# Heat energy usage optimization in Fertilizer producing biogas plants

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Bioenergy Systems, Master's Thesis

2022

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ABSTRACT

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74 pages, 23 figures, 14 tables

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Keywords: Biogas production, Fertilizer production, Heat demand, Thermal energy balance

Biogas is formed from the organic content of biomass by a set of microbiological processes. It is composed primarily from methane and carbon-dioxide. Cleaned and upgraded biogas can be used to replace non-renewable energy sources, for example natural gas or transport fuels. Digestate is the non-gassed matter from the biomass. Digestate contains valuable substances, for example nutrients. The most sustainable utilization method of digestate is as fertilizer. Biogas and fertilizer production contain multiple thermal processes. The thermal processes increase heat demand, but also the production rate and value of the products.

This thesis observes the heat flows and heat demand of the fertilizer producing biogas plant project draft. Additionally, multiple different heat supply technologies are introduced. The heat flows and demand are calculated based on the project draft values. From the received results the waste heat flows are observed, and possibilities for heat usage optimization are considered. Based on the heat demand, the most suitable heat supply technology is considered. Additionally, the minimal requirements for residual heat flow from other industries were identified.

It was observed that the project draft contained one remarkable waste heat flow. Other observation was the possible need for reactor cooling, as the energy balance of the reactor could go positive with warm outside temperatures. The design of the process has high impact to the heat demand, and multiple heat supply technologies exist. The process design and heat supply technology selection should be tailored initially based on the target location.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Energiatekniikka

Atro-Matti Puruskainen

**Lämmönkäytön optimointi lannoitteita tuottavassa biokaasulaitoksessa**

Energiatekniikan diplomityö

2022

74 sivua, 23 kuvaa, 14 taulukkoa

Tarkastajat: Professori Esa Vakkilainen

Tutkijatohtori Svetlana Proskurina

Ohjaaja: DI Sanna Ruuhela

Avainsanat: Biokaasutuotanto, Lannoitetuotanto, Lämmöntarve, Lämpöenergiatase

Biokaasu muodostuu biomassan orgaanisesta aineksesta mikrobiologisten prosessien seurauksena. Se koostuu pääosin metaanista ja hiilidioksidista. Puhdistettua ja jalostettua biokaasua voidaan käyttää korvaamaan uusiutumattomia energialähteitä, esimerkiksi maakaasun korvikkeena tai liikennepolttoaineena. Mädätysjäännös tarkoittaa kaasuuntumatonta ainesta biokaasun tuotannossa, joka sisältää arvokkaita aineita kuten esimerkiksi ravinteita. Ympäristöllisesti kestävin vaihtoehto on tuottaa mädätysjäännöksestä lannoitteita. Biokaasu- ja lannoitetuotanto sisältää termisiä prosesseja, jotka kasvattavat laitoksen lämmöntarvetta, mutta myös tuotantoastetta sekä lopputuotteiden arvoa.

Tämä työ tarkastelee lannoitteita tuottavan biokaasulaitoksen lämpövirtoja ja lämmön tarvetta. Lisäksi työ esittelee laitokselle soveltuvia lämmöntuotantomenetelmiä. Lämpövirrat sekä lämmön tarve ovat laskettu projektiluonnoksen pohjalta. Saatujen tuloksien pohjalta tarkastellaan prosessin sisältämiä hukkalämpövirtoja, sekä arvioidaan mahdollisuuksia lämmön käytön optimoinnista. Saadulle lämmöntarpeelle arvioidaan paras lämmöntuotantomenetelmä. Lisäksi työssä määritetään vähimmäisvaatimukset hyödynnettävälle muun teollisuuden hukkalämpövirralle.

Työn aikana projektiluonnoksesta havaittiin yksi merkittävä hukkalämpövirta. Lisäksi havaittiin mahdollinen reaktorien jäähdytystarve, sillä reaktoreiden lämpötase saattaa olla positiivinen ulkolämpötilojen lämmetessä. Laitoksen teknisillä valinnoilla on suuri vaikutus lämpötaseeseen, ja sopiviksi lämmontuotantomenetelmiksi on useita vaihtoehtoja. Optimaalisimmat tekniset valinnat ja käytettävä lämmöntuotantomenetelmä ovat tapauskohtaisia.

ACKNOWLEDGEMENTS

This Thesis was a challenging yet educating experience. The project was long and exhausting, and multiple times desperation towards the Thesis rose. However, as always, development keeps developing, and finally this project got to an end, and it is time to thank people who were along.

Firstly, I would like to thank the examiners Esa Vakkilainen and Svetlana Proskurina. The role of the examiners was not significant in this project, but the required information and refining comments were received.

Secondly, I would like to thank my colleagues who supported and provided guidance and information in the beforehand unfamiliar topic. Special acknowledgements I would like to point towards Jussi and Mari, who not only attended to the selection of the topic, but also followed the progress and provided opinions and comments when asked.

The biggest thanks go to the Thesis supervisor Sanna Ruuhela. The received effort from you was irreplaceable, all the way from the comments and opinions to the mental support and faith in the process. Additionally, you set the standards higher than what I would have put initially, and now afterwards I can be somewhat proud of the result.

Finally, I would like to thank the background groups. Thanks to my parents, who saw the progress in the Thesis while I was blind to my own work. Thank you, my friends, who provided laughs and activities when I was struggling with the process. The last and the most special thanks I would like to point to Elmo-dog and Elisa. The amount of effort in the everyday life was priceless, all the way from listening my frustration to doing my chores. Also, the breaks and walks outside refreshed my mindset, and the happy tail-wagging provided some happy moments in the desperate mind.

Thanks for everybody!

11.11.2022 Espoo

Atro-Matti Puruskainen

SYMBOLS AND ABBREVIATIONS

Roman characters

| | | |
|---|---|---|
| $h$ | enthalpy | [kJ / kg] |
| Q | Energy flow | [kW] |
| $q_m$ | mass flow rate | [kg/h] |
| C | specific heat capacity | [kJ / kg K] |
| $A$ | area | [$m^2$] |
| $T$ | temperature | [ºC, K] |
| $U$ | heat transfer coefficient | [W / $m^2$ K] |
| $y$ | methane yield | [$m^3$ / h] |
| $X$ | vapour content | [ % ] |
| x | fraction | |

Greek characters

| | | |
|---|---|---|
| λ | latent heat of evaporation | [kJ/kg] |
| $\eta$ | efficiency | [%] |

Subscripts

| | |
|---|---|
| 0 | outlet |
| 1 | inlet |

Abbreviations

| | |
|---|---|
| TS | Total solids |
| VS | Volatile solids |
| MVR | Mechanized vapor recompression (evaporator) |

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# 1 Introduction

Biogas is a versatile form of renewable energy. Biogas can be used for example to replace natural gas in the gas grid or gasoline as vehicle fuel (Suomen biokaasuyhdistys ry. 2015 p. 17). Biogas production volatizes the volatile organic carbon from the feedstock through a set of microbiological processes (Speight 2019 p. 4 - 5). The non-volatized fraction from biogas production, the digestate, contains valuable substances, for example nutrients. The digestate can be refined to organic fertilizers, which can be used to replace non-organic fertilizer usage. (Suomen biokaasuyhdistys ry. 2015 p. 94, 114)

The biogas and fertilizer production contains thermal processes. In the biogas industry the biogas yield and production rate can be maximized with suitable and stable operating temperature. The microbiological activity increases at the mesophilic and thermophilic temperatures, which results in faster biogas production. The digestate treatment has a variety of thermal treatment methods, which aim to concentrate the product, recover water back to the process, or generate specific fertilizing product. (IEA Bioenergy 2013 p. 268)

Well planned and executed heat supply and heat usage increases the efficiency of the plant by reducing the heat demand and heat losses. The target in the fertilizer producing biogas plants is to obtain energy efficient production with high quality products. This thesis aims to optimize the heat usage in fertilizer producing biogas plant.

## 1.1 Background and aim of the thesis

This thesis is done for a company operating in the biogas and fertilizer industry. The purpose of the thesis is to investigate the heat flows in the fertilizer producing biogas plant and optimize the heat energy usage in the plant processes. Proper heat usage reduces the operating costs and increases the overall efficiency of the process. This thesis includes the determination of the heat demands and temperature levels in the different subprocesses, and selection for the most suitable heat supply technology.

The aim of thesis is to study the heat flows and heat demands in the fertilizer producing biogas plant. The research questions regarding the heat flows are:

*RQ1: Does the process contain any recoverable waste heat flows?*

*RQ2: How the heat flows can be optimized?*

The research questions regarding the heat demands are:

*RQ3: What are the minimal requirements for the heat supply?*

*RQ4: What is the most suitable heat supply technology?*

The topic area of this thesis is at the energy balance of fertilizer producing biogas plant. Several studies were found concerning the same topic area, for example Grim et al. (2014) have studied the heat demand of biogas plant, and Li et al. (2015) have studied the energy balance of the biogas plant. Both studies consider only biogas production processes, but the fertilizer production was not considered further. The fertilizer production is the most sustainable alternative for digestate management, and therefore the heat demands in the fertilizer production subprocesses should be investigated.

## 1.2 Conducting the thesis

This thesis approaches the subject by presenting the formation and production of biogas in the section 2.1. The fertilizer production and other options for digestate management are presented in section 2.2. In third chapter is presented the thermal processes, equipment, and heat calculations. Latter part of the chapter 3 considers alternative heat supply technologies that could be applied to fertilizer producing biogas plant. In chapter 4 is calculated the heat demand and initial heat flows for a real planned fertilizer producing biogas plant. In the chapter 5 is reviewed the results and selected the most suitable heat supply technologies in four scenarios.

The thesis observes the biogas and fertilizer production from the energy consumption point of view. The alternative options in digestate treatment and used equipment are done based on the literature. Heat supply technologies consider the options provided from the company, complemented with typical heat supply technologies in other industries. The calculations are done based on the methods found on literature, such as Luostarinen (2013) and Hackett (2018). The values for the calculation are received from the company.

# 2 Fertilizer producing biogas plant processes

In this thesis, the description for fertilizer producing biogas plant is the following: it produces biogas from the volatile organic substances in the feedstock and fertilizers from the remaining non-volatile matter. The process is fueled with biomass.

In this chapter is first presented the formation of biogas and the characteristics and requirements for industrial biogas production. The first section presents the microbiological processes in biogas generation. Second section introduces the variety and characteristics of the feedstock alternatives. Third and fourth sections present alternative selections for biogas production design, and fifth section contains information about the production itself. Last section presents the treatment requirements for the produced biogas.

Second chapter considers the digestate treatment. The first section presents the alternative options for digestate utilization. Second section presents the digestate treatment processes and typical used equipment.

## 2.1 Biogas production and characteristics

Biogas is gas mixture which is produced by series of microbiological processes and where the main components are methane ($CH_4$) and carbon-dioxide ($CO_2$). Biogas is generated from the organic substances of renewable biomass, which makes biogas carbon-neutral energy source. (Speight 2019 p. 4 - 5)

### 2.1.1 Biogas formation

Biogas formation is a set of four microbiological processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The processes degrade the organic material of the feedstock, resulting $CH_4$ and $CO_2$. The different microbiological processes are done by different types of organisms, which some have high selection of suitable alternatives, and therefore the conditions of the biogas formation vary depending on the organisms used. (GIZ 2010 p. 21) The $CH_4$-producing methanogenic bacteria can be found in the nature, but in controlled environment the biogas production can be maximized and gathered for consumption (Speight 2019 p. 8 - 9).

The first phase in the biogas formation is hydrolysis, which is caused by the hydrolytic bacteria. The hydrolytic bacteria generate enzymes that decompose and to dissolve the strict compounds of carbohydrates, proteins, and fats. The enzymes affect the molecules by breaking them into smaller products, for example proteins dissolve to amino acids, carbohydrates dissolve to sugars, and fats dissolve to alcohols or fatty acids. The hydrolytic bacteria are permissive for changing conditions, and do not cause any remarkable requirements to the process. (Suomen biokaasuyhdistys ry. 2015, p. 61)

The second phase in the biogas formation is called the acidogenesis, or alternatively fermentation, which is done by the fermentative bacteria. In acidogenesis the fermentative bacteria process the sugars, amino acids, and alcohols to volatile fatty acids (Suomen biokaasuyhdistys ry. 2015 p. 62). During acidogenesis is also formed hydrogen, $CO_2$, and some alcohols. The accurate composition of the generated products in the fermentation phase is very volatile and is dependent on the used microbe species and surrounding conditions (GIZ 2010 p. 21). Fermentative bacteria have wide selection of organisms, and suitable species can be found for different conditions (Suomen biokaasuyhdistys ry. 2015 p. 62).

Third phase in the biogas formation is called the acetogenesis, where the acetogenic bacteria process volatile fatty acids to acetic acids, hydrogen, and $CO_2$. Acetogenic bacteria cause anaerobic oxidation to the matter by using oxidated compounds such as nitrate, sulphate, and carbonate. (Suomen biokaasuyhdistys ry. 2015 p. 62) The performance of the acetogenic bacteria is heavily inhibited with too high hydrogen content, but the hydrogen balance is reached by keeping the acetogenic bacteria close to the hydrogen consuming bacteria, methanogenic bacteria, which produce the next phase (GIZ 2010 p. 21).

