000\ 000\ € \cdot \frac{(1+0{,}015)^5}{(1+0{,}05)^5} = 3\ 210\ 000\ €$$

The FCR-N is now used in Finland and Germany cases. The electricity price in China is regulated by government and now it is estimated that there is no frequency control markets. FCR-N returns are now estimated by using electricity prices and frequency control prices. First it is calculated the profitable electricity price that the Power-to-Gas is profitable to operate and doesn't make losses. It is also calculated how much of power

(MW) Power-to-Gas gives for frequency control. This amount of power it reserved for frequency services and it is not used in SNG production.

Because the integration can be regarded as a renewable energy project, it is supposed to receive a tariff or an investment support. There are different types of tariffs, but the most common one feed-in tariff is a minimum price that is paid from electricity production with renewable energy, usually by government. Investment support is paid to reduce the investment costs. Tariffs are paid to support renewable energy sources and to help to compete against fossil fuels. Renewable energies are nearly always unprofitable and therefore tariffs are commonly needed. Tariffs are usually paid for specific period, like 10 years. The amount of different tariffs has increased during recent years and different nations have their own tariff systems. In this integration study, different tariffs and investment supports are examined.

The annual profits are calculated by subtracting the discounted variable costs, fixed costs, and additional investments from the returns. Profits are then also discounted to present time. The annual profitability percent is calculated by dividing the profit by invested capital. The picture of economic calculations (Picture 21) is in Appendix 2.

7.2 Finland case of Power-to-Gas in WWTP

The Finland case is based on an integration of Power-to-Gas to WWTP at southern Finland. This WWTP is one of the largest plants in Finnish scale and therefore a suitable for the integration studies. This plant has its own biogas production too.

Finland has its own tariff-system for renewable energy sources. A biogas production plant can receive feed-in tariff for production or investment support. The feed-in-tariff that is probably the largest is for new plant that produces electricity for national grid. The tariff is 83,5 €/MWh plus 50 €/MWh heat premium. The tariff is paid only when biogas is used in electricity production and then this integration cannot receive it. The investment support can be divided into the basic investment support and the farm investment support. The second one is off course for farms that produce energy for their own use. The investment support is for biogas plant that produces energy but doesn’t produce electricity to grid. The investment support varies between 8 and 30 % of the accepted costs of investment. These costs are investment itself, building and supervising, planning, installation and excavation. The main terms for the investment support are that the project reduces the use of the fossil fuels and it is economically profitable. The amount of investments support has dropped in recent years (Åkerlund 2015). In this integration case, the investment support would be the selected support method.

The average electricity price for industry in Finland is quite low in Europe scale, 75 €/MWh that can make the Power-to-Gas technology affordable. Off course smaller electricity prices are used now in calculations when it is considered that plant is operated only in profitable prices.

The price of the product, SNG, is now compared to biogas prices in transportation. The average price for biogas in Gasums gas station is 1,45 €/kg (Gasum 2014). Now it is considered 10% of distribution costs that are included in the gas station price, so the SNG-price is 1274 €/t, 91,8 €/MWh. The gas network in Finland is very small compared to other European countries and highly concentrated to southern Finland. Also the use of the renewable energy sources and technologies like wind power is still restricted. However, Finnish gas company Gasum has invested a lot to its biogas production.

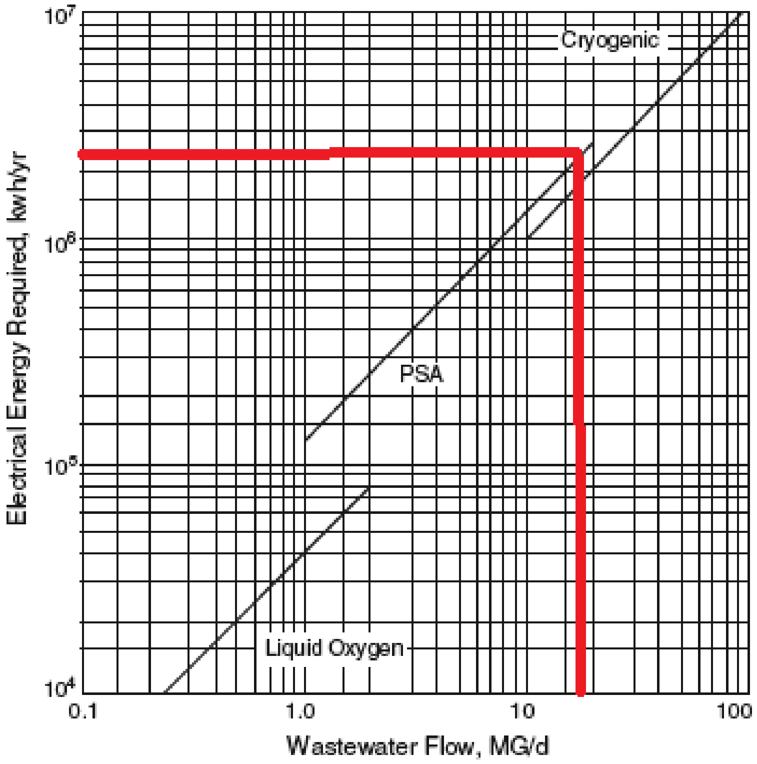
The personnel and maintenance costs as well as building costs in Finland are high. This raises the fixed annual costs and investment costs. The investment costs are for electrolyser 760-1100 €/kW$_e$ (Bertuccioli et al. 2014,13) and for methanation 1000 €/kW$_{SNG}$ (NeoCarbon WP3 reference data and platform). In these costs is added 15% of the investment the building costs and other appliance costs. Now the costs are estimated from the default Power-to-Gas prices that are little lower. The default investment cost for Power-to-Gas is according to the default prices 1000 €/kW. In Finnish case the electrolyser costs are set to 1000 €/kW$_e$ and methanation costs 1000 €/kW$_{SNG}$. The overall investment costs are:

$$1{,}15(5650\ kW \cdot 1000 \frac{€}{kW_e} + 1347\ kW \cdot 1000 \frac{€}{kW_{SNG}}) = 8\ 050\ 000\ €$$

The personnel costs can be estimated that salary for one plant operator is 3100 €/ month. (Kuntatyönantajat 2014). Overall personnel costs for employer in Finland are roughly 1,4-1,5 times the worker's salary (Yrittäjät). When it is considered that there is one operator present all the time in 3-shiftwork so it requires total of 5 employees at the plant and the overall personnel costs are:

$$3100 \frac{€}{month} \cdot 12\ months \cdot 1{,}5 \cdot 5 = \ \ 279\ 000\ €$$

The oxygen price is now estimated with energy consumption in treatment plants oxygen production. Energy consumption in oxygen production can be estimated from Picture 18.



Picture 18: Energy consumption in oxygen production at WWTP (Wang et al., 2009, 287)

With 97 260 m^3/day (25 693 000 gal/day) wastewater flow the electricity consumption is 1500 - 2 500 MWh/a, depending the method (PSA or cryogenic). With 75 €/MWh average electricity price (electricity is bought outside= transfer fees are added) the annual cost is 112 500...187 500 €. The WWTP's oxygen demand is calculated with calculator from Lenntech (Lenntech 2015). For Finland case the oxygen demand is 475 kg/h that is 3800 ton/a. The production cost of oxygen is then:

$$Oxygen\,production\ cost\colon \frac{112\,500\ \dots\ 187\,500\ €}{3800\ ton} = 29{,}6\ \dots 49{,}3\ €/ton$$

Now it is selected the cryogenic-method, 29,6 €/ton. PSA can be thought to be more common, but cryogenic is used for larger wastewater flows and therefore it is also selected in other cases as well.

The WWTP in Finland case produces annually 2400 tons of CO_2 and Power-to-Gas requires 2613 tons, so with 100 €/t_{CO2}-price annual carbon dioxide costs are:

$$CO_2 - costs\colon 100\frac{€}{t}(2613 - 2400)t = 21\,300€$$

7.3 China case of Power-to-Gas in WWTP

China has suffered from serious environmental issues and started to improve its waste management. China is improving its wastewater treatment and renewable energy production rapidly. China is an interesting country for Power-to-Gas integration, because of the low prices and growing economy. China is building numerous new WWTPs with support from other countries such as Japan. Average electricity price is for industry (transfer fees included) 110 €/MWh (OECD 2013, 133). The price of the normal petrol is lower than in Europe and therefore the price of the SNG is also lower. This will decrease the returns significantly and may require a large electrolysis plant for decent returns. Also the investment and personnel costs can be considered lower than in Europe. However, the Power-to-Gas technology is the same as in Europe and still expensive. The investment cost for electrolyser and methantion are now selected as little cheaper as in default prices, 800 €/kW_e and 800 €/kW_{SNG}. The investment costs are:

$$1{,}15(23\,860\ kW \cdot 800\frac{€}{kW_e} + 12\,130\ kW \cdot 800\frac{€}{kW_{SNG}}) = 33\,110\,000\ €$$

The support and tariff systems for renewable energies in China are very complex. In Beijing alone there are roughly 300 different support systems. Therefore evaluating the size of the investment support or tariff is quite difficult. In Finland and in Germany grid-injected synthetic methane receives investment support and therefore it is selected that China has same kind of support system. (WantChinaTimes.com 2013.)

In China the Power-to-Gas is integrated to large wastewater treatment plant at northeast China and it is one of the largest WWTPs in China. Plant treats 365 million m^3 of waste annually. Plant has a sludge digester and it produces biogas that is used in electricity production. Electricity production can be as high as 10 000 MWh per year, which is 20% of the plants electricity consumption. (Chinagate.cn 2015.)

The personnel costs are calculated as in the Finnish case. China is notorious for its low production and the personnel costs although these costs have risen fast recently. The average engineer in China can now earn as much as in Finland. The salaries are doubled from the year 2009 (HS.fi 2013). The higher salaries have driven the European and US industry back from China (Tiilikainen 2012). The average prices in basic jobs are still lower, minimum prices in Beijing region: 210 - 240 €/month (China labour Bulletin 2013) The monthly salary is now selected in 1650 €/month and the multiplier factor is estimated as 1,2. The factor is lower than in Finland because it is considered that even when the salaries are higher the costs for employer are lower. Again there is one operator in 3-shiftwork that requires total 5 employees. The annual personnel costs are now:

$$1650 \frac{€}{month} \cdot 12\, months \cdot 1{,}2 \cdot 5 = 118\,800\ €$$

The transportation fuel prices in China are controlled by government and in 2010 the average petrol price was 1,08 $/ litre that is 0,99 €/litre. This is lower than in Europe and therefore it can be considered that also the price of the gas sold in petrol stations is lower.

The oxygen price is calculated as in Finland case. Now with 1 million m^3/day (264 Mgallons/day) wastewater flow the electricity consumption is roughly 10 times the consumption in Finland case, 15 000 MWh/a. With 110 €/MWh electricity price the cost is 1,65 M€. The annual oxygen need at WWTP is 39 120 tons/a. The oxygen price is then:

$$Oxygen\ price\colon \frac{1\,650\,000\ €}{39\,120\ ton} = 42{,}2\ €/ton$$

The WWTP produces annually 24 000 tons of carbon dioxide and Power-to-Gas plants consumption is 27 444 tons so the annual CO_2-costs are:

$$CO_2 - costs\colon 100\frac{€}{t}(27444 - 24000)t = 344\,400€$$

7.4 Germany case of Power-to-Gas in WWTP

The Germany case represents an integration of Power-to-Gas to a typical Central-European wastewater treatment plant. Germany is the leading country in biogas market in Europe and it also has several large WWTPs that make Germany an ideal for Power-to-Gas integration studies. The example plant is located at northern Germany and plant is quite large treating 160 million m^3 wastewater annually. Plant produces digester gas that is mostly used at the plant to cover electricity and heating costs but some is also refined to biomethane and fed to the national grid (Laurich 2013).

Germany has a long history of using renewable energies and therefore there are also good tariffs for biogas production. Like in Finland, feed-in tariffs are paid only for electricity production and grid-injected biomethane receives only investment support. (Hahn et al. 2010.)

The electricity price in Germany is quite high, 152 €/MWh, transfer fees included, (Europa.eu 2014), and that can seriously affect to the profitability of the integration. This is off course the average price for industry and smaller prices are used in calculations. The investment costs are now same as in Finland, for electrolyser are 1000 €/kW$_e$ and for methanation 1000 €/kW$_{SNG}$. The investment costs are:

$$1{,}15(15210\ kW \cdot 1000 \frac{€}{kW_e} + 6206\ kW \cdot 1000 \frac{€}{kW_{SNG}}) = 24\ 628\ 000\ €$$

Salaries in Germany have risen clearly less than in Finland during recent years (Kauhanen and Saukkonen 2011, 1-14). The personnel costs are now calculated with same method as in Finland and China case, but now the costs for employee are lower. The monthly salary for plant operator is now 3000 €/month and the multiplier factor is 1,3. The overall personnel costs are:

$$3000 \frac{€}{month} \cdot 12\ months \cdot 1{,}3 \cdot 5 = 234\ 000\ €$$

The electricity price is not off course high all the time, when there are periods when it is considerably lower. The calculated profitable electricity price in Germany is 45 €/MWh The technology is however same and therefore expensive. There are more companies that provide high-tech products in Germany than in Finland so the price of the appliances and maintenance is lower. The petrol prices in Germany are little lower than in Finland, therefore the price of the SNG is also considered little lower than in Finland.

The oxygen price is calculated as in Finland case. Now with 438 000 m^3/day (116 Mgallons/day) wastewater flow the electricity consumption is roughly four times the consumption in Finland case, 6 000 MWh/a. With 152 €/MWh electricity price the cost is 0,91 M€. The annual oxygen need at WWTP is 17 150 tons/a. The oxygen price is then:

$$Oxygen\ price: \frac{912\ 000\ €}{17\ 150\ ton} = 53{,}2\ €/ton$$

The WWTP produces annually 9600 tons of carbon dioxide and Power-to-Gas plants consumption is 12 033 tons so the annual CO$_2$-costs are:

$$CO_2 - costs: 100 \frac{€}{t} (12\ 033 - 9\ 600)t = 243\ 300€$$

7.5 Economy calculations

In this chapter is calculated the economics of the integration in all three cases, in Finland, in China and in Germany. First the default prices are used and then the values are changed. The values are raised and/or decreased depending on the value. For example the SNG price is raised to improve the returns. By fixing the values it can be studied that which of them affect the most to the profitability. The results from fixed value calculations are shown now in calculations and the figures are in appendices.

7.5.1 Finland input values

In the Finland case and in other cases the investment support is set to 30%. The electrolyser size is now 5,65 MW and 3 MW is now used for FCR-N so 2,65 MW is available for SNG production. Water price is 1 €/t. The annual operating hours are 6000 with annual production of 558 tons of SNG. The price of the SNG is 1273 €/t or 91,8 €/MWh with 0,5% price development. The gas price is quite high, but it is considered that Finland is willing to support renewable energies. The extra SNG production from biogas is 16 575 MWh/a that is 1 520 000 €.

The profitable electricity price with these input values is 48,5 €/MWh. The average electricity Spot- price is 41,16 €/MWh. Now when the annual operating hours are 6000 the price can be considered as little lower, roughly as 34 €/MWh. The taxes and transfer prices are now 11,82 €/MWh that is price for industrial electricity use in taxation class 2 (Elenia 2015). The overall electricity price in Finland case is then 46 €/MWh.

The returns from FCR-N are also calculated. The electricity regulation price is on average 15- 25 €/MWh (Fingrid 2015). It is selected that Power-to-Gas gives now 3 MW of power for regulation services. Now with 20 €/MWh regulation price the annual returns from FCR-N are 525 600 €. The input values are also Table 7.

7.5.2 China input values

In China case the investment costs are 33 100 000 million euros. The electrolyser size is now 23,9 MW with 5860 ton SNG production. The SNG price is set to 1100 €/t, 79

€/MWh and with 10% distribution costs the price is 71,1 €/MWh. The price of water is now dropped to 0,7 €/t that is still high in China standards, but China has suffered of serious dryness and water pollution so price of fresh water is therefore little high. The extra SNG production from biogas is estimated as 32 500 MWh/a that is 2 022 000 €. This biogas production is quite low when the WWTP in China is 10 times the size of the Finland WWTP, but in the Germany WWTP the biogas production is also relatively small comparing to Finland plant. Therefore when there were no accurate data from the biogas production in China WWTP, the biogas production is estimated as 2 times the Germany WWTP biogas production.

The profitable electricity price with these input values is 60,5 €/MWh. The average electricity spot- price is not available for China so it is estimated as 45 €/MWh. Now when the annual operating hours are 7000 the price can be considered as little lower, roughly as 34 €/MWh. The taxes and transfer prices are now 11 €/ MWh. The overall electricity price in China case is then 45 €/MWh. The input values are also Table 7.

7.5.3 Germany input values

In Germany the SNG price is now considered as little higher than the natural gas price in petrol station. The natural gas price is 1,05 €/kg (Gas-tankstellen.de 2015). The SNG price is now 1150 €/t, 83 €/MWh and with 10 % distribution costs the price is 74,7 €/MWh. The overall investment is now 24 600 000 million euros, the same than in Finnish case. The extra SNG production from biogas is 15 600 MWh/a (Laurich 2013) that is 1 165 000 €. This is quite low when comparing to Finland. Annual operating hours is 6000 hours. The electrolyser size is now 15,2 MW and 3 MW is now used for FCR-N so 12,2 MW is available for SNG production.