The last phase of the biogas formation is methanogenesis where the methanogenic bacteria and archaea convert the products from acetogenic phase (acetic acids, hydrogen, and $CO_2$) to bio-$CH_4$ (GIZ 2010 p. 22). The methanogens can be divided to two categories depending on the used raw material, to the hydrogen-consuming hydrogenotrophic organisms and to the acetic acids consuming acetoclastic organisms, from which the latter are considered to produce 70 % of the generated $CH_4$ (Suomen biokaasuyhdistys ry. 2015 p. 62). Methanogenic organisms die if they are affected with oxygen, for which they require anaerobic conditions. The temperature level and pH of the feedstock also affect to the activity of methanogens. (GIZ 2010 p. 22)

### 2.1.2 Feedstock and key characteristics

Feedstock selection is important in biogas production. Biogas production process can utilize any biomass which contains carbohydrates, proteins, fats, cellulose, and hemicellulose as main components. Only biomass types with high lignin-content, for example woody products, are not suitable for biogas production, because the microbes are not capable to dissolve lignin compounds. (Speight 2019 p. 99) The feedstock types can be divided to three categories which are waste fractions, industrial by-products, and energy crops (IEA Bioenergy 2013 p. 52 – 53). In the Table 1 is presented the different types of waste flow in each category.

Table 1. Typical feedstock in biogas production (IEA Bioenergy 2013 p. 52 - 53)

| Waste fractions | Industrial by-products | Energy crops |
|---|---|---|
| Municipal solid waste | Distillery waste | Grass |
| Biowaste (household) | Slaughterhouse waste | Beet (e.g. Sugar-beet) |
| Kitchen waste | Agricultural harvest and manure | Corn |
| Gardening waste | | |
| Sewage sludge | | |

Different feedstock types have different characteristics that affect the production. The key characteristics of the feedstock are biogas yield, $CH_4$ content, retention time, total solids (TS), and volatile solids (VS). Total solids present the solid content of the feedstock at the receiving, and volatile solids of total solids present the share, that can be gasified in the process. Biogas yield presents the amount of produced biogas and is presented in relation to volatile solids. $CH_4$ content presents the share of $CH_4$ in the produced biogas. Retention time is the timespan in which the microbiological processes are done, and the potential biogas yield is achieved. In the Table 2 is presented the key characteristics for several different feedstock. (Dahiya 2014 p. 289 - 291)

Table 2. Key characteristics of different feedstock (edited from Dahiya 2014 p. 290 - 291)

| Feedstock | Total solids (TS %) | Volatile solids (VS/TS %) | Biogas yield ($m^3/kg_{vs}$) | Retention time (d) | $CH_4$ content (%) |
|---|---|---|---|---|---|
| Cow slurry | 5-12 | 75-85 | 0,20-0,30 | 20-30 | 55-75 |
| Chicken slurry | 10-30 | 70-80 | 0,35-0,60 | >30 | 60-80 |
| Straw | 70 | 90 | 0,35-0,45 | 20-50 | No data |
| Grass | 20-25 | 90 | 0,55 | 10 | No data |
| Food remains | 10 | 80 | 0,50-0,60 | 10-20 | 70-80 |

The presented values in the table are typical values for each feedstock. Different values can be achieved with different feedstock gathering methods and different selections in the process. Other considerable characteristics in feedstock are C/N (Carbon/Nitrogen) ratio and if the feedstock contains pathogens. The ideal C/N ratio is 20-30, lower and higher values affect to the microbes. (Speight 2019 p. 101) Pathogens infect micro-organisms and restricts digestate management (Suomen biokaasuyhdistys ry. 2015).

### 2.1.3 Temperature levels in biogas production

The temperature levels of the processes correspond with the activity of the $CH_4$ producing methanogens. The biogas production processes can be categorized to three based on the used temperature level. The first category is psychrophilic process, where the temperature is under 20 °C. The second category is mesophilic process, which operates at temperature 30 – 38 °C. The third category is thermophilic process, which operates at 50 – 57 °C. (Speight 2019 p. 82 - 83) The activity at different temperatures is presented in the Figure 1.

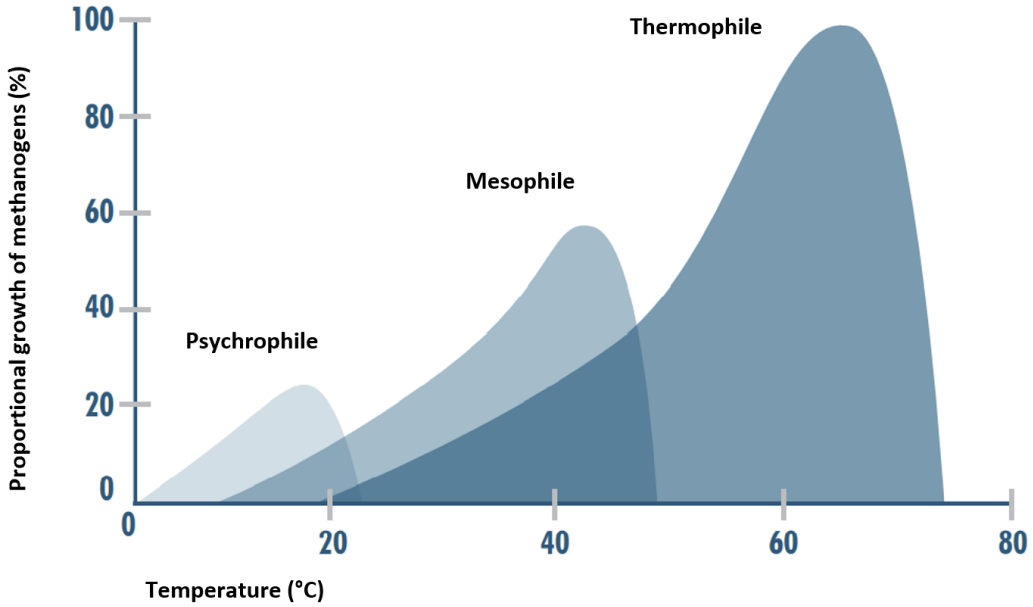



Figure 1. Activity of methanogens in relation to temperature. (Edited from Suomen biokaasuyhdistys ry. 2015 p. 64)

The stability of the temperature is more important than the temperature level. The methanogens are vulnerable to fluctuation in the temperature, and 2 °C rapid change can harm the microbe population. (Suomen biokaasuyhdistys ry. 2015 p. 64) The temperature level can be adjusted to other levels than the mentioned ranges, if the change is done slowly and microbes get time to adjust (Speight 2019 p. 82).

Thermophilic processes have higher activity, which results in higher $CH_4$ yield. Thermophilic processes are also faster, requiring lower retention times. On the other hand, thermophilic methanogens are more vulnerable to rapid changes in temperature, and thermophilic processes have higher energy demand. The number of different species of methanogens operating at mesophilic temperatures is also higher, for which the mesophilic processes are faster to adjust new temperature levels and generally more stable. (Speight 2019 p. 83 - 84)

### 2.1.4 Anaerobic digestion types

The anaerobic digestion processes can be divided to wet digestion and dry digestion. Wet digestion process is pumpable and has TS under 15 %. Dry digestion has TS 20-40 %. The feedstock can be diluted with additional process water to achieve the selected TS. Wet digestion is more common technology, as it is easier to operate and ensure the releasing of

the biogas. Dry digestion requires smaller reactors due to higher loading rate of feedstock, but the transporting of substrate inside the plant and mixing inside the reactor requires more effort. (Suomen biokaasuyhdistys ry. 2015 p. 82 - 83)

The digestion process can be done in the same reactor as single-stage digestion, or the process can be divided to two-stage digestion. In the single-stage digestion, all the biogas formation phases take place in the same reactor. In the two-stage digestion, the hydrolysis and acidogenesis are done in separate reactor, while acetogenesis and methanogenesis are done in separate reactor. Single-stage digestion is easier to operate and requires less investment costs, but two-stage digestion enables more accurate operation and possibility to adjust the substrate corresponding the needs of different microbes, such as pH adjustment, different temperature levels, or optimized retention times. (IEA Bioenergy 2013 p. 196)

### 2.1.5 Feedstock pretreatment and biogas production

The biogas production starts with the pretreatment of the feedstock. Proper pretreatment reduces the retention time of digestion process, and results in a faster biogas yield. Pretreatment methods can be categorized to biological, chemical, mechanical, and thermal processes. (Speight 2019 p. 109)

The different pretreatment processes have different approaches to the feedstock. Biological and chemical pretreatment aim to increase the solubility of the feedstock by breaking the hard-breaking compounds. Biological pretreatment uses enzymes and chemical pretreatment uses for example acids. Mechanical pretreatment aims to reduce the particle size of the feedstock, resulting in increased surface area. The microbes have larger access to the feedstock, which results in improved anaerobic digestion. Thermal pretreatment has main target in eliminating the pathogens, but also reducing the viscosity of the feedstock. The need for pretreatment varies depending on the used feedstock. (Speight 2019 p. 109 - 110) After the required pretreatment processes are done, the feedstock must be diluted to the targeted TS or corresponding amount of dilution water must be fed to process (Suomen biokaasuyhdistys ry. 2015 p. 83).

After the pretreatment, the diluted feedstock (substrate in this work) is fed to the digestion unit, where the microbiological processes take place. The digestion unit is an insulated and airtight tank, which has implemented heating system to maintain operating temperature. The

heat can be supplied with either heating coils, or external water circulation system. The digestion unit contains also substrate mixing system, and inlet, outlet, overflow, and overpressure valves. (Speight 2019 p. 88 - 89) Digestion unit also contains either external gas storage, or gas membrane roof as internal gas storage (IEA Bioenergy 2013 p. 202 - 203). Similar digestion units can be used in one-stage digestion, or in two-stage digestion's first and second stage.

The substrate is maintained and stirred in the digestion unit based on the feedstock's estimated retention time. The digestion units produce biogas from the volatile organic content, and the remaining non-volatized matter is called digestate. (IEA Bioenergy 2013 p. 196 - 198) In two-stage digestion the digestate from first digestion unit can be treated before feeding to the second digestion unit (Speight 2019 p. 93). Biogas require further treatment before consumption, which is presented in following section. The digestate contain valuable substances, that can be recovered, and the digestate treatment is presented in section 2.2.

### 2.1.6 Biogas impurities, treatment, and upgrading

The vaporized fraction from digestion unit needs to be treated before consumption. The fraction contains $CH_4$ and $CO_2$, but also vaporized water (H2O), impurities such as hydrogen sulphides and ammonia, and small organic particles (IEA Bioenergy 2013 p. 329)) Unwanted substances in the biogas can cause corrosion, toxic emissions, and wearing in equipment, for which they need to be removed (Speight 2019 p. 247). The most critical substances to be cleaned are hydrogen sulphides, water, and halogenated compounds. Hydrogen sulphides together with water generate sulphuric acid, which is highly corrosive. Water can react with another substances, cause corrosion alone, and reduces the heating value of biogas. Halogenated compounds can cause corrosion and acidification in the combustion process. The need for further cleaning depends on the purpose of end-use. (IEA Bioenergy 2013 p. 329 - 330)

Biogas cleaning technologies are for example adsorption, absorption, addition of different chemicals or substances, filtering, and cooling (IEA Bioenergy 2013 p. 335 - 337). Hydrogen sulphate removal technologies are for example adsorption, absorption, and chemical treatment. Water removal can be done with for example absorption, adsorption, and cooling. (Speight 2019 p. 254 - 255) The removal technologies for halogenic compounds are adsorption, absorption, and cooling (Suomen biokaasuyhdistys ry. 2015 p. 131). Selected

cleaning technology depends on the composition of the produced raw biogas, and the end-use method (Speight 2019 p. 247).

The cleaned biogas is composed of $CH_4$ and $CO_2$ with only small traces of other compounds. $CO_2$ is inert gas which does not have heating value, but neither is corrosive, and therefore not necessary to remove. (Suomen biokaasuyhdistys ry. 2015 p. 131) The cleaned biogas can be combusted in power generation plants, but it can be treated further (Speight 2019 p. 303).

The upgrading of biogas means increasing the $CH_4$-content by removing the inert gases ($CO_2$ and N2 for example) from the biogas. Upgraded biogas can be injected to the gas grid, transformed to transporting fuels, or transported in higher energy density to save logistical costs. Some upgrading technologies for biogas are pressure swing adsorption (PSA), water scrubbing, physical and chemical absorption, membrane technologies, and cryogenic technology. (IEA Bioenergy 2013 p. 333, 339) The upgraded biogas has different quality demands, for example vehicle fuel production requires pressuring the biogas to 200 bar (Speight 2019).

## 2.2 Digestate Management

Digestate means the non-volatized matter after the digestion unit. As stated in the previous section, the anaerobic digestion process volatizes carbon and hydrogen content from the substrate, but other compounds, such as nutrients, remain in the digestate. Utilisation of the digestate increases the sustainability of the biogas plant. (IEA Bioenergy 2013 p. 268) Key value nutrients in the digestate are nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg). (Deng et al. 2020 p. 320) Another key characteristic of digestate is purity, for example heavy metal content or impure particles such for example glass, which can cause restrictions in digestate utilisation. (IEA Bioenergy 2013 p. 268) The composition of the digestate is mostly water, as part of the volatile solid content is volatized to biogas (see Table 2).