The profitable electricity price with these input values is 75,5 €/MWh. The average electricity Spot- price is 33,6 €/MWh (NeoCarbon 2015). Now when the annual operating hours are 6000 the price can be considered as little lower, roughly as 28 €/MWh. The taxes and transfer prices are in Germany are higher than in Finland and are now estimated as 20 €/MWh. The overall electricity price in Germany case is then 48 €/MWh.

The returns from FCR-N are also calculated in Germany case. The electricity regulation price is set on 24 €/MWh. It is selected that Power-to-Gas gives now 3 MW of power for regulation services. Now with 24 €/MWh regulation price the annual returns from FCR-N are 630 720 €. Other values are in Table 7.

Table 6: Input default values

Country	**China**	**Germany**	**Finland**
Investment [M€]	33,19	24,69	8,12
Electricity price [€/MWh]	45	48	46
Investment support	30 %	30 %	30 %
Operating hours	7000	6000	6000
SNG production [tons]	5 861	2 570	558
SNG price [€/MWh]	71,1	74,7	91,8
Biogas production [MWh]	32 500	15 600	16 600
Oxygen sales [tons]	39 120	17 150	3800
Oxygen price [€/tons]	42,2	53,2	29,6
FCR-incomes [M€]	-	0,6	0,5
WACC [%]	5	5	5
Annual price development [%]	0,5	0,5	0,5

7.5.4 Results with default values

With given inputs the integration is quite profitable in all three cases: the integration is profitable after 5 years in China and after 6 years in Germany and after 1 year in Finland (Table 7). The cumulative cash flows are positive after 9 years in China and 12 years in Germany and after 1 year in Finland.

Table 7: Results with default values

Country	**China**	**Germany**	**Finland**
Returns [M€] (SNG, oxygen, FCR)	10,10	5,37	2,87
Fixed costs [M€] (investment, O&M)	4,04	3,21	1,39
Variable costs [M€] (electricity, CO_2, H_2O)	8,16	3,95	0,93
CAPEX [M€] (Capital payment, interest)	3,48	2,59	0,85
OPEX [M€] (Fixed costs, variable costs, interest)	11,04	6,29	2,04
EBIT* [M€]	-0,94	-0,92	0,83
First operational profitable year	5	6	1
Cumulative cash flow positive [NPV]	9 years	12 years	1 year

*earnings before interests and taxes

The returns are high in all three cases and there are no large negative cash flows (Figure 1).The investment is now divided to economic lifetime (10 years) and it is included in fixed costs. Therefore there are not large negative cash flows at beginning. The Finnish case looks very profitable: cash flow is positive after first year when investment payment is divides to 10 years. This can even too profitable; in reality the profits can be smaller and this indicates that there are some errors in Finland case, such as the SNG price is too high or the FCR-N is unrealistic to implement in reality. The returns even rise via the price development and costs decrease. China and Germany have clearly relatively larger costs and smaller returns than Finland and the NPV is 12 years in Germany and 9 years in China. The smaller returns result from the relatively smaller biogas production in WWTP and therefore smaller SNG-production. The EBIT figure (profits before taxes) is negative in China and in Germany, but positive in Finland.

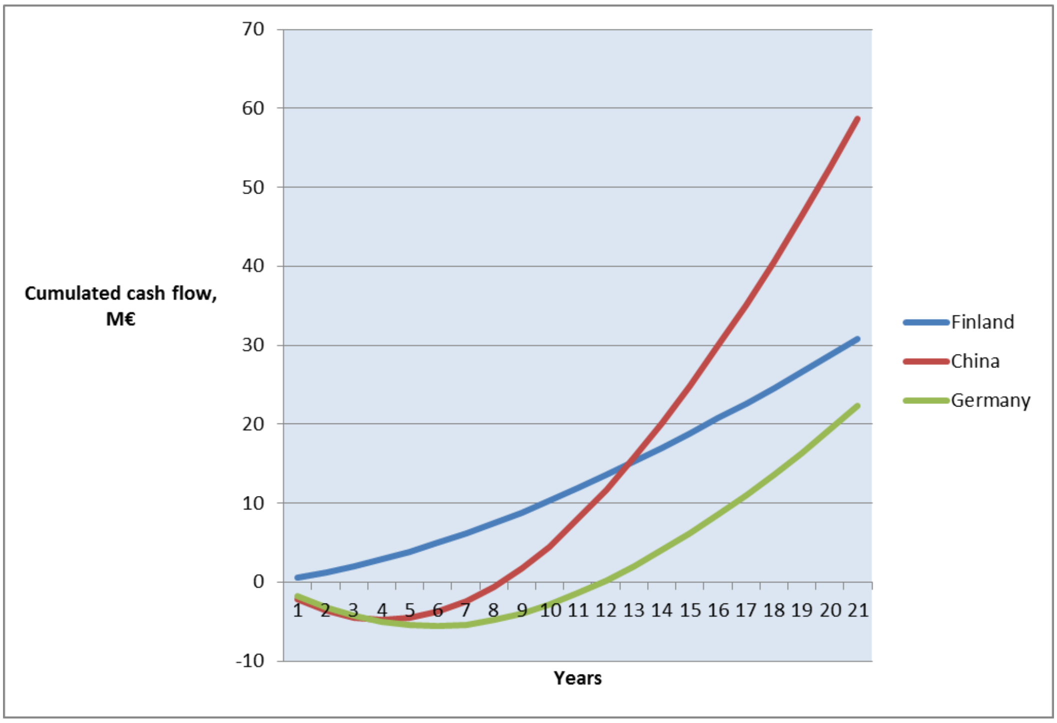


Figure 1: First year results with default values, investments split to 10 years.

Next is studied the key factors are studied. The key factors are the electricity and SNG prices and the investment costs. The costs are divided to fixed and variable costs. The largest cost in every case and especially in China is the electricity cost (variable costs). Also the investment (fixed costs) and O&M (fixed costs) are large (Figure 2). The largest returns come from SNG sales, but also oxygen brings large returns, especially in China. Also the FCR-N service brings considerable returns for Finland and Germany. The CO_2-costs are clearly smaller in Finland, when the plant is considerably smaller and CO_2-need is therefore low.

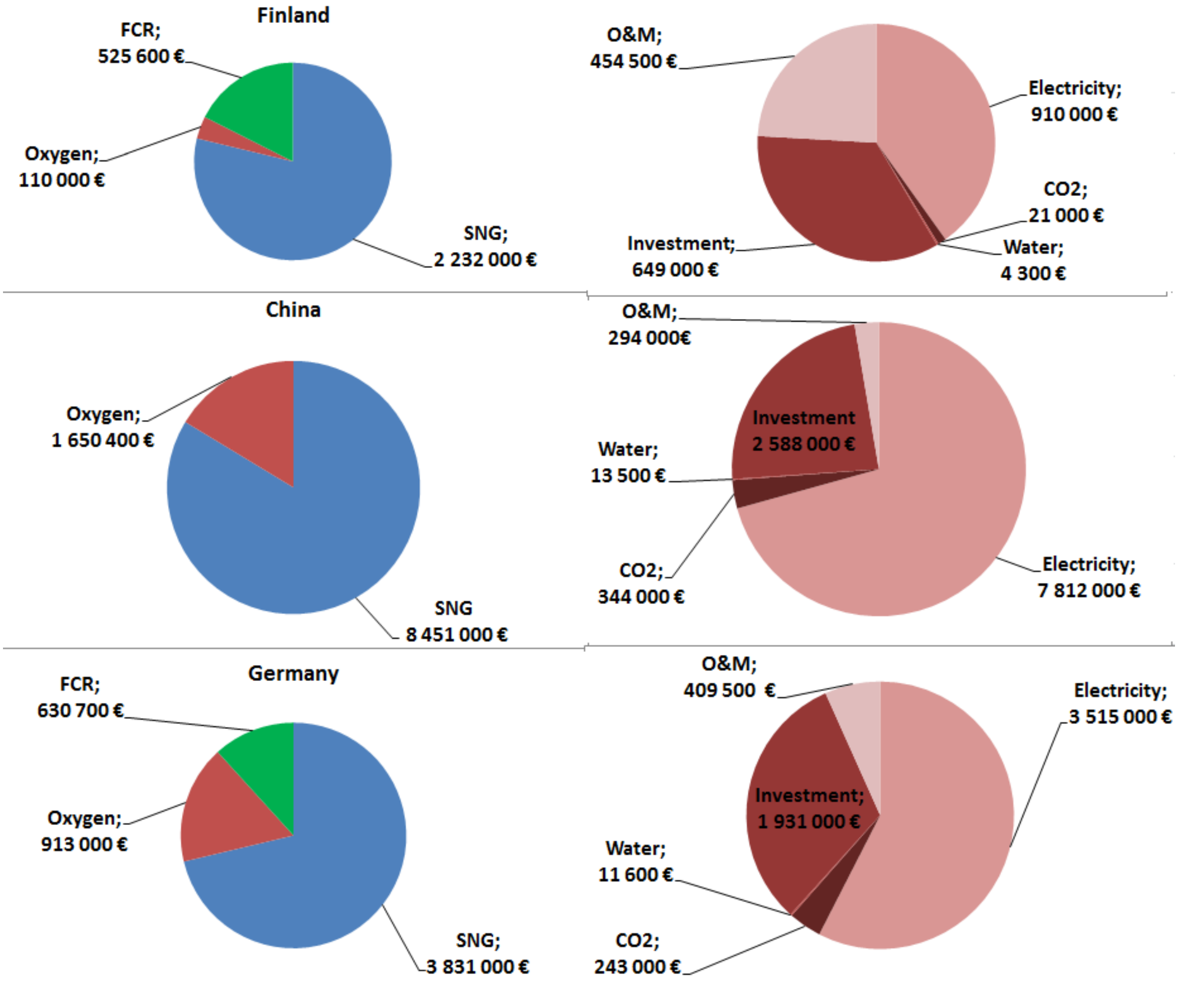


Figure 2: First year costs and returns with default values for Finland, China and Germany.