The digestate treatment methods depend on the used feedstock and end-use, but alternative targets are to concentrate the digestate, purify the water, or create commercial products (IEA Bioenergy 2013 p. 268). This section presents the typical digestate end-products and treatment technologies.

### 2.2.1 Digestate utilization

The most sustainable digestate utilization method is as a fertilizer. (IEA Bioenergy 2013 p. 268) Alternative fertilizer types are for example base fertilizers, topdressing, soil improvers, and further processed fertilizers, for example composted pellets (Deng et al. 2020 p. 329 - 350). If the digestate contains impurities (heavy metals, pathogens, impure particles such as glass), the digestate can be utilized as a land cover. (IEA Bioenergy 2013 p. 268) The digestate can be also utilized in other industries, for example as a raw material in construction industry and as energy source in combustion. The digestate can also be utilized as a feed for animals, for example to eels or earthworms. (Deng et al. 2020 p. 329 - 350) This report considers only fertilizer and soil improver production.

Most commonly the digestion treatment starts with solid-liquid separation, which divides the digestate to liquid fraction and solid fraction (Deng et al. 2020 p. 319, Suomen biokaasuyhdistys ry. 2015 p. 99 - 100). Solid-liquid separation is presented later in section 2.2.2. Both separated fractions can be utilized directly as a fertilizer or treated further to for example commercial fertilizing products (Deng et al. 2020 p. 329 - 350). The two most used solid fraction treatment methods are composting and drying (IEA Bioenergy 2013 p. 287 - 288). They are presented more accurately in the section 2.2.2. The liquid fraction can be utilized directly as a fertilizer, or treated further, for example concentrating the fraction by reducing the water content, which can be returned to the process (IEA Bioenergy 2013 p. 288). The most common liquid fraction treatment technologies are evaporation, stripping, and membranes (Suomen biokaasuyhdistys ry. 2015 p. 102). The technologies are presented more accurately in the section 2.2.2.

### 2.2.2 Subprocesses and digestate treatment equipment

The raw digestate can be used directly as a fertilizer, but the large volume causes significant costs to farmers, which is why the digestate is usually treated. (IEA Bioenergy 2013 p. 268) The digestate treatment processes and used equipment vary depending on the type of digestate and the targeted end-product. This section introduces the typical subprocesses in the digestate treatment and the equipment used for the subprocess. The following Figure 2 presents the chronological order for the digestate treatment processes.

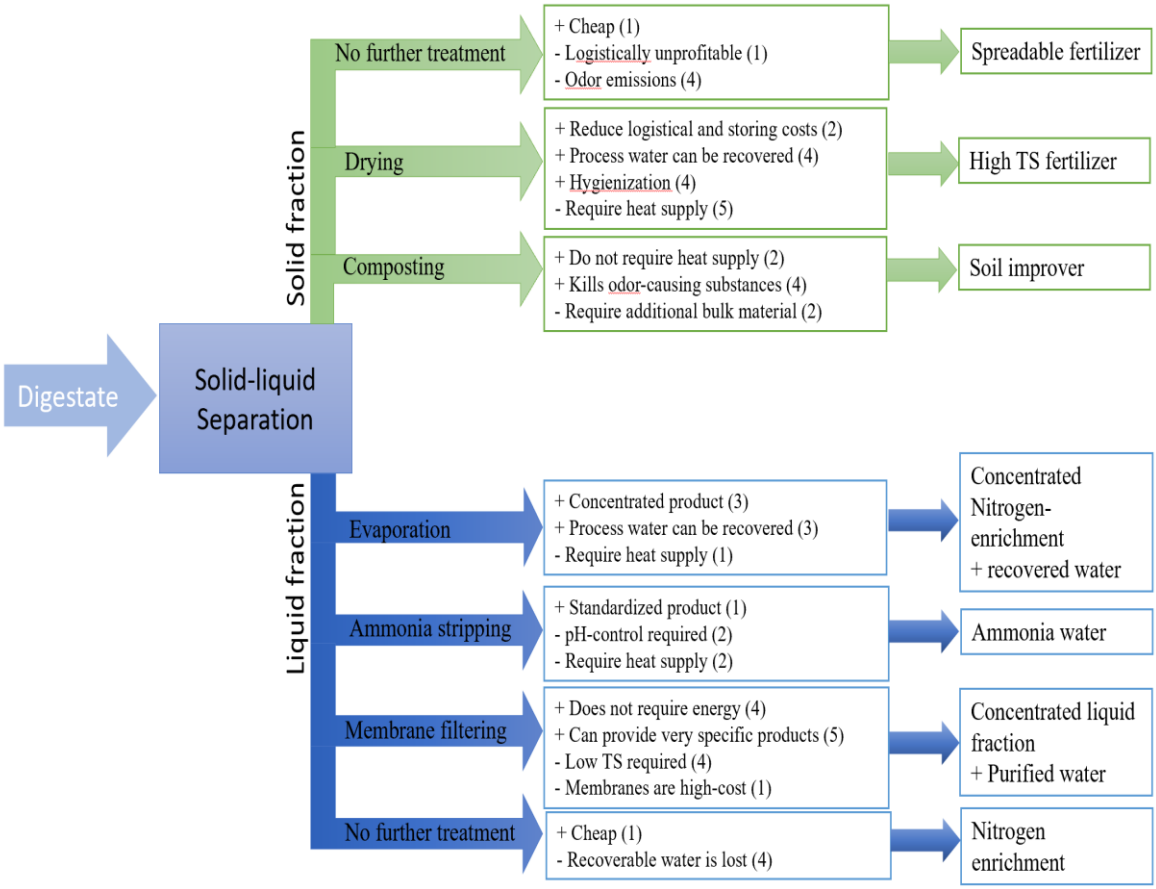



Figure 2. Digestate treatment methods and end-products. (1: IEA Bioenergy 2013, 2: Suomen biokaasuyhdistys ry. 2015, 3: Minton 1986, 4: GIZ 2010, 5: De Haan A. B. and Bosch 2013)

## Mechanical solid-liquid separation

Mechanical solid-liquid separation is the most common treatment process for raw digestate (Deng et al. 2020 p. 319). The solid-liquid separation divides the digestate to two fractions, dry and liquid fraction. The targets in solid-liquid separation are to create concentrated (in total solid content) fraction for digestate utilization and return water to process (Suomen biokaasuyhdistys ry. 2015 p. 99 - 100). The main target in the solid-liquid separation is to reduce the water content of digestate, which lowers the storing, transporting, and digestate handling costs. The separation also shifts majority of the phosphorus to solid fraction, and majority of nitrogen to liquid fraction. The mechanical separation shifts 80 – 90 % of the raw digestate to liquid fraction containing around 70 % of the nitrogen. The solid fraction contains 50 – 60 % of total solids in raw digestate, and around 60 % of the phosphorus. (IEA Bioenergy 2013 p. 282 - 285)

The most cost-effective and mature technologies for solid-liquid separation of the raw digestate are centrifuges and screw presses (IEA Bioenergy 2013 p. 282). Centrifuges

separate the fractions by weight difference while screw presses use particle size difference (Suomen biokaasuyhdistys ry. 2015 p. 101). The screw presses are popular technology in applications that use energy crops or other high-fibrous feedstock, while centrifuges are used more in low-fibrous, for example manure feedstock, applications (IEA Bioenergy 2013 p. 282). The centrifuges can achieve liquid fraction with very low TS, while screw presses provide solid fraction with higher TS (De Haan A. B. and Bosch H. 2013 p. 252 – 253, Suomen biokaasuyhdistys ry. 2015 p. 102). Screw pressing is also cheaper technology and requires less electricity supply (IEA Bioenergy 2013 p. 282).

Ammonia stripping

The aim of ammonia stripping is to remove nitrogen from the liquid fraction. The ammonia removal is necessary to either recover nutrients, or to reduce the nitrogen ratio in the process water, which could inhibit the microbial processes. (IEA Bioenergy 2013 p. 280, Suomen biokaasuyhdistys ry. 2015 p. 68) Ammonia stripping also provides standardized nitrogen fertilizer (IEA Bioenergy 2013 p. 288)

In ammonia stripping the evaporable ammonia is evaporated from the liquid fraction to a separate fraction based on the different vaporisation temperatures (Suomen biokaasuyhdistys ry. 2015 p. 104). The ammonia in liquid fraction is either as evaporable free ammonia (NH3) or as non-evaporable ammonium ions ($NH^+_4$). The ammonia-water reaction is equated as following

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \quad (1)$$

(Liu et al. 2014)

The management of the form can be adjusted with pH- and temperature-control. The share of free ammonia is increased with increased temperature and pH. Patoczka and Wilson (1984) have presented a correlation for the effect of pH and temperature to the percent of ammonia in undissociated form, which is the following equation

$$P = \frac{1}{1 + 10^{10.06 - pH - 0{,}0327 * t}} \quad (2)$$

Where P The percentage of free evaporable ammonia

t Temperature of the substrate, °C

pH pH value of the substrate

The equation 2 is valid in the typical wastewater temperatures (0 – 25 °C). In the Figure *3* is presented according to the equation 2 the effect of pH change for several different temperatures. (Patoczka and Wilson 1984)

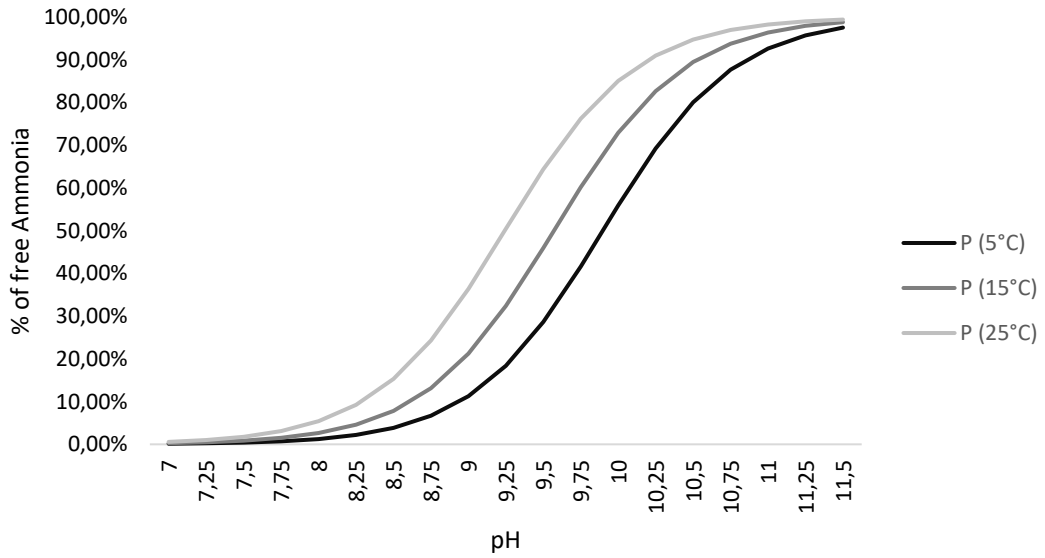



Figure 3. The share of free ammonia in correlation to pH and temperature (Patoczka and Wilson 1984)

The main equipment in the stripper is for example a packed column, where the nitrogen is removed through evaporation. The heating medium can be either heated air (air stripping) or steam (steam stripping). (Nitsche and Gbadamosi 2017 p. 279)

In the air stripper, the heated air is injected directly to the column where it evaporates ammonia and water. The vaporized fraction is removed from the column, and either condensed to ammonia water or transformed for example to ammonia sulphate or struvite in a separate scrubber-column. (Suomen biokaasuyhdistys ry. 2015 p. 104, Liu et al. 2014) The nitrogen concentration of the end-product in scrubber-technology is depending on the product around 10 %, while the condenser can provide ammonia water with 5 % nitrogen concentration. The ammonia-removal rate in air stripping is around 80 – 95 %. Ammonia removal rate can be increased with higher air flow. (Suomen biokaasuyhdistys ry. 2015 p. 104 - 105) In the Figure *4* is presented the air stripping system producing ammonium sulphate.