7.5.5 Decreased costs

Therefore by decreasing the electricity price and/or investment costs the profitability raises. The impact of decreasing the electricity price and investment are studied next.

7.5.5.1 Decreased and increased electricity prices

First the impact of decreased costs is examined by lowering the electricity price. Lower electricity price decreases the annual variable costs. The share of electricity is the largest in variable costs and water and carbon dioxide costs are less significant. New electricity price is 25 €/MWh in each case and all other values are as default (Table 8).

Table 8: Results with decreased electricity prices, old values market in parenthesis

Country	**China**	**Germany**	**Finland**
Electricity price [€/MWh]	(45) 25	(48) 25	(46) 25
Variable costs [M€]	(8,16) 4,82	(3,95) 2,27	(0,93) 0,59
OPEX [M€]	(11,04) 7,70	(6,29) 4,61	(2,04) 1,69
EBIT [M€]	(-0,94) 2,40	(-0,92) 0,76	(0,83) 1,18
First operational profitable year	(5) 1	(6) 2	(1) 1
Cumulative cash flow positive [NPV]*	(9) 1 year	(12) 2 years	(1) 1 year

*investment divided to 10 years

When the electricity price has the largest share from the variable costs, decreasing it also decreases significantly the annual variable costs, for example in Germany from 3,95 M€ to 2,27 M€. This improves the profitability significantly: in China the NPV drops from 9 to 1 year that is a large improvement. These results show that the impact of the electricity price is huge in this integration at least in Germany and China cases. In Finland case the impact of decreased price is minor: variable costs are decreased only over 300k€. The electrolyser in Finland case is clearly smaller (2,65 MW) and then the share of the electricity is also smaller. The figure of the results is shown in Appendix I. The rest of the results are in Table 12 (Chapter 8).

Because the impact of the electricity price is clearly large for the integration and during finalizing of the thesis (summer 2015) the electricity prices are exceptional low level (Europa.eu 2015), it also studied the scenario were the electricity price rises. Now the price is 55 €/MWh in each case, the rest values are as before (Table 9).

Table 9: Results with increased electricity price, old values market in parenthesis

Country	China	Germany	Finland
Electricity price [€/MWh]	(45) 55	(48) 55	(46) 55
Variable costs [M€]	(8,16) 9,83	(3,95) 4,47	(0,93) 1,09
OPEX [M€]	(11,04) 12,71	(6,29) 6,81	(2,04) 2,19
EBIT [M€]	(-0,94) -2,61	(-0,92) -1,43	(0,83) 0,68
First operational profitable year	(5) 7	(6) 8	(1)1
Cumulative cash flow positive [NPV]	(9) 14 years	(12) 15 years	(1) 1 year

Now the variable costs are larger: in China the variable costs are increased by over 1,5 M€ and NPV is raised from 9 to 14 years. The increase of the price was relatively small, in Germany it was only 7 €/MWh, but the impacts were still clear. This shows that variations in electricity price clearly affects to profitability of this integration. The figure is in Appendix I. The rest of the results are in Table 12 (Chapter 8).

7.5.5.2 Decreased investments

Next the investments are significantly decreased to the lower level. The investment costs are high that shown in high fixed costs. The investments are decreased 4 million € and in Finland the investments are now 4,6 M€ and Germany the new investments are 20,6 M€ and 29,1 M€ in China the (Table 10). The electricity prices are as original.

Table 10: Results with decreased investments, old values market in parenthesis

Country	China	Germany	Finland
Investments [M€]	(33,1) 29,1	(24,6) 20,6	(8,6) 4,6
Fixed costs [M€]	(4,04) 3,59	(3,21) 2,76	(1,84) 0,94
CAPEX [M€]	(3,48) 3,06	(2,59) 2,17	(0,85) 0,43
EBIT [M€]	(-0,94) -0,63	(-0,92) 0,61	(0,83) 1,14
First operational profitable year	(5) 4	(6) 6	(1) 1
Cumulative cash flow positive [NPV]	(9) 7 years	(12) 10 years	(1) 1 year

The fixed annual costs decrease quite low, less than 500 k€ in Germany, but still the cumulative cash flow is quite well improved: from 9 to 7 years in China. The impact of decreasing fixed costs is lower, because fixed costs consists also from other values, such as personnel costs. The figure is shown in Appendix I and the rest of the results are in Table 12 (Chapter 8).

7.5.6 Increased returns

In addition of decreasing the costs of the integration, another way of making the project profitable is to increase the returns. This can be done by raising the price of the SNG or increasing the plant production. Increased capacity will also thus increase investment and variable costs.

7.5.6.1 Increased SNG-price

The increased product price will only raise the returns and profits. The integration receives its largest returns from the SNG and therefore an increase in SNG price can well increase the returns. The SNG prices are now raised 30 €/MWh and the new prices are: 121,8 €/MWh in Finland, 104,7 €/MWh in Germany and 101,1 €/MWh in China (Table 11).

Table 11: Results with increased SNG-price, old values market in parenthesis

Country	**China**	**Germany**	**Finland**
SNG price [€/MWh]	(71,1) 101,1	(74,7) 104,7	(91,8) 121,8
Returns [M€]	(10,1) 10,96	(5,37) 6,91	(2,87) 3,76
EBIT [M€]	(-0,94) -0,09	(-0,92) 0,62	(0,83) 1,56
First operational profitable year	(5) 4	(6) 2	(1) 1
Cumulative cash flow positive [NPV]	(9) 6 years	(12) 3 years	(1) 1 year

Now the returns are improved for example in Germany from 5,37 M€ to 6,91 M€. The cumulated cash flows are also well improved, in China the first operational year is the fourth year, the NPV-value has drop from 9 to 6 years. In Germany the NPV value decreased to 3 years. This results show the influence of the SNG price. The figure is shown in Appendix I. The rest of the results are in Table 12 (Chapter 8).

8 DISCUSSION

The results of previous economic calculations area now discussed in this chapter. The aim is to examine different factors and find the key factors of the profitability. The economics of the integration in three countries Finland, China and Germany are compared together. All three cases, Finland, China and Germany were quite profitable with default prices, Finland, in fact, very profitable. The key factors are separately studied for Finland.

In addition of SNG, that is quite valuable when sold for transportation, also the oxygen has good value in wastewater treatment. Without the integration WWTP needs to produce oxygen with expensive electricity and Power-to-Gas-technology can provide the oxygen as a by-product. The returns from FCR-N are also quite significant, 500 k€ - 600 k€ per year. The FCR is now an extra service for this integration and it might not be possible to use with large numbers of integrations, at least in Finland. In Finland the profits were 548 k€ after the first year and without the FCR-N incomes (526 k€) the profits would be close to zero (20 k€) and the profitability of the integration would be more sensitive.

One economic issue in Power-to-Gas is to produce gas from electricity that is usually done conversely. The impact of electricity cost is large for this integration. Electricity cost is the largest cost in all three cases, from 0,9M€ to 7,8M€ and changes in electricity prices affected to the profitability. For example when the electricity price was reduced (Table 12) from 48 €/MWh to 25 €/MWh, the positive cash flow with investment split to 10 years was 2 years in Germany and to 1 year in Finland and in China. And conversely when electricity price was increased to 55 €/MWh the variable costs were clearly higher and reaching the positive cash flows took longer. In China the impact of changing the electricity price seem to affect more than in other cases, because the P2G-plant is considerable large and consumes plenty of electricity. In Finland case reaching the positive cash flow took 2 years with 80 €/MWh price that is nearly 2 times the default price. This shows the good profitability of the Finland case. Currently the electricity prices are in low level, at least in Finland. In future the electricity prices can rise significantly.

Table 12: Results with default and fixed values

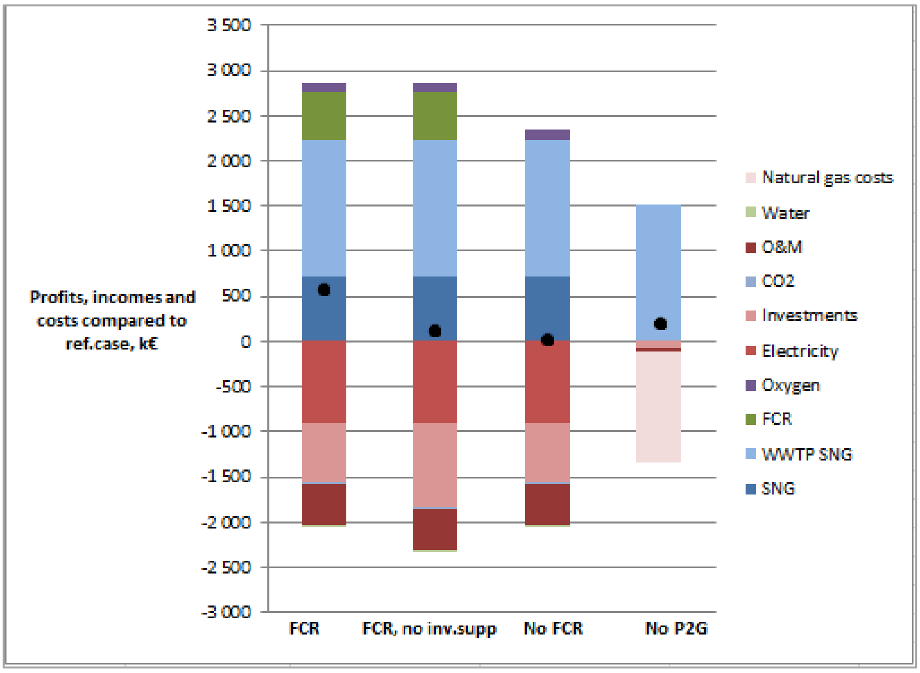
	Finland	China	Germany
	Cash flow positive [NPV] [years]	Cash flow positive [NPV] [years]	Cash flow positive [NPV] [years]
Electricity price			
25 €/MWh	1	1	2
35 €/MWh	1	3	7
Default price	1	9	12
55 €/MWh	1	13	15
65 €/MWh	1	18	20
80 €/MWh	2	-	-
Investments			
- 4M€	1	7	10
Default inv.	1	9	12
+ 4M€	1	10	15
+ 6M€	3	11	16
+ 8M€	6	-	-
SNG price			
- 30 €/MWh	5	-	-
- 15 €/MWh	1	10	19
Default price	1	9	12
+ 15 €/MWh	1	7	7
+ 30 €/MWh	1	6	3

The amount of investment costs in Power-to-Gas is quite high and these costs are the second largest in this integration. The very complex and expensive technology that is currently rarely used, decreases the profitability. Also the annual maintenance costs can be high especially during the first years if the technology is unreliable. The realistic figure from the maintenance need may be only achieved from pilot plants. In the future the investment costs are however estimated to decrease via technology improvements. The impact of investment costs for profitability are quite minor, for example when the investment costs in China were decreased (Table 12) with 4 million €, reaching the positive cash flow was decreased from 9 years to 7 years. Conversely when the investments were increased, the fixed costs were larger and, for example in Germany case with extra 6 M€ investment reaching the positive cash flow period was took 4 years longer. In Finland case with 8 M€ extra investments reaching the positive cash flow took 6 years.

The good incomes from biogas upgraded to transportation SNG, 1,6M€ - 2M€, raises question about implementing only the biogas. If WWTP receives good profits only by upgrading the raw biogas, there might be no need to build the P2G-plant at all. Then WWTP would need to buy extra natural gas to cover the biogas used in CHP-plant and also a sulphur removal plant. The sulphur removal costs are now 0,0108 €/m^3 annually. The WWTP now produces 22 100 MWh (3 400 000 m^3) of biogas annually and after methanation the SNG value is 1,52 M€. With 56 €/MWh natural gas price (Finland, industrial) the annual SNG returns after costs are:

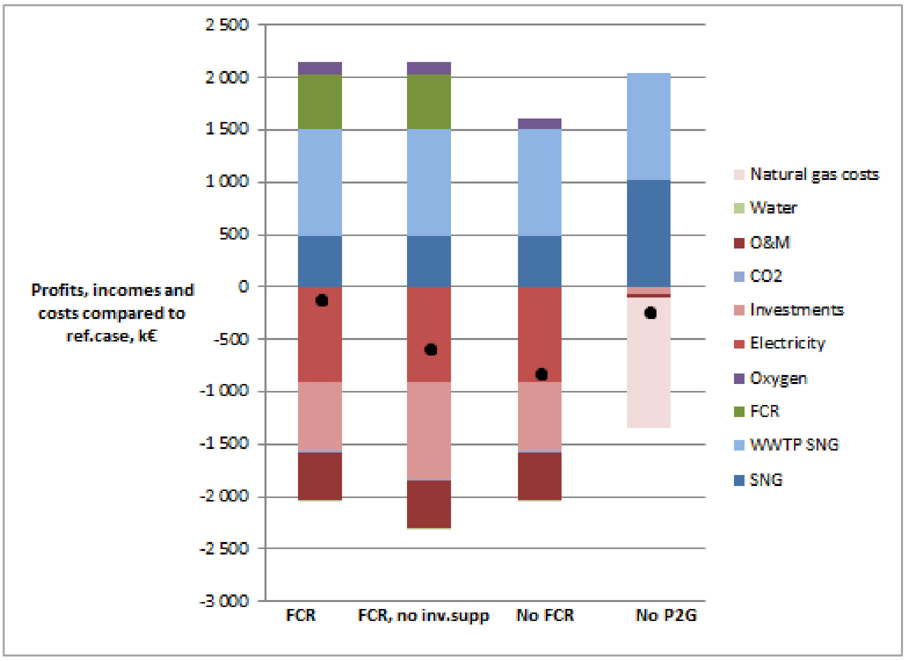
$$SNG - returns\colon 1{,}52M€ - 0{,}0108\frac{€}{m^3} \cdot 3\,400\,000\,m^3 - 22\,100\,MWh \cdot 56\frac{€}{MWh}$$
$$= 245\,680€$$

The annual returns are smaller than in P2G integration, but still considerable large and by only upgrading the raw biogas there are significantly less risk factors for the profitability. The annual profits in Finland case in different scenarios are also now studied. Integration can be implemented without FCR or without investment support. The profits after first year in different scenarios are shown in Picture 19.



Picture 19: Profits, incomes and costs after first year in Finland in different integration scenarios, profits marked with dots

The profits are positive in all four cases, but the largest profits are in FCR-case (548 k€) and then in No P2G-case (246 k€). This supports the idea that it is profitable to WWTP to only upgrade the biogas. Different scenarios were also studied with lower SNG-price, 61,8 €/MWh and results are in Picture 20.



Picture 20: Profits, incomes and costs after first year with lower SNG-price

Results show that the profits in all three scenarios are negative, but best still in FCR-case and then in No P2G-case. It is important to consider how large negative profits are in case No FCR. It is likely that the FCR is used only with one integration and if the SNG price is closer to 60 -70 €/MWh than 90 €/MWh, the integration is highly unprofitable. Then in reality the No P2G would likely be the most profitable case.

This kind of renewable energy project may need some kind of support from government and this support is vital for this project's profitability. Without the electricity production the project receives only investment support in all cases. The investment support decreases the investment costs and its impact is quite significant to overall profitability. Now the level of supports was set to 30%, but it is considered that nations are willing to invest renewable energy and energy self-sufficiency.

When the gas is sold to grid-injection the gas distributor pays certain price from the gas. The amount of this price is quite difficult to estimate accurately, it is lower than the retail price. In the calculations the price is first estimated as lower than the gas sold in petrol stations. Prices can also be higher than the retail prices, when EU allows 4 times larger price for renewable fuels made from non-biological sources.

The impact of the product price is quite large. The returns from the SNG sales are the largest returns of the integration. The default SNG price is quite high in all three cases. The impact of increasing the SNG price (Table 12) was also large, especially in China when the price was raised from 71 €/MWh to 101 €/MWh, reaching the positive cash flow took 6 years. On the other hand when the price was decreased by 15 €/MWh the annual returns were lower and for example in Germany it take 7 years longer to reach positive cash flow, in China the same it take only 1 year longer. It is interesting that the impact of SNG price is considerably larger for Germany than for China. In Finland case when the SNG price was drop to 57 €/MWh (-40 €/MWh), close to natural gas price, reaching the positive cash flow took 4 years. This shows the good profitability of making the SNG. As a transportation fuel the SNG price is quite connected to traditional petrol price which cannot be raised to too high level. Therefore if the SNG price is increased the gas distributor (and petrol station owner) needs to pay higher price from the SNG than it is sold. Then the difference of these two prices should be paid by government or the gas distributor itself.