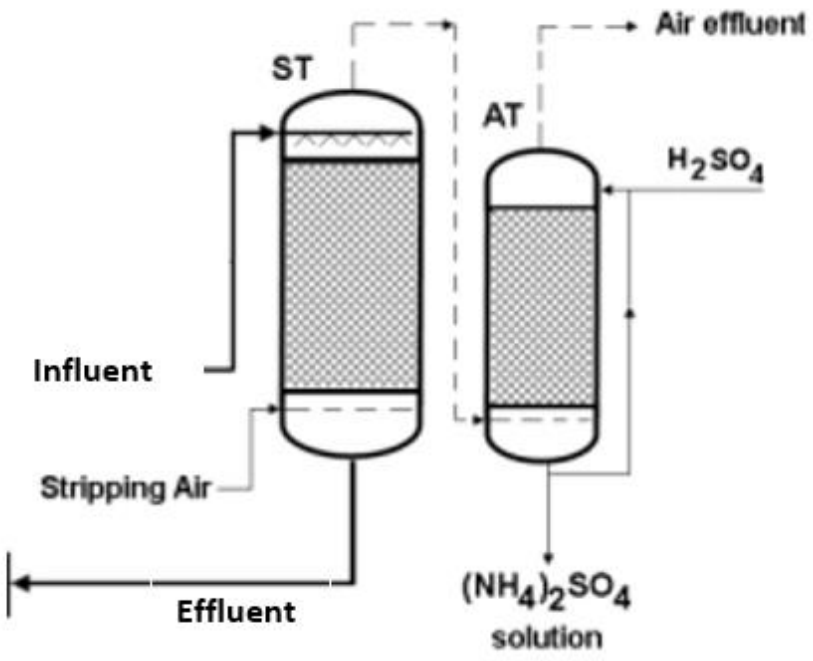



Figure 4. Air stripping system with ammonium sulphate production. ST = Stripping tower, AT = Absorption tower. (Capodaglio et al. 2015)

The steam stripper can operate either by injecting external steam to the column, or by evaporating the water from the feed through reboiler. The reboiler technology causes more calcification and fouling than the direct injection, but it does not require external steam. The vaporized fraction is removed from the column and fed to separate cooler where the fraction is condensed to ammonia water. (Nitsche and Gbadamosi 2017, p. 262, 282-284) In the following Figure *5* is presented the flow chart of steam stripper with direct steam injection.

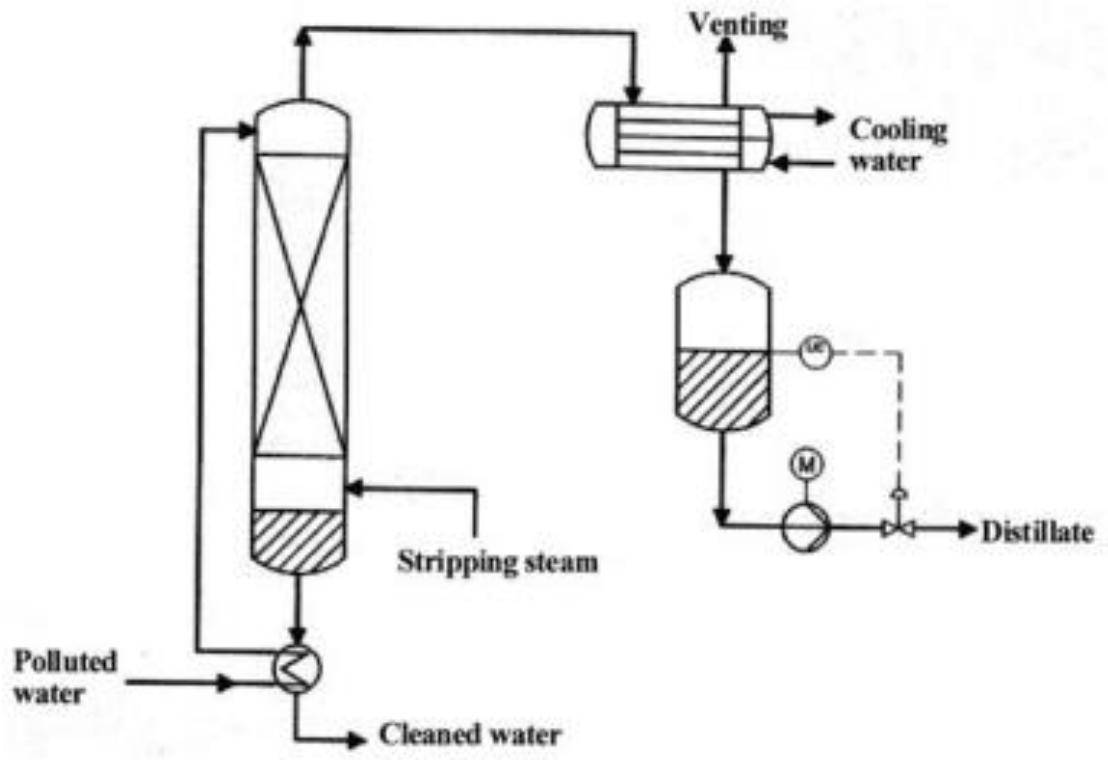



Figure 5. Steam stripper flow diagram (Nitsche and Gbadamosi 2017 p. 279)

The steam stripping can produce ammonia water with nitrogen concentration of 25 %, and ammonia removal rate of 95 %. The operating temperature of the steam stripper is around 100 °C. (Nitsche and Gbadamosi 2017, p. 262, 282-284)

Evaporation

Evaporation process separates fractions from the solution in the form of vapor, generating vaporized fraction and concentrated fraction. In majority of evaporation applications, the evaporated solvent is water. The evaporation technology is common in all types of industries, and the selection of evaporation types is wide. The purpose of evaporation can be either to recover water or other substances from the solvent or to create concentrated product by evaporating water or other substances. (Minton 1986 p. 1 - 2)

In the biogas plants the purpose of the evaporation is primarily to concentrate the nutrient-ratio in the liquid fraction and recover the evaporated water to reduce the water supply in the process (IEA Bioenergy 2013 p. 290). Controversary to the stripping process, in the evaporation process the ammonia is often targeted to stay in the liquid fraction, and the pH control is done to lower the pH value and increase the share of non-evaporable ammonium-ions (GIZ 2010 p. 201).

The evaporation process is very energy-intensive and is often applied in the biogas plants if surplus heat is available, and typically the evaporation is only partial instead of evaporating all the water content (IEA Bioenergy 2013 p. 290, Minton 1986 p. 2). The energy demand of the process can be reduced for example by selecting proper evaporation technology, recirculating the heat, or evaporating in vacuum conditions which lowers the vaporisation temperature (Minton 1986 p. 70 – 72, Hackett 2018).

The most common evaporator type is evaporator with tubular heating surface. The evaporators can be divided to single-effect and multiple-effect evaporators, depending on the columns in the evaporator. The simplest single-effect evaporators consist of one evaporator column and integrated heat exchanger. (Minton 1986 p. 70) In the following Figure *6* is presented the flow diagram of single-effect evaporator. (Hackett 2018)

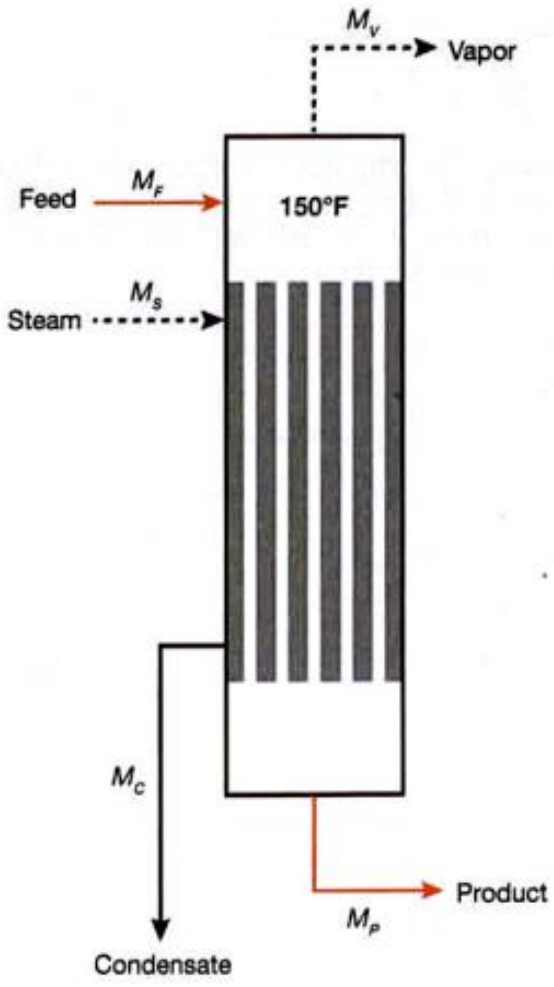



Figure 6. Evaporator flow diagram. Heating steam and feed are in different cycles, and heat is transferred through a heat exchanger (Hackett 2018)

Multiple-effect evaporator consists of several columns in a row. The columns operate in vacuum conditions, and the evaporated fraction from previous effect is utilized as a heating medium in the following effect. In the following Figure *7* is presented multiple-effect evaporator. (Hackett 2018)

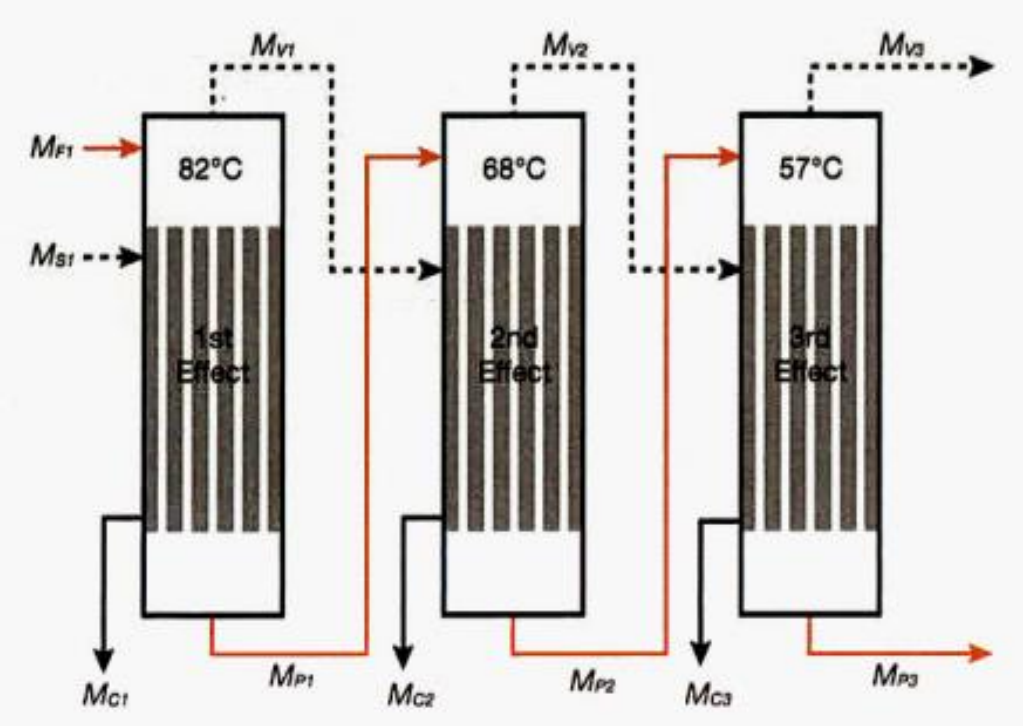



Figure 7. Multiple-effect evaporator flow diagram with exemplary temperatures (Hackett 2018)

One modification of the single-effect evaporator is the Mechanized Vapor Recompression (MVR) technology. In MVR technology the evaporated fraction is reheated and utilized as a heating medium. MVR technology requires same energy supply as the single-effect evaporator, but does not require heat at the operating stage, requiring only the electricity demand of the re-compressor. (Minton 1986 p. 186) In the Figure *8* is presented the MVR evaporator.

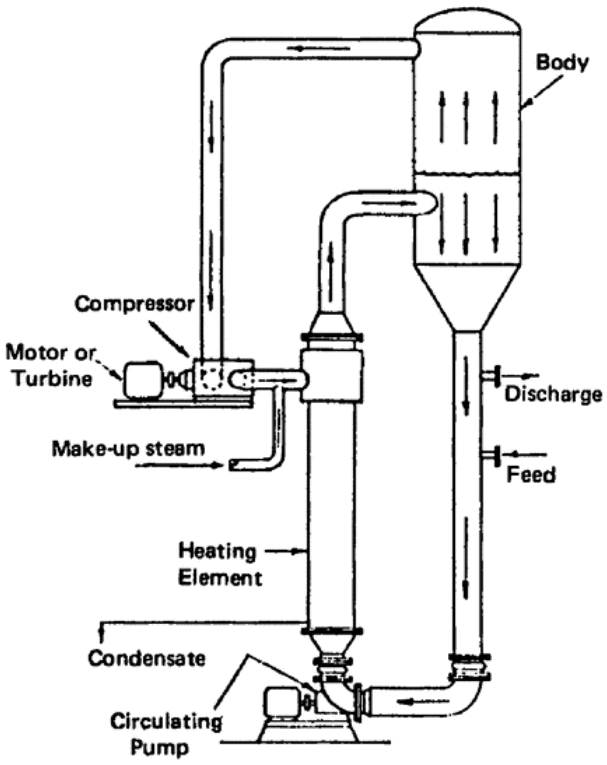



Figure 8. Mechanical vapor recompression evaporator (Minton 1986)

Membrane filtration

Membrane filtration is a treatment technology for liquid fraction, which contains solids less than 3 % (GIZ 2010 p. 201). The particle filtration is done with microfilters and ultrafilters, while the molecular filtration is done with reverse osmosis and nanofiltration. The finest filters can remove 0,5 nm sized particles from the liquid fraction. (De Haan A. B. and Bosch H. 2013 p. 300) Membrane filtration can provide three products: first the biggest impurities can be filtered to a separated fraction, second a concentrate including the nutrients, and last is produced purified water (GIZ 2010 p. 201). The membrane filtration does not require increased temperatures, which makes it less energy intensive than evaporation or ammonia stripping, but the membranes are considered expensive (GIZ 2010 p. 201, IEA Bioenergy 2013 p. 289).

Composting

Composting a treatment method for solid fraction. Composting is an aerobic degradation process, which aims to stabilise the organic matter and eliminate the odour-causing substances (GIZ 2010 p. 200). Composting also increases the nutrient ratio of the digestate (IEA Bioenergy 2013 p. 288). The composting microbes require aerobic conditions and

organic processable matter. The process results mainly as released water, $CO_2$, nutrients compounded in organic matter, and heat. (Suomen biokaasuyhdistys ry. 2015 p. 111) The digestate often requires additional bulk material to provide better conditions for composting process. The bulk material makes the dry fraction more aerobic for microbes to progress, but also provides more organic material to the compostable matter, which enables the composting process to maintain. Bulk material can be for example wood chips, bark, peat, or mixture of those. (Suomen biokaasuyhdistys ry. 2015 p. 111)

The composting does not necessarily require heat energy, as the heat is generated in the composting process. The process requires electricity to mixers for maintaining the aerobic conditions. (Suomen biokaasuyhdistys ry. 2015 p. 111) The composted digestate can be utilised directly as fertilizer or soil conditioner. If the nutrient content is too low, it can also be concentrated with enrichments. (Suomen biokaasuyhdistys ry. 2015 p. 111)

Drying

Thermal drying is treatment method for the solid fraction, which aims to evaporate volatile liquid from the targeted solution with heat (De Haan and Bosch 2013 p. 177). In the fertilizer industry, the drying is done to reduce the transporting and storing capacity demands. Thermal drying can also provide the hygienisation treatment if the solid fraction contains pathogens. The evaporated fraction might contain impurities, such as ammonia or small particles, which require cleaning. The evaporated liquid fraction can be condensed and returned to process. (GIZ 2010 p. 201) The solid content of the solid fraction can be increased to over 90 % with thermal drying (Suomen biokaasuyhdistys ry. 2015 p. 111).

Thermal dryers are either direct dryers or indirect dryers. The direct dryers supply the heat by convection or radiation, and the indirect dryers use conduction or radiation (De Haan and Bosch 2013 p. 193). Dryers can be categorized based on their loading to batch loaded dryers and continuous loaded dryers or based on their conditions to vacuum and atmospheric dryers (Couper et al. 2010 p. 226 - 228). The suitable drying technology is dependent on the properties of the feed and targeted outcome. A common method to find out the suitable drying method is to try samples in different dryers. (De Haan and Bosch 2013 p. 177)

The drying process takes place in three different phases. The first phase is the heating phase, where the moisture content evaporates with accelerating rate. The second phase is the stationary drying state, when the liquid evaporates at a constant rate, until the drying process

achieves the third phase. The third and the last phase is falling drying state, where the evaporable moisture content of the feed approaches to zero, and the drying rate starts to vary. The drying phases are presented in the Figure *9*. (De Haan and Bosch 2013 p. 188 - 190)

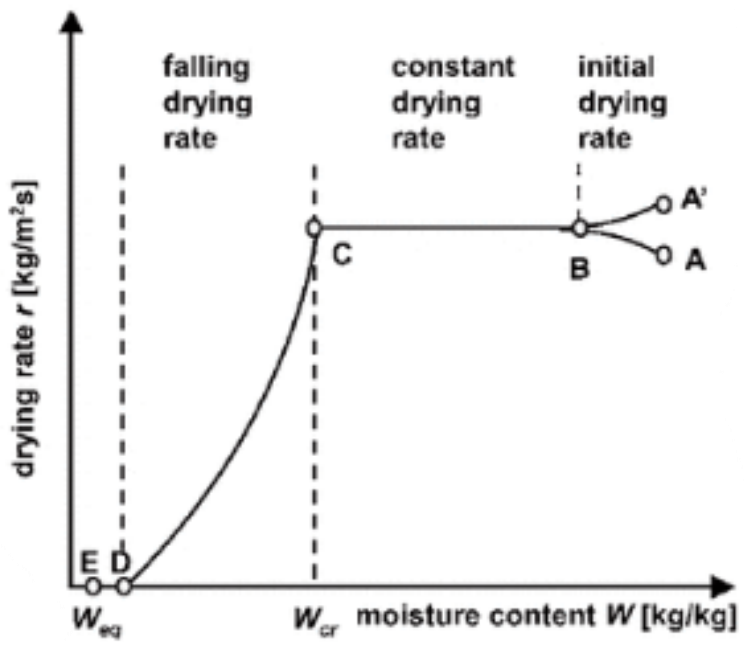



Figure 9. The drying phases of the drying process (de Haan and Bosch 2013 p. 188)

In the biogas and fertilizer plants commonly used thermal dryer is belt dryer (GIZ 2010 p. 201). Belt dryer is a continuously loaded direct dryer. The belt dryer consists of a rotating belt conveyor, which rotates inside a container. The dry fraction is fed to the conveyor and is conveyed to the other end of the belt where it is removed from the drier. The container is equipped with blowers, that aerate the feed on the conveyor, and evaporate the liquid. (De Haan and Bosch 2013 p. 195) The belt dryers can be single or multi-staged dryers. In the multi-staged belt dryers, the first conveyor drops the feed on the conveyor below, which is rotating to other direction. (Alamia A. et al. 2015) In the Figure *10* is presented three-stage belt dryer.

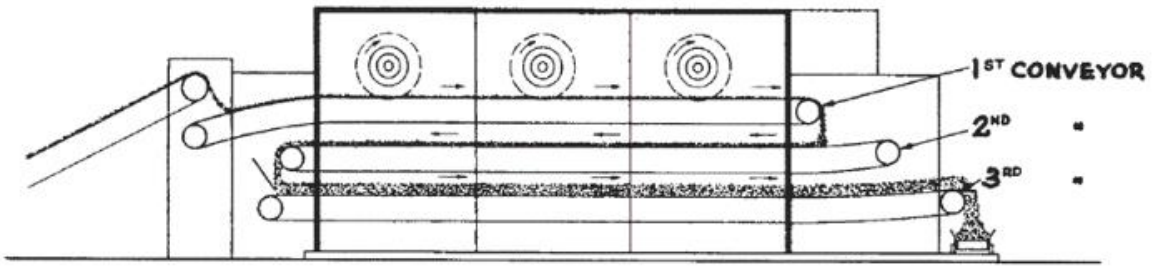



Figure 10. Three-staged belt dryer. Feed is dropped to belt below and rotated to opposite direction. (Couper et al. 2010 p. 240)

The heating medium in belt dryers is typically heated unsaturated air (Döring 2013 p. 102 - 105). The operating temperature in the belt dryers is usually 130 °C at most (Alamia A. et al. 2015). The unsaturated air strives to achieve saturation, and it absorbs the moisture from the feed (Döring 2013 p. 102 - 105). The belt dryers have efficiency of 46 – 58 % (Ratio of heat to evaporation and heat input) (Couper et al. 2010 p. 232).

Pelletizing

Pelletizing is a treatment method for thermally dried solid fraction. The pelletizing process produces compressed, homogeneous, and stabile pellets. The product enables easier storing and transporting. (Suomen biokaasuyhdistys ry. 2015 p. 111) Pellets are done with the pellet press, where the fed mass is compressed in pellet dies. The pellet press requires lot of electricity to the compression, but the production rate can be up to 4 – 5 tonnes / hour (with the installation power of 450 kW). The pellet press design, such as the pressing channels and the die shaping, vary depending on the used feed. (Döring 2013 p. 130 – 132)

# 3 Heat flows in biogas production plant

This chapter focuses on the energy flows, especially heat energy flows, in fertilizer producing biogas plant. The first section presents the temperature-levels and the heat energy calculations for typical biogas and fertilizer production phases. In the second section are presented the suitable energy production methods and considered the main features of each method.

## 3.1 Heat demands in different processes

This section presents the temperature levels and heat demand calculation methods for thermal processes in biogas production and digestate treatment. From the stripper technologies, only steam stripping is presented, as it has higher ammonia removal capability and standardized end-product. The evaporator has multiple different technologies presented, as it was assumed to be remarkable factor in the total heat demand.

### 3.1.1 Reactors

Reactors provide the conditions for micro-organisms to generate biogas (See chapter 2.1.1). The typical temperature-levels in the reactors are at mesophilic (30 – 38 °C) or thermophilic (50 – 57 °C) level, and the heating can be supplied with either water-circulation or electric heaters. (Luostarinen 2013) The volume of energy demand depends on the reactor type, used temperature levels, used digestion method, geological location, and insulation quality. It is estimated that fermenter operating on the mesophilic temperatures requires 5 – 15 % of the total energy available in the biogas. (IEA Bioenergy 2013 p. 215)

The heating demand of the reactor can be calculated with the energy required for substrate heating, the heat losses, the energy produced in the microbiological processes, and the kinetic energy transferred to the substrate. The equation for determining the reactor heating demand is

$$Q_{th} = Q_{sub} + Q_{h,loss} - Q_{mic} - Q_{eq} \quad (3)$$

Where $Q_{th}$ The total heat demand, kW

$Q_{sub}$ Heat required for substrate to achieve the targeted temperature, kW

$Q_{h,loss}$ Heat losses of the reactor, kW

$Q_{mic}$ Generated heat in the microbiological processes, kW

$Q_{eq}$ The heat transferred to substrate from substrate mixing, kW

(Luostarinen 2013)

The required energy for substrate heating can be calculated, when the specific heat capacity of the substrate, the mass flow, and the temperature change, are known. The equation is

$$Q_{sub} = C * q_m * dT \quad (4)$$

Where C Specific heat capacity of the substrate, kg / kJ K

$q_m$ Mass flow of the substrate, kg / h

dT Difference between receiving and target temperature of substrate, °C

(Luostarinen 2013)

The heat losses of reactor can be calculated with reactor surface area, heat transfer coefficient and temperature difference between reactor and the environment. The heat losses for each part of the reactor are calculated with the equation

$$Q_{h,loss} = U * A * dT \quad (5)$$

Where U Heat transfer coefficient of the reactor part, W / $m^2$ K

A Area of the reactor, $m^2$

dT Temperature difference outside and inside, °C

(Luostarinen 2013)

The total heat losses can be achieved by summing the heat losses of the different parts. The heat generation of the microbiological processes can be estimated with the following equation

$$Q_{mic} = 0{,}21\ kWh * y_{m^3_{ch4}} \quad (6)$$

Where $y_{m^3_{ch4}}$ Production of $CH_4$, $m^3$ / h

0,21 Estimated heat production of microbes per $m^3$ $CH_4$

(Luostarinen 2013)

The kinetic energy transfer is estimated with the assumption, that the required power of the mixers inside the reactor is transferred to heat energy.

(Luostarinen 2013)

### 3.1.2 Ammonia steam stripper

Ammonia steam stripper evaporates the free evaporable ammonia from the feed. The effect of pH and temperature control to the share of evaporable ammonia is presented earlier in Figure *3*.

The structure and flow diagram of ammonia steam stripper is presented in Figure *5*. Heat is brought to process in steam. The mass balance of the steam stripper can be determined with the incoming and outcoming flows. Incoming flows are feed input and steam input, and the outcoming flows are feed output and distillate. The mass balance of the steam stripper is the following

$$q_{m,f,in} + q_{m,s} - q_{m,f,out} - q_{m,d} = 0 \quad (7)$$

Where $q_{m,f,in}$ feed mass flow to stripper, kg / h

$q_{m,s}$ heating steam mass flow, kg / h

$q_{m,f,out}$ feed mass flow out from the stripper, kg / h

$q_{m,d}$ distillate mass flow, kg / h

(Nitsche and Gbadamosi 2017 p. 9 - 17)

The energy balance of the steam stripper can be determined based on the mass balance. The energy of the evaporated fraction is divided to condenser and outflowing distillate. The stripper column also conducts heat energy to atmosphere, which causes heat losses. The energy balance of the steam stripper can be presented as following

$$Q_s + Q_{f,in} - Q_c - Q_d - Q_{f,out} - Q_l = 0 \quad (8)$$

Where $Q_s$ heating steam heat flow, kW

$Q_{f,in}$ energy flow of the feed input, kW

$Q_c$ energy flow transferred in condenser, kW

$Q_d$ energy flow of the distillate, kW

$Q_{f,out}$ energy flow of the feed output, kW

$Q_l$ heat losses, kW

(Nitsche and Gbadamosi 2017 p. 9 - 17)

From the energy balance the steam heat input can be determined as following

$$Q_s = Q_c + Q_d + Q_{f,out} + Q_l - Q_{f,in}$$

The energy flows of the feed input, feed output, and distillate can be calculated with the following equation

$$Q = q_m * h \quad (9)$$

Where $q_m$ mass flow of the flow

H enthalpy of the flow

The energy flow of the condenser can be calculated with the equation

$$Q_c = q_{m,e} * \left(\lambda_{ev} + c_p * (t_k - t_r)\right) \quad (10)$$

Where $q_{m,e}$ flow rate of the evaporated fraction

$\lambda_{ev}$ latent heat of evaporation

$c_p$ specific heat capacity

$t_k$ temperature of the evaporated fraction

$t_r$ reflux temperature after condenser

Heat losses of the column are estimated.