The integration itself is well reasonable, when both wastewater treatment and Power-to-Gas can utilise well the by-products. Wastewater treatment needs oxygen or air. Oxygen is the most important by-product from Power-to-Gas-technology. Wastewater treatment is also a compulsory for societies and usually it cause costs for municipalities. Therefore an improvement that can cut the waste treatment costs and also produce renewable energy at the same time is welcomed. Currently there is also already biogas production at some WWTPs, so there are installations ready for synthetic natural gas production too. Oxygen use in the WWTP also increases the efficiency and can provide savings in the WWTP, too, when e.g. investment needs to new and larger aeration tanks with land beneath them, are eliminated.

The ozone synthesis and methanol production are quite unnecessary processes in this integration. Although ozone and methanol are used in some WWTPs, their production in Power-to-Gas means extra appliances and extra costs both in investments and in maintenances. Methanol production also requires a carbon source, such as coal that should be bought outside. Ozone production has a very low efficiency too and ozone synthesis is better to replace with oxygen feed when oxygen is always needed at the WWTP.

The one key factor for this integrations profitability is the amount of annual returns. When Power-to-Gas is operated shorter times, the annual productions are also lower. However, the operating hours are still in quite high level, from 6000 to 7000 hours. The operating hours depend on the electricity prices, when Power-to-Gas plant is profitable to drive during lower electricity prices. In these calculations the annual operating hours were estimated using couple past years. Recently electricity prices have dropped significantly that is good for this integration, but the electricity prices can also rise heavily. It is important to notice that the annual SNG production depends also from the WWTP the P2G is integrated. Now in the Finland case the profits were good when the WWTP produced relatively good amounts of biogas that is upgraded to SNG. Therefore it is important for the profitability that the WWTP has a sufficient sized digestion plant. WWTPs without digestion and biogas production can be unprofitable to this integration.

The most important factors for Power-to-Gas integration seem to be the electricity price, investment costs, SNG price and the biogas production in WWTP. Electricity causes most of the costs and variations in electricity price can seriously affect to the integration profitability. The share of the investment costs were, all in all, less than first expected. The investment costs are even expected to decrease in the future. The most important factor for the profitability is the efficient biogas production in WWTP. The produced biogas is upgraded to transportation SNG that is very valuable for the integration. All three cases were well profitable even without changing any of these factors. These economic studies were still based on calculations, not actual P2G+WWTP-integrations and therefore the results can be different in reality. The more accurate data from the profitability could be achieved properly only with actual integrations and pilot-plants.

Now in calculations it was used the Net Present Value method. There are also other methods to evaluate economic profitability that can give more thoughtful and specific information of certain key factor. This NPV-method was selected to receive a wide viewpoint of the overall profitability of the integration. Despite of the wide viewpoint, the key factors affecting to the profitability were now considered and studied. In the calculations there were plenty of different values that were received from reliable sources and in Finland and in Germany cases these values can be considered accurate. From China there are thus less accurate data available or the correct data is more difficult to find. Therefore it can be considered that results from the calculations are accurate for Finland and Germany, but less accurate for China.

9 CONCLUSIONS

Power-to-Gas integration to wastewater treatment plant can be very profitable, but this project has other than economic values too. A renewable energy source that not only increases the energy self-sufficiency, but also improves the use of the other renewable energy sources is very important. Power-to-Gas-technology can also reduce the costs from municipal or industrial facilities. With default values the integration reached the positive cash flow in Finland after 1 year, in Germany after 12 years and in China after 9 years. However there are some aspects that can seriously affect to the profitability.

Biogas and synthetic natural gas are gaseous fuels that are becoming more common in transportation. Both of these gases can be well utilised in transportation, such as in cars, busses and ships, but also in heat and electricity production. Gases can be utilised in the same applications as natural gas. These gases have also quite good heat values. Raw biogas includes extra substances that must be removed before they can be used in vehicles.

Wastewater treatment is a combination of different treatment stages. It has remained as quite a same process during last decades, but studies have made to improve the treatment processes. The demand for wastewater treatment is increasing especially in the growing cities in China where lack of fresh water has become a serious problem. Wastewater treatment consumes mainly different chemicals and electricity. Wastewater treatment can produce also biogas from digestion. Digestion is an anaerobic process that is also a treatment process. The produced biogas can be utilised at the WWTP to cover electricity and heat costs or it can be sold for transportation.

Power-to-Gas technology offers a solution for storing energy in to SNG. Power-to-Gas increases renewable energy production and stabilises the energy production peaks. In Power-to-Gas hydrogen is first produced by dissolving water with electricity in electrolyser. This process also produces oxygen and heat that are valuable by-products and they also can be utilised. The produced hydrogen is refined to SNG in methanation. Energy is stored in the form of SNG with the produced electricity. SNG can be then fed to natural gas grid. Therefore Power-to-Gas utilises existing natural gas systems. Natural gas is widely used globally and then Power-to-Gas can be easily utilised. This technology improves also energy self-sufficiency and reduces carbon hydroxide emissions from non-renewable sources. The competition of energy sources between nations and corporations have always been and will be tight and a solution for producing own natural gas can offer a good option for buying energy. Power-to-Gas can increase the use of the renewable energy, such as solar power when the surplus energy can be stored.

The integration of Power-to-Gas to WWTP can reduce the production costs in both technologies when the by-products can be effectively utilised. WWTP uses oxygen for aeration and heat for digestion and Power-to-Gas uses carbon dioxide for methanation. Aeration costs are often the largest costs in operating costs in wastewater treatment and these might be decreased with oxygen feed from Power-to-Gas. Some WWTPs have already own biogas production and can therefore be suitable for the integration. WWTPs are usually also large facilities where the integration can be easily completed.

The economics of integrating Power-to-Gas technology to wastewater treatment is affected by numerous factors. The most important factors are WWTPs biogas production volume, SNG and electricity prices and investment costs. Power-to-Gas uses complex technology, such as the fuel cells in electrolysis have now high investment costs that are expected to decrease in the future. Electrolysis and methanation are currently expensive technologies, but it is estimated that their prices are decreasing in the future. In the calculation when the investments were decreased 4 M€ the positive cash flow was reached after 1 year in Finland (same as default), after 7 years in China (2 years earlier than default), after 10 years in Germany (2 years earlier). The investment support can effectively reduce the investment costs, now it was used 30% support.

Power-to-Gas is operated only with low electricity prices and therefore annual operating hours are little lower. Electricity costs are still the largest costs in this integration and changes in electricity price can cause variations to the profitability. In the calculation when the electricity prices were decreased to 25 €/MWh, the positive cash flow was reached after 1 year in Finland (same as default), after 1 years in China (8 years earlier than default), after 2 years in Germany (10 years earlier). The integration however receives well returns from SNG sales, oxygen and FCR-N -service. SNG price is now high when compared to electricity price, because SNG is sold for transportation. In the calculation when the SNG prices were increased by 15 €/MWh, the positive cash flow was reached after 1 year in Finland (same as default), after 7 years in China (2 years earlier than default), after 7 years in Germany (5 years earlier). FCR-N brings well incomes in Finland and in Germany cases and is very valuable for Power-to-Gas. Oxygen is also very valuable by-product that can be effectively utilised in this integration. The FCR-N may not be used with many integrations and without the FCR-incomes the profits are clearly smaller at least in Finland case and the profitability is more sensitive to other key-factor variations.

Power-to-Gas integration to wastewater treatment plant is not only supporting the implementation of renewable energies and self-sufficiency, but also economically profitable. It is good to remember that the implementation of renewable energies is a valuable action itself. In this thesis the economic studies were still based on desktop calculations and by building pilot-plants with integration, realised data from them could be available and the integration could be more examined. The topic of this thesis is very wide and includes a wide range of subjects (e.g. efficient use of FCR, the best methods to utilize the by-products) that are reasonable to study more.