(Nitsche and Gbadamosi 2017 p. 9 - 17)

### 3.1.3 Evaporators

Evaporation separates the liquid substances based on the different vaporization temperatures. The evaporation technology is simple and can achieve very pure separated fractions, but the technology requires heat. Earlier in this report in Figure *6*, Figure *7* and Figure *8* are presented the flow diagrams of the different evaporators. (Hackett 2018)

Single-effect evaporator

The energy balance of the single-effect steam evaporator can be presented with mass flows and enthalpies of the incoming and outcoming flows as

$$q_{m,s,in} * h_{s,in} + q_{m,f,in} * h_{f,in} = q_{m,s,out} * h_{s,out} + q_{m,f,out} * h_{f,out} + q_{m,v} * h_v \quad (11)$$

Where $q_m$ mass flow, kg / h

h enthalpy, kJ / kg

s steam

f feed

v vaporized fraction

(Hackett 2018)

The energy balance assumes the heat losses to be 0. In the real applications heat losses are assumed to be around 2 %, which should be considered in the energy balance (Hackett 2018). From the energy balance, the heat demand for heating steam can be calculated.

$$Q_{evap} = \frac{q_{m,s,in} * h_{s,in}}{x_{hl}} = \frac{q_{m,s,out} * h_{s,out} + q_{m,f,out} * h_{f,out} + q_{m,v} * h_v - q_{m,f,in} * h_{f,in}}{x_{hl}} \quad (12)$$

Where $Q_{evap}$ heat demand for the evaporator

$x_{hl}$ heat losses

(Hackett 2018)

Multiple-effect evaporator

In the multiple-effect evaporator the evaporated fraction is used to heat the following effect. Condensates are removed from the process (Hackett 2018). The energy balance of the multiple-effect evaporator can be presented with the following equation (in the equation 4 effects)

$$Q_{heatdemand} + q_{m,f,in} * h_{f,in} = q_{m,cs1} * h_{cs1} + q_{m,cs2} * h_{cs2} + q_{m,cs3} * h_{cs3} + q_{m,v4} * h_{v4} + q_{m,p} * h_p \quad (13)$$

The presented equation does not include heat losses. The heat demand for multiple-effect evaporator including the heat losses can be presented with the following

$$Q_h = \frac{q_{m,cs1} * h_{cs1} + q_{m,cs2} * h_{cs2} + q_{m,cs3} * h_{cs3} + qm_{,v4} * h_{v4} + q_{m,p} * h_p - q_{m,f,in} * h_{f,in}}{x_{hl}} \quad (14)$$

(Hackett 2018)

MVR Evaporator

The MVR technology is a single-effect evaporator where the evaporated fraction is reheated and fed back to the evaporator as heating medium. The mechanical power of the re-compressor transfers to heat energy in the fluid, and the power demand for maintaining the process can be calculated with the efficiency of the re-compressor and the difference between the heat demand of the single-effect evaporator and the energy flow of the exiting evaporated fraction of the single-effect evaporator. (Minton 1986 p. 186 – 187)

The compressor work is proportional to the energy change in the fluid. The compressor's power demand can be calculated with the energy change entering and exiting the compressor, and with the compressor efficiency. (Gresh T. 2001 p. 16) The equation is

$$Q_{el} = \frac{q_{m,s,in} * h_{s,in} - q_{m,v} * h_v}{\eta_{rc}} \quad (15)$$

Where $Q_{el}$ The power demand, kJ / h

$q_m$ Mass flow, kg / h

h enthalpy, kJ / kg

s,in steam entering the evaporator

v vaporized fraction to recompression

### 3.1.4 Thermal dryer

Thermal dryers dry the feed by evaporating the volatile liquid. The drying rate is corresponsive to the temperature, and in the higher temperatures the drying process can be shortened. (Alamia A. et al. 2015) The drying process is presented in Figure *9*. The first phase heats the feed to targeted medium temperature in the dryer. The energy required for heating the feed to the target temperature can be calculated by using the mass flow of the feed, specific heat capacity of the feed and the temperature difference, with equation

$$Q = q_{m,s} * c_{ps} * (T_0 - T_1) \quad (16)$$

Where Q required heat energy, kW

$q_{ms}$ mass flowrate of the feed, kg / h

$c_{ps}$ specific heat capacity of the feed, kJ / kg K

$T_0$ outlet temperature, °C

$T_1$ inlet temperature, °C

The second phase of the drying process is the stationary drying phase, when the liquid is evaporated at stable rate. The energy balance between the heating substance and the feed partial evaporation has been approximated in the continuous process as following

$$Q \approx q_{m,s} * (X_1 - X_0) * \lambda_{ev} + Q_{wl} \quad (17)$$

Where Q required heat energy, kW

$q_m$ mass flowrate, kg / h

X solids moisture content, %

λ latent heat of evaporation, kJ / kg

1 inlet

0 outlet

s solid

$Q_{wl}$ Heat losses, kW

(Kemp and Gardiner 2001)

Combining the equations 16 and 17 the required heat for drying the feed can be determined as

$$Q \approx q_{m,s} * \left[(X_1 - X_0) * \lambda_{ev} + C_{ps} * (T_0 - T_1)\right] + Q_{wl} \quad (18)$$

Typical heating fluid is heated air or exhaust gases from the biogas boiler (GIZ 2010 p. 172). Realistically the heat transfer is not perfect between the heating fluid and the feed, and the realistic heat demand is bigger. The heat input demand for the dryer can be calculated with the required heat energy and dryer efficiency as following

$$Q_d = \frac{Q}{\eta_d} \quad (19)$$

Where $Q_d$ heat input to the dryer, kW

$\eta_d$ dryer efficiency, ratio of evaporation heat and heat input

### 3.1.5 Other

In addition to the presented equipment, the biogas plant requires low temperature heat supply for example to prevent the feed substrate and equipment from freezing. The processes such as separation, transferring the feed from equipment to another, and the storing, cause heat losses. (GIZ 2010 p. 36, 53, 65, 66) The heat demand of the biogas plant is calculated from

the coldest season and is dependent on the location of the plant. The heat demand for preventing the freezing also depends on the storing method of substrate, the infrastructure around the equipment, and insulations of the pipes. The heat demand for maintaining the progress is estimated.

## 3.2 Heat source options

This chapter considers the alternative options for supplying the heat. The heat demanding processes in biogas and fertilizer production are presented in earlier chapters. The ideal heat supply method is cheap, reliable, efficient, and simple. In the following sections are presented the most typical heat sources for biogas production and considered some possible implementations.

### 3.2.1 Gas turbines

Gas turbine is a compact energy source for multiple applications and multiple fuels. Gas turbines have extremely high power / weight – ratio, for which the gas turbines are the main energy source in aircrafts, and common technology especially in marine industry. In the recent decades, gas turbines have become more common in other fields of industry, for example in paper and food industry. (Jansohn P. (ed.) 2013 p. 3 - 4) The gas turbines have applications from microturbines with 20 kW power output up to frame type heavy-duty gas turbines with 480 MW power output. In this section the focus is on small gas turbines with the power output of 0,5 – 2,5 MW and on industrial type gas turbines with the power output of 2,5 – 15 MW. (Boyce M. P. 2012 p. 15)

Gas turbine works similarly to Brayton cycle. Brayton cycle consist of four phases, which are compression, combustion, expansion, and cooling. In the Figure 11 is presented the entropy-temperature diagram of Brayton cycle. (Boyce M. P. 2012 p. 89 - 90)

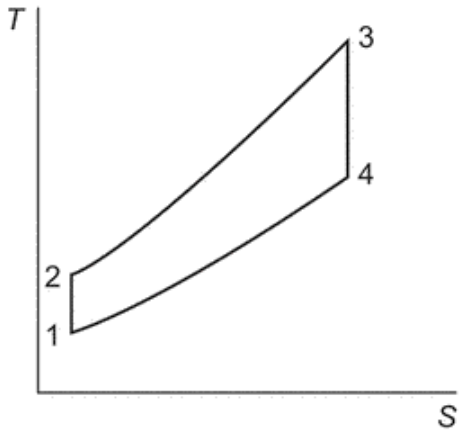



Figure 11. Brayton cycle in relation to entropy and temperature (Boyce M. P. 2012 p. 90)

The Brayton cycle can also be expressed with pressure and volume. Figure *12* presents the pressure-volume diagram of Brayton cycle. (Boyce M. P. 2012 p. 90)

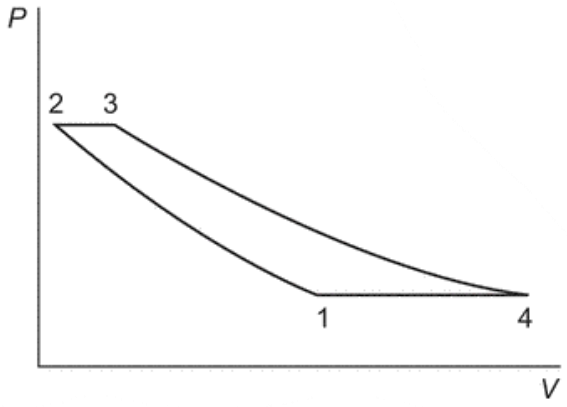



Figure 12. Brayton cycle in relation to pressure and volume (Boyce M. P. 2012 p. 90)

The first phase is compression, where air is compressed to the pressure ratio of 5 – 15 : 1 in industrial gas turbines and 8 : 1 in small gas turbines. The compressed air is partly directed to the combustion chamber, where the fuel is injected and ignited. (Boyce M. P. 2012 p. 40 - 44) The compressed air provides increased temperature and pressure to the combustion chamber, which improves the combustion process. (Rangwala A. S. 2014 p. 5)

Second phase in the process is combustion, which takes place in the combustion chamber. In the gas turbines the combustion process is very efficient, due to the high-pressured air feeding, and can achieve very high temperatures (Rangwala A. S. 2014 p. 5 – 6). In the industrial scale gas turbines, the combustion temperature can be up to 1200 °C, while in the

small gas turbines the combustion temperature is around 1000 °C (Boyce M. P. 2012 p. 40 - 44). The exhaust gases are directed from the combustor to the turbine (Rangwala A. S. 2014 p. 5 - 6).

The third phase is expansion, where main component is the turbine. The exhaust gases expand through the turbine, which rotates and provides power to the generator. Most of the energy from turbine is required to compress the air in compressor, and the net electrical output in the small gas turbines varies from 15 % to 25 %. In the industrial scale gas turbines, the electrical efficiency of the turbine is around 30 %. (Boyce M. P. 2012 p. 40 - 44)

The last phase of the Brayton cycle is cooling, in which exhaust gases after the turbine are directed to the recuperator. Recuperator works as a heat exchanger, using the heat in exhaust gases to pre-heat the compressed combustion air. (Boyce M. P. 2012 p. 89 - 90) In the Figure *13* is presented gas turbine structure and the air flow.

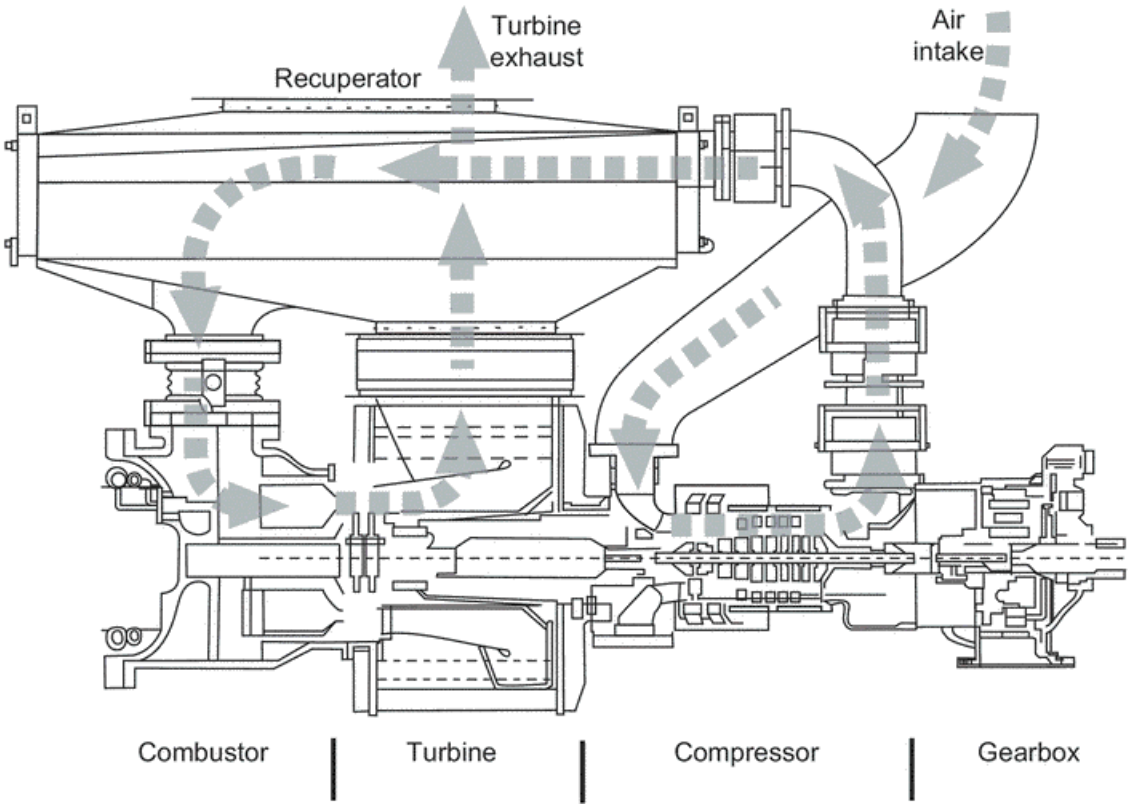



Figure 13. Air flow path in the gas turbine (Boyce M. P. 2012 p. 42)

The primary function in gas turbines is to provide electricity, but in the modern gas turbines the heat in the exhaust gases is also recovered. The heat can be recovered for example with heat exchanger but can also be used directly for example as a heating medium in the dryer.