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APPENDICES

Results with fixed values

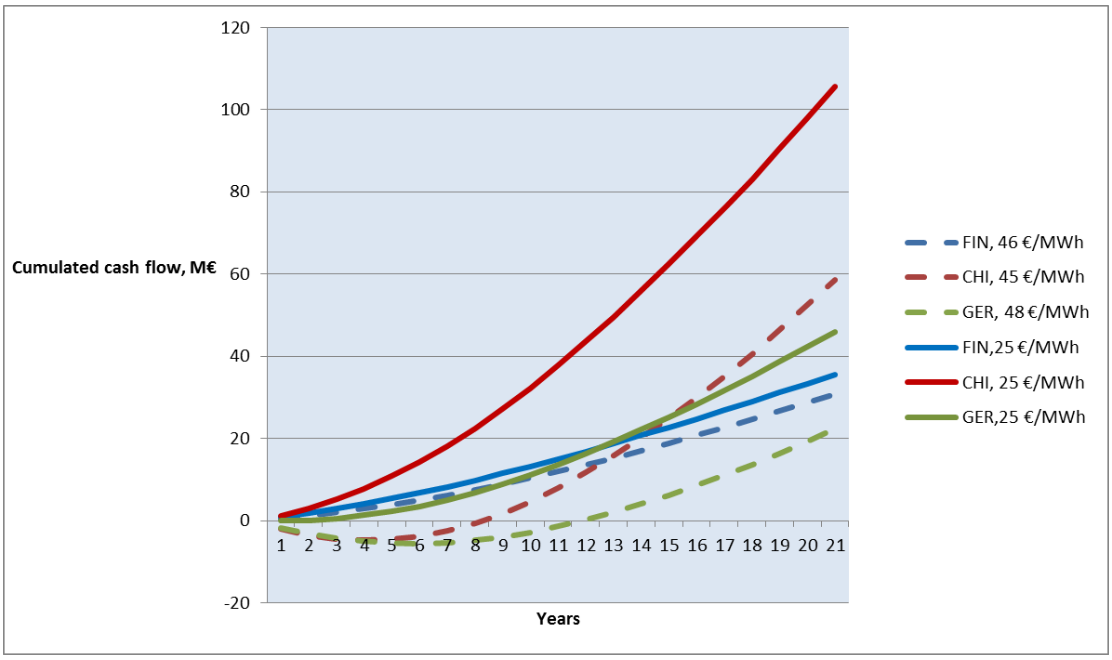


Figure 3: Results with decreased electricity price

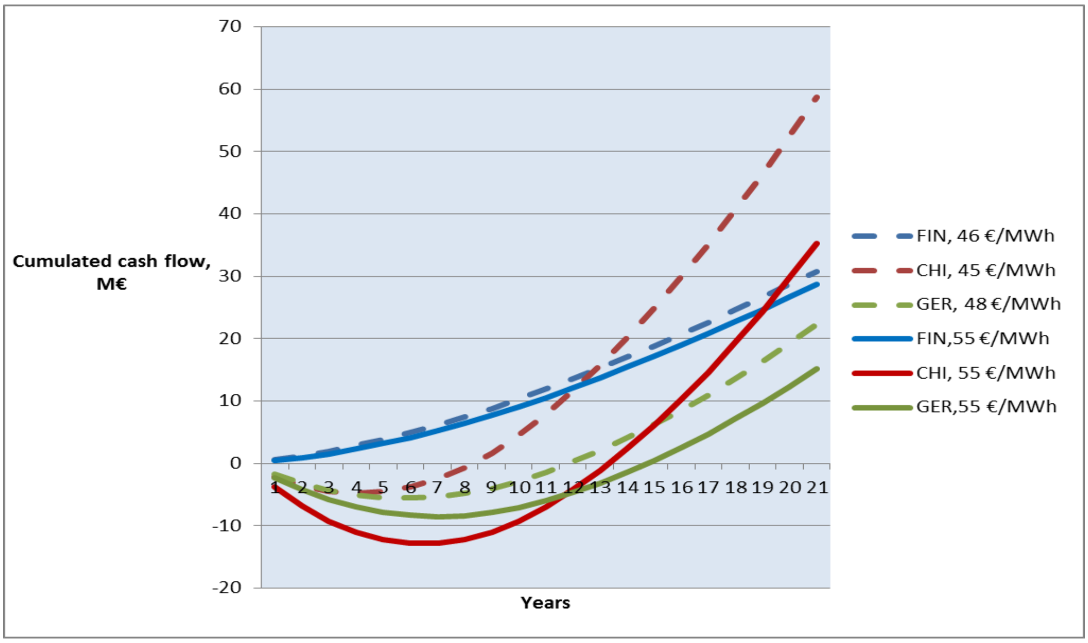


Figure 4: Results with increased electricity price

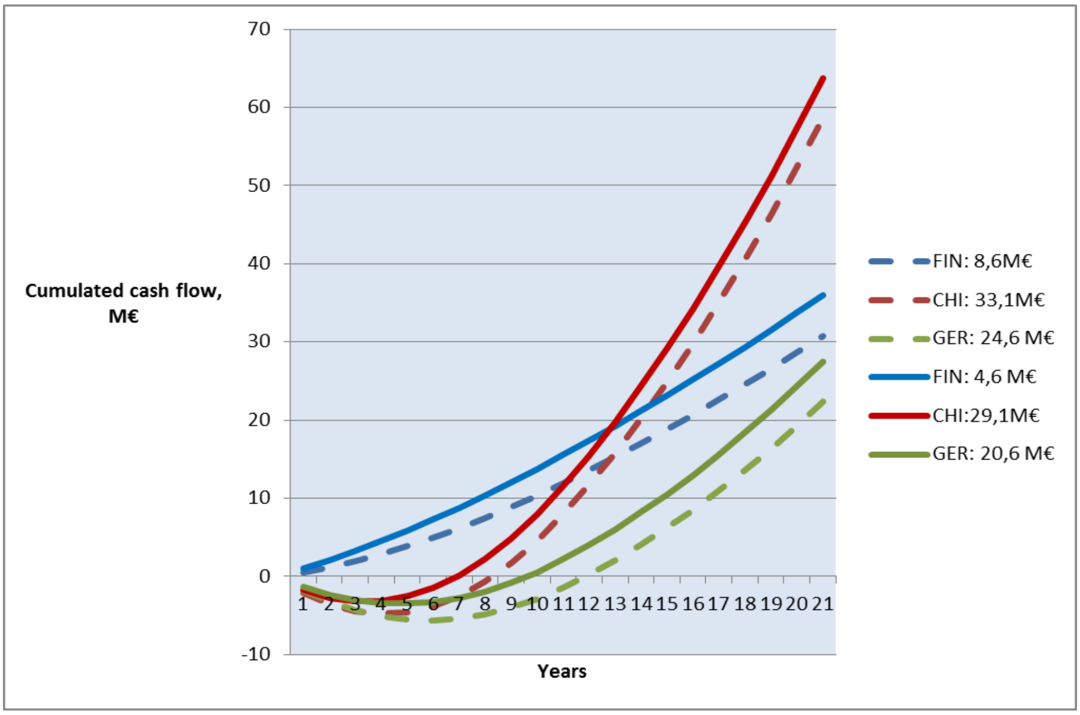


Figure 5: Results with decreased investments

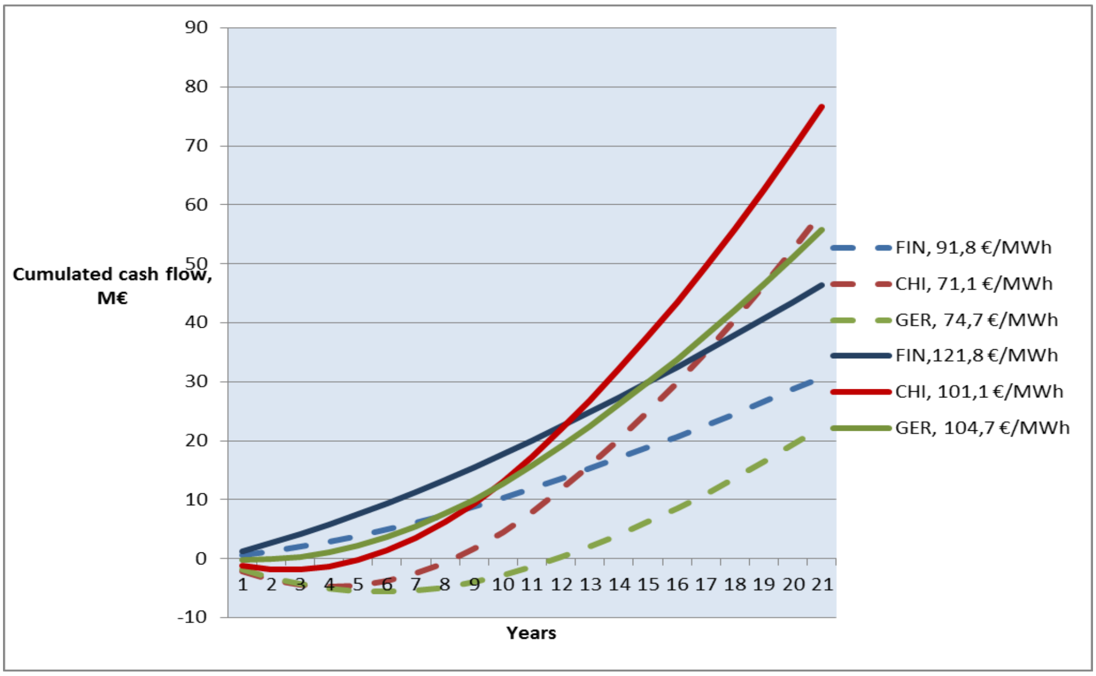
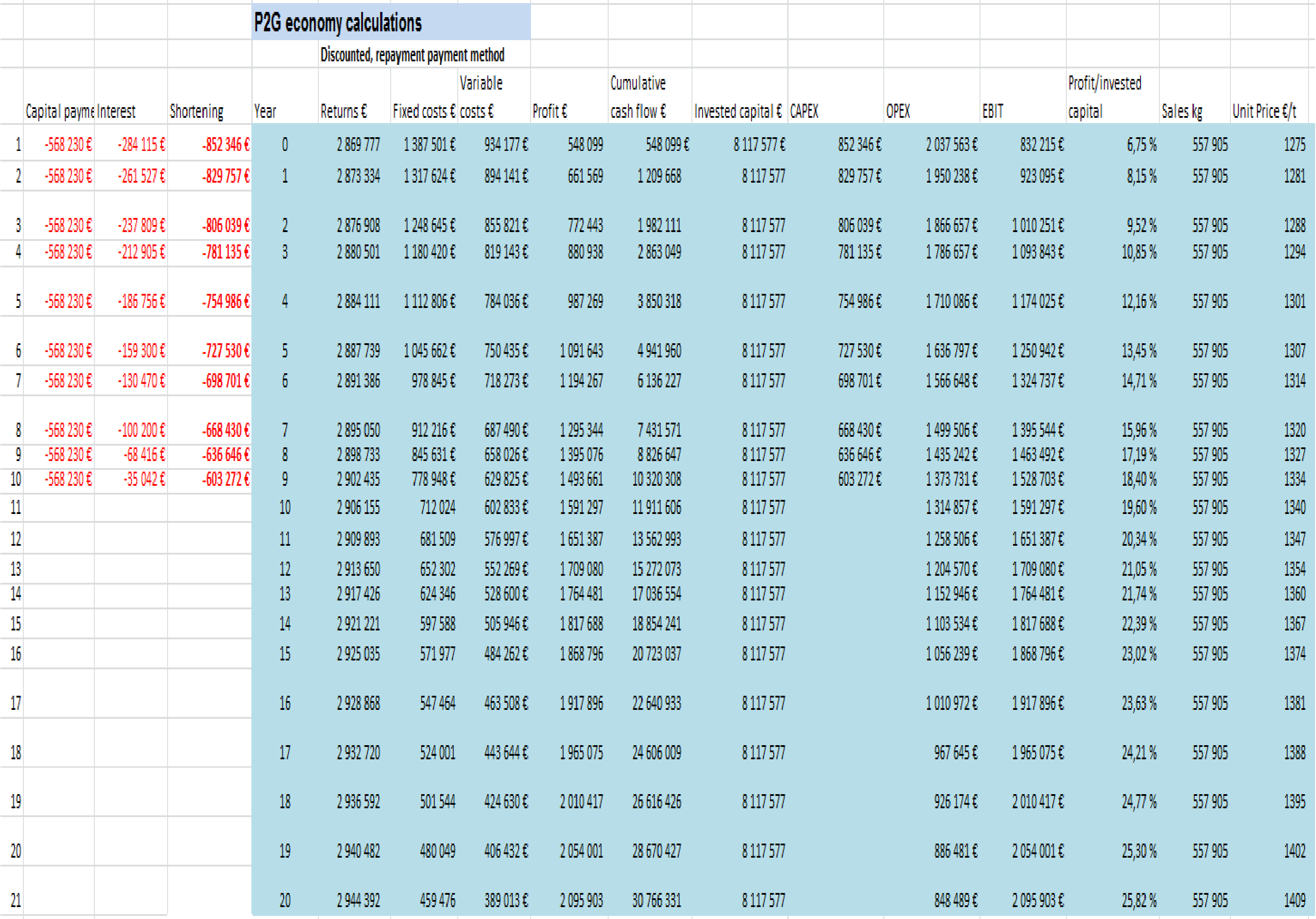


Figure 6: Results with increased SNG-price

Calculation tool



P2G economy calculations

Discounted, repayment payment method

	Capital payme	Interest	Shortening	Year	Returns €	Fixed costs €	Variable costs €	Profit €	Cumulative cash flow €	Invested capital €	CAPEX	OPEX	EBIT	Profit/invested capital	Sales kg	Unit Price €/t
1	-568 230 €	-284 115 €	-852 346 €	0	2 869 777	1 387 501 €	934 177 €	548 099	548 099 €	8 117 577 €	852 346 €	2 037 563 €	832 215 €	6,75 %	557 905	1275
2	-568 230 €	-261 527 €	-829 757 €	1	2 873 334	1 317 624 €	894 141 €	661 569	1 209 668	8 117 577	829 757 €	1 950 238 €	923 095 €	8,15 %	557 905	1281
3	-568 230 €	-237 809 €	-806 039 €	2	2 876 908	1 248 645 €	855 821 €	772 443	1 982 111	8 117 577	806 039 €	1 866 657 €	1 010 251 €	9,52 %	557 905	1288
4	-568 230 €	-212 905 €	-781 135 €	3	2 880 501	1 180 420 €	819 143 €	880 938	2 863 049	8 117 577	781 135 €	1 786 657 €	1 093 843 €	10,85 %	557 905	1294
5	-568 230 €	-186 756 €	-754 986 €	4	2 884 111	1 112 806 €	784 036 €	987 269	3 850 318	8 117 577	754 986 €	1 710 086 €	1 174 025 €	12,16 %	557 905	1301
6	-568 230 €	-159 300 €	-727 530 €	5	2 887 739	1 045 662 €	750 435 €	1 091 643	4 941 960	8 117 577	727 530 €	1 636 797 €	1 250 942 €	13,45 %	557 905	1307
7	-568 230 €	-130 470 €	-698 701 €	6	2 891 386	978 845 €	718 273 €	1 194 267	6 136 227	8 117 577	698 701 €	1 566 648 €	1 324 737 €	14,71 %	557 905	1314