(Boyce M. P. 2012 p. 3 – 7) With the heat recovery, the thermal efficiencies of 30 – 35 % can be achieved, which increases the overall efficiency of the small and industrial scale gas turbines to around 60 % (Boyce M. P. 2012 p. 40 - 44).

The gas turbine combustion is well aerated due to the air compression, and the resulting substances are often products of complete combustion. The share of different substances in the exhaust gases of hydrocarbon fuel combustion is presented in Table 3.

Table 3. Exhaust gas composition from hydrocarbon fuel combustion (Giampaolo T. 2003 p. 134)

| Constituent | % by weight | Remarks |
|---|---|---|
| N2 – Nitrogen | 74,16 | Mostly inert, from combustion air |
| O2 – Oxygen | 16,47 | From excess air |
| $CO_2$ - Carbon Dioxide | 5,47 | Product of complete combustion |
| H2O – Water | 2,34 | Product of complete combustion |
| A – Argon | 1,26 | Inert, from combustion air |
| UHC - Unburned hydrocarbons | Trace | Product of incomplete combustion |
| CO - Carbon Monoxide | Trace | Product of incomplete combustion |
| NOx - Oxides of Nitrogen | Trace | From fuel bound nitrogen or fixation of atmospheric N2 |
| SOx - Oxides of Sulfur | | From sulfur in fuel |

In the complete combustion, the hydrocarbons such as $CH_4$ transforms to $CO_2$ and H2O. If the combustion process is incomplete, the exhaust gases might contain substances like CO (Carbon-monoxide) and UHC (Unburned hydrocarbons). The exhaust gases also contain the products contained in the combustion air, such as Nitrogen, which may stay as Nitrogen or transform together with oxygen to NOx (Oxides of Nitrogen). The formation of NOx increases, and formation of CO reduces in higher combustion temperatures. (Giampaolo T. 2003 p. 131 - 134)

### 3.2.2 Combustion co-generation boiler

The boiler technology is common and widely known technology among different fields of industry (Tanuma 2017 p. 3). The pressure levels, purpose of use, and the combustion methods vary in different applications, but the primary working principle is similar (Vakkilainen 2017 p. 61). The primary working principle of the co-generation boilers

(combined heat and power, CHP) can be described with the Rankine cycle. Rankine cycle consists of the four main processes, pressurization, heating, expansion, and condensing. The Rankine cycle is presented in Figure *14*. (Tanuma 2017 p. 12 - 14)

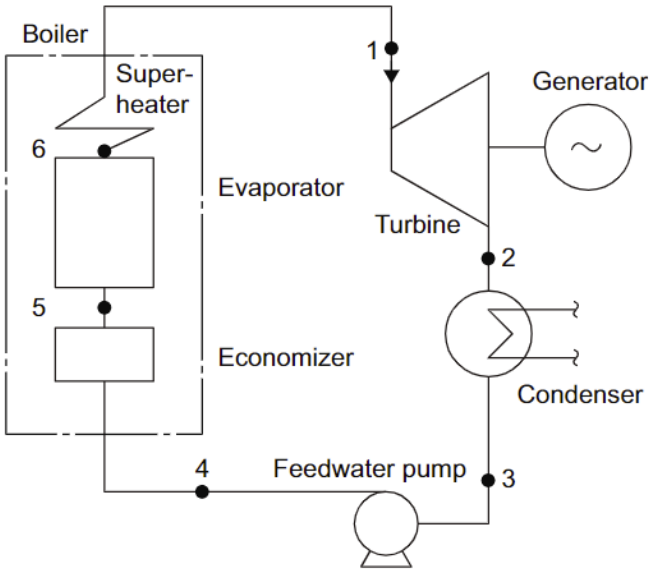



Figure 14. System description of a Rankine cycle with economizer (Tanuma 2017 p. 13)

The most common working fluid in the CHP-boilers is H2O. The heating phase of the cycle is divided to multiple steps. The T,s-diagram of the cycle is presented in Figure *15*. (Tanuma 2017 p. 13)

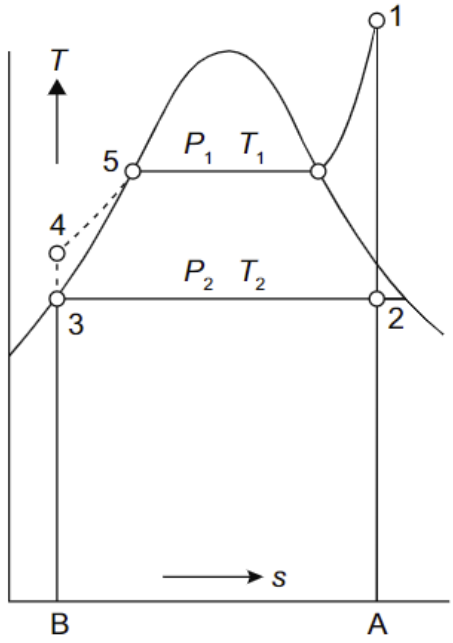



Figure 15. Temperature-entropy-diagram of a Rankine cycle (Tanuma 2017 p. 13)

The Rankine cycle begins with pressurization and from feed water tank. The water is pumped with feed pumps to the superheater. In the ideal process, the pressure increase is adiabatic. The used working fluid is recirculated, and the temperature of the feed water is close to the output temperature of the condenser in the last phase of the Rankine cycle. (Tanuma 2017 p. 14 - 15)

The heat to the Rankine cycle process is brought in the second phase of the Rankine cycle, by combusting the fuel in the combustion chamber. The working fluid flows in the superheater, which is located on the top part of the combustion chamber. The output of the superheater is superheated steam in high temperature and pressure. The combustion technology varies depending on the used fuel and the energy output. In the applications with energy output under 10 $MW_{th}$ (thermal energy), the most common combustion methods are grate combustion for solid fuels and direct firing for pulverized fuels. In the larger scale (more than 10 $MW_{th}$) the different versions of fluidized bed combustion have become the most common combustion method. (Vakkilainen 2017 p. 74, 211, 203 - 204) This report considers only the direct firing and grate firing due to the small heat demand in fertilizer producing biogas plants, and only biofuels as considerable fuel options. In the Figure *16* is presented the direct firing technology.

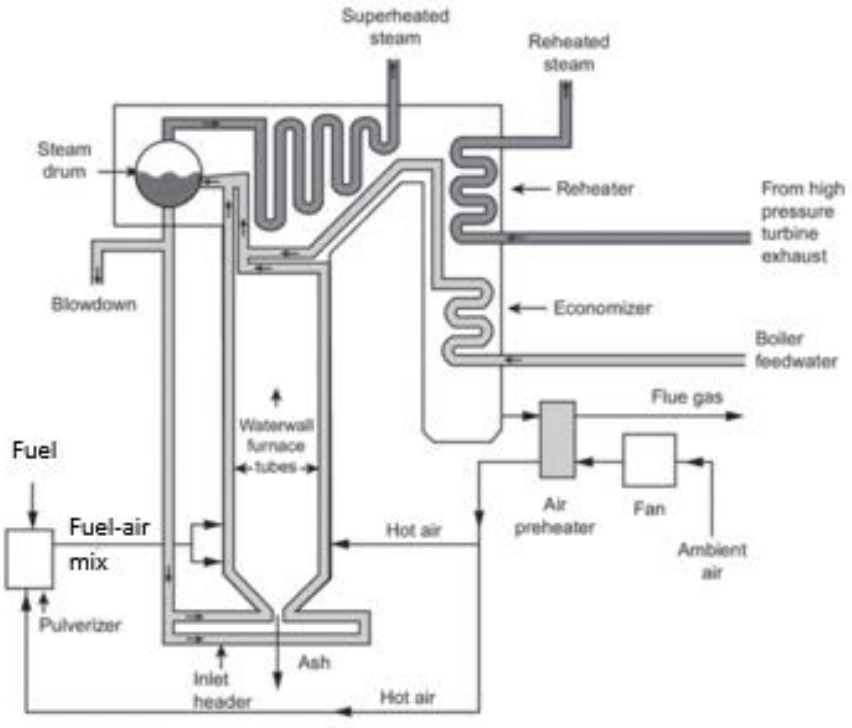



Figure 16. Direct firing boiler (Breeze 2014)

The suitable temperature for pellet combustion with direct firing method is 900 – 1000 °C, while in the grate firing the burning temperature may achieve average temperature up to 1300 °C (Abdoli et al. 2018 p. 169, Tu et al. 2018). In the Figure *17* is presented grate firing boiler.

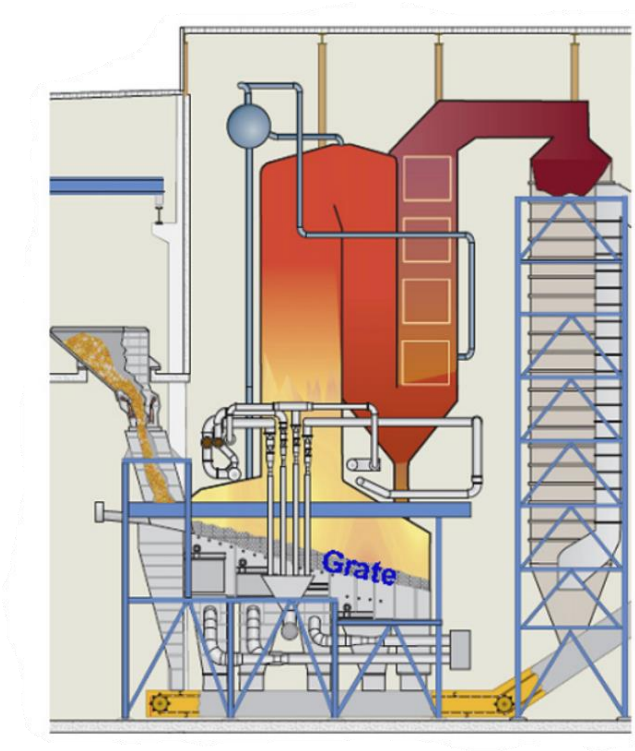



Figure 17. Grate boiler (Yin et al. 2008)

The third phase in the cycle is expansion. The superheated steam is directed to flow through the turbine, and in the ideal conditions the expansion is adiabatic. The steam is in the superheated conditions and can vary from 2 MPa and 320 °C to 25 MPa and 600 °C. (Tanuma 2017 p. 17) The pressure and heat levels are selected based on the heat level demands from the energy users (Vakkilainen 2017 p. 61). In the adiabatic expansion the outlet temperature is the same as the input temperature, but the pressure is reduced in the turbine outlet to around 10 kPa. In reality, the expansion causes small drop in the temperature due to heat losses. (Tanuma 2017 p. 19) Multiple variations of steam turbines exist, but in the industrial applications the main product is often the heat, and the electrical efficiency is lower, around 20 % (Vakkilainen 2017 p. 73).

The last phase in the Rankine cycle is condensing which takes place in condenser. Condenser transforms the outcoming low-pressure steam from turbine to water, and the heat released in the process is transferred to another medium with heat exchanger. (Tanuma 2017 p. 14)

Majority of the energy output in boiler technology is heat energy, and the thermal efficiency can reach up to 60 %. (Vakkilainen 2017 p. 73) The condensed water is returned to feed water tank. (Tanuma 2017 p. 14)

The Rankine cycle is the simplified principle of the steam cycle, but in the reality the cycle is more complex. The heating phase can be divided to multiple stages with preheater, evaporator, and superheater. In addition, the expansion phase can be divided to multiple stages as high- and low-pressure turbines, and reheating can be added in the expansion phase. (Tanuma 2017 p. 13 - 15) The modern boilers with complex steam cycle can achieve overall efficiencies of 90 % with electrical efficiency of over 40 % (Vakkilainen 2017 p. 75, Kaya et al. 2021 p. 57). In the industrial applications, where the heat output is priority, the overall efficiency is around 80 % with electrical efficiency of 20 % (Vakkilainen 2017 p. 73).