8	-568 230 €	-100 200 €	-668 430 €	7	2 895 050	912 216 €	687 490 €	1 295 344	7 431 571	8 117 577	668 430 €	1 499 506 €	1 395 544 €	15,96 %	557 905	1320
9	-568 230 €	-68 416 €	-636 646 €	8	2 898 733	845 631 €	658 026 €	1 395 076	8 826 647	8 117 577	636 646 €	1 435 242 €	1 463 492 €	17,19 %	557 905	1327
10	-568 230 €	-35 042 €	-603 272 €	9	2 902 435	778 948 €	629 825 €	1 493 661	10 320 308	8 117 577	603 272 €	1 373 731 €	1 528 703 €	18,40 %	557 905	1334
11				10	2 906 155	712 024	602 833 €	1 591 297	11 911 606	8 117 577		1 314 857 €	1 591 297 €	19,60 %	557 905	1340
12				11	2 909 893	681 509	576 997 €	1 651 387	13 562 993	8 117 577		1 258 506 €	1 651 387 €	20,34 %	557 905	1347
13				12	2 913 650	652 302	552 269 €	1 709 080	15 272 073	8 117 577		1 204 570 €	1 709 080 €	21,05 %	557 905	1354
14				13	2 917 426	624 346	528 600 €	1 764 481	17 036 554	8 117 577		1 152 946 €	1 764 481 €	21,74 %	557 905	1360
15				14	2 921 221	597 588	505 946 €	1 817 688	18 854 241	8 117 577		1 103 534 €	1 817 688 €	22,39 %	557 905	1367
16				15	2 925 035	571 977	484 262 €	1 868 796	20 723 037	8 117 577		1 056 239 €	1 868 796 €	23,02 %	557 905	1374
17				16	2 928 868	547 464	463 508 €	1 917 896	22 640 933	8 117 577		1 010 972 €	1 917 896 €	23,63 %	557 905	1381
18				17	2 932 720	524 001	443 644 €	1 965 075	24 606 009	8 117 577		967 645 €	1 965 075 €	24,21 %	557 905	1388
19				18	2 936 592	501 544	424 630 €	2 010 417	26 616 426	8 117 577		926 174 €	2 010 417 €	24,77 %	557 905	1395
20				19	2 940 482	480 049	406 432 €	2 054 001	28 670 427	8 117 577		886 481 €	2 054 001 €	25,30 %	557 905	1402
21				20	2 944 392	459 476	389 013 €	2 095 903	30 766 331	8 117 577		848 489 €	2 095 903 €	25,82 %	557 905	1409

Picture 21: Picture of the calculation tool