The steam boiler processes circulate the same water through the Rankine cycle, and it requires pre-treatment. Natural water contains lot of salts and other impurities, such as oxygen, $CO_2$, and calcium, which react in different temperatures and cause corrosion to the surfaces. All the impurities are impossible to remove, but proper pre-treatment reduces maintenance time and improves the predictability of the process. Typical pre-treatment technologies are membranes, chemical additives, and ion-exchange technologies. (Manivasakam 2011 p. 31 - 34)

The emissions from the boiler unit depend on the used fuel. Some characteristics from different boiler types can be determined. In the grate firing, the aeration is done with air-blowers under the grates, which may remove unburned solid particles to the exhaust flow. Grate boiler technology typically has products of incomplete combustion in the exhaust gases, such as CO. (Yin et al. 2007) The direct firing of pulverized pellets has efficient combustion process, and the emissions of unburned substances are very low. The disadvantage in direct firing is, that up to 85 % of ash content end up to the exhaust gas flow. The ash in the exhaust gases cause requirements for exhaust gas filtering, and it also causes slag to the heat surfaces reducing the heat transfer efficiency. (Raghavan V. 2016 p. 155 - 156)

### 3.2.3 Combustion condensing boiler

Another considered application in this thesis is condensing boiler. Condensing boiler does not differ from the CHP boiler from the combustion technology, but condensing boiler produces only heat. The water-steam cycle in condensing boilers consist of boiler, where the water is evaporated, and from the condenser, where the heat is recovered. The thermal efficiencies of condensing boilers are from 85 % to 90 %. Additional increases in efficiency can be achieved with for example fume gas heat recovery and combustion air pre-heating. (Lee et al. 2015) In the Figure *18* is presented the process chart of condensing boiler with fume gas heat recovery.

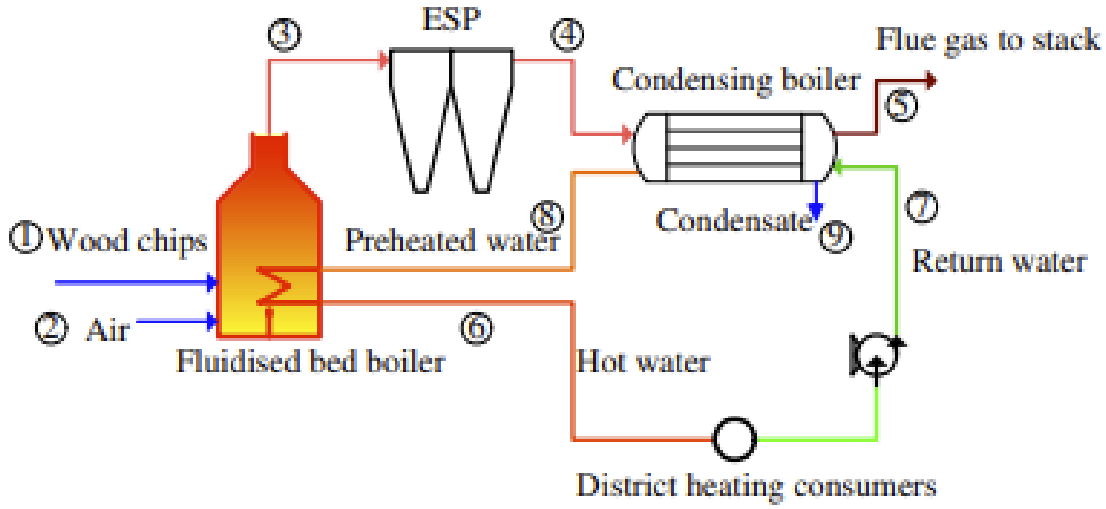



Figure 18. Condensing boiler with fume gas heat recovery (Chen et al. 2010)

Condensing boilers require less installations than CHP, because the turbine and power generators are not required. The fuel pre-treatment requirements and fume gas treatment requirements vary depending on the used fuel.

### 3.2.4 Residual heat flow

Residual heat flows are unutilized energy flows and appear everywhere from residential heating systems to industrial thermal processes. In 2014 was estimated, that one third of the total energy supply was consumed in residual heat flows and heat losses. In the industry, the residual heat flows are utilized typically to the point that they can be recovered to the process, and the temperature-levels become too low for further utilization for the process. The

remaining heat could be recoverable for other applications, and in the recent years cross-sectorial operation has become more common to reduce waste heat flows. (IPCC 2014 p. 377, 85) The energy in the waste heat flow can be calculated with the equation

$$Q = h_f * m_f \tag{20}$$

The biogas production requires stable temperature, and the thermal digestate treating processes can be continuous processes, so the suitable residual heat flow must be continuous. The heat in the residual heat flow is typically recovered with a heat exchanger with high operating capacity, but in smaller scale heat pump recovery applications exist (IPCC 2014 p. 746, Farshi et al. 2018). The utilization of residual heat flow requires the source to be close to the plant.

### 3.2.5 Heat pumps

Heat pumps are technology that is capable for heating and cooling in ambient temperatures and are familiar concept in the residential sector. In this section, only the heating system is considered further. The heat pumps primarily follow the Carnot cycle, which consists of four main phases: compression, condensing, expansion, and evaporation. (Grassi 2018 p. 3 – 5) The T,s-diagram of Carnot cycle is presented in Figure *19*.

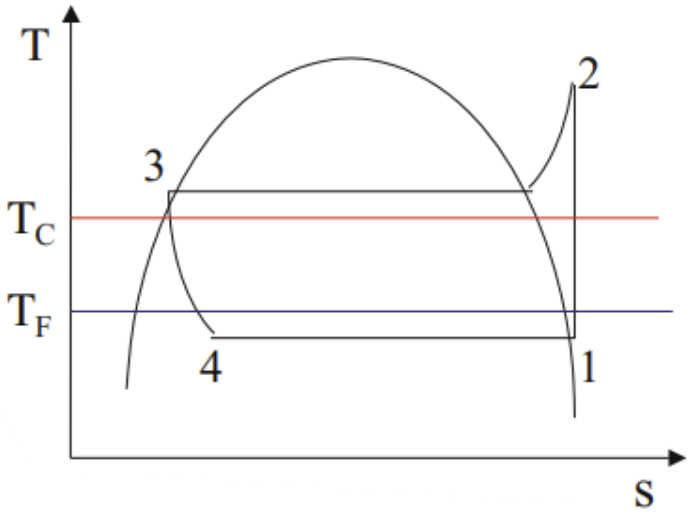



Figure 19. Temperature-enthropy diagram of a carnot cycle (Grassi 2018 p. 5)

The circulating working fluid is typically some synthetic refrigerant, which has low evaporation temperature. The evaporation process is endothermic, and restricts heat energy to the evaporating fluid, while the condensation is exothermic process that releases energy. The compressor and expansion valve maintains the Carnot cycle. The flow chart of compression heat pump following Carnot cycle is presented in Figure *20*. (Grassi 2018 p. 73 - 74)

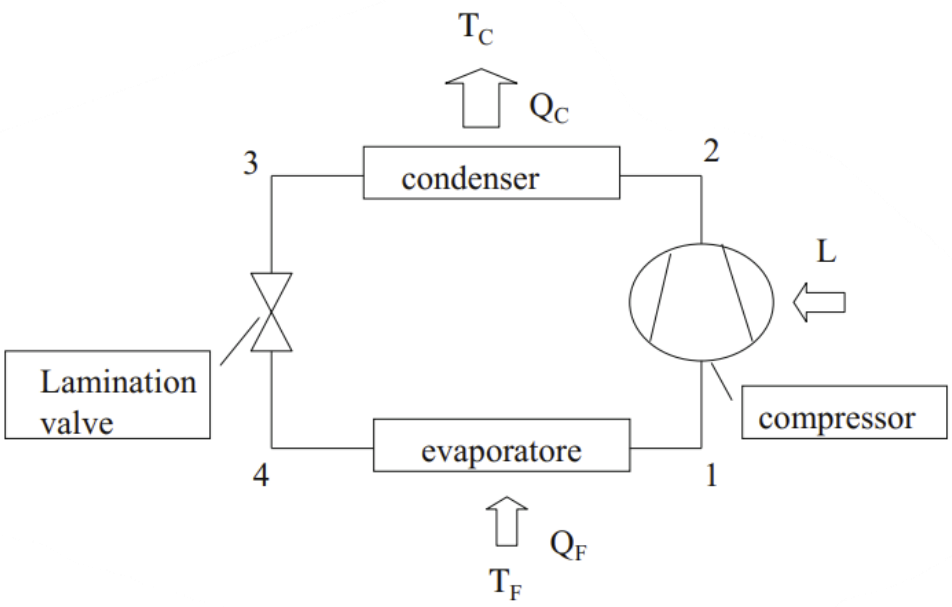



Figure 20. Working principle of compression heat pump (Grassi 2018 p. 5)

The performance of heat pumps can be determined with the coefficient of performance (COP), which is the ratio of transferred heat from heat source to heat sink and the energy supply to the machine. In the residential applications, the heat sources have typically been either outdoor air, water, or ground, and the heat sink indoor air or water. In the industry the heat pumps are primarily used for cooling but have been implemented also for example in district heating. (Grassi 2018 p. 1 - 4) The article conducted by Jiang et al. (2022) presents multiple heat pumps and refrigerants that operate in the maximum required temperatures in the fertilizer producing biogas plants, where the COP-values vary from 1,9 to 4,02 and heating capacities vary from 3,5 kW up to 500 kW. The heat sinks in the conducted article vary mainly around 80 and 120 °C. (Jiang et al. 2022)

Heat pumps are more efficient heating method than electrical heaters. They do not cause emissions from exhaust gases as combustion is not required. (Grassi 2018 p. 3) The heating

capacities of the heat pumps are restricted and multiple heat pumps in parallel might be required to fulfill the energy demand (Jiang et al. 2022). In addition, some synthetic refrigerants are extremely hazardous for the nature. (Grassi 2018 p. 116)

### 3.2.6 Electric boilers

Electric boilers generate hot water and steam by transferring electricity to thermal energy. The technology uses resistant heating elements inside an insulated container, where the fluid is heated. (Farooq et al. 2014) Scientific data was not found regarding electric boilers, but the manufacturers promise close to 100 % efficiency between power demand and heat output. (Babcock Wanson 2020) The industrial and commercial electric boilers require high-voltage power supply (15 kW and larger units). (Flexiheat UK 2021) The boiler steam output varies from 15 kW up to 17 MW. (Babcock Wanson 2020)

The electric boilers do not need large installations. They are also fast to start and shut down. (Babcock Wanson 2020) Flexible operation possibilities, light installations and high-efficient heat generation is a considerable option in applications where excessing electricity is available. Electric boilers are itself emission free technology, but to be carbon-neutral the consumed electricity should be generated from renewable sources. (Flexiheat UK 2021)

### 3.2.7 Electric heaters

Electric heaters convert power to heat. Electric heaters are widely known and versatile technology, which have high variety of applications. Common heating technologies for electric heaters are for example resistance heating, induction heating, and radiation heating. (Dryden 1982 p. 95)

Similarly to the electric boilers, electric resistance heaters have close to 100 % efficiency, but the radiating heaters have efficiency of around 70 % (IRENA 2019, Dryden 1982 p. 106). The electric heaters can achieve very high temperatures, exceeding 1000 °C. Capacities of the electric heaters are dependent on the heat transfer area, varying from 10 $kW/m^2$ to 80 $kW/m^2$. (Dryden 1982 p. 106)

### 3.2.8 Summary of the heat generation technologies

This section summarizes the key aspects of the previous sections. Table *4* presents the summary of the introduced heat generation technologies, and their key properties. The gathered properties are operation ranges in supply volume and temperature, efficiency, and other mentionable issues. The waste heat supply from other industries is calculated for 100 °C water and steam. The mass flow is calculated to cover the heat demand.

Table 4. Summary of the heat generation technologies

| Heat generation method | Operating range, Heat supply | Operating range, Temperature | Efficiency/ fuel demand | Side-products / other mentionable issues |
|---|---|---|---|---|
| CHP Boiler | 0 - 10 MW | 320 - 600 °C (Produced steam temperature) | 60 % | 20 % electrical efficiency<br>Circulating water requires treatment<br>Fume gas requires treatment |
| Heat boiler | 0 - 10 MW | 320 - 600 °C (Produced steam temperature) | 85 - 90 % | Circulating water and fume gas requires treatment. |
| Small gas turbine | 0,5 - 2,5 MW | 1000 °C (Fume gas) | 30 % | 15 - 25 % electrical efficiency |
| Industrial gas turbine | 2,5 - 15 MW | 1200 °C (Fume gas) | 30 % | 30 % electrical efficiency |
| Electric boiler | 15 kW - 17 MW | Steam & Hot water (No data of quality) | Close to 100 % | |
| Heat pumps | 10 kW - 500 kW | 80 - 120 °C Water | COP 2 - 4 | Require heat source |
| Electric heaters | 10 - 80 kW / m2 | 50 - 1000 °C | Depends on the technology, 70 % - 99% | Multiple different alternatives |
| Waste heat from other industry | 1 kg / s<br>6,6 kg / s | 100 °C steam<br>100 °C water | Depends on the heat recovery technology | Long transporting distances reduce the profitability |

The presented technologies have high variety in the operating range both in volume-vice and temperature-vice. Multiple options are capable for steam production, and several technologies can provide electricity as a side product.

# 4 The optimized heat energy flow in fertilizer producing biogas plant

This chapter presents calculations of the heat consumption for fertilizer producing biogas plant. The mass flows for the calculations are received from an existing mass balance for a project draft.

## 4.1 Initial status

The fertilizer producing biogas plant is planned to be built in the Nordic country. The coldest temperatures at the target area were estimated to be -30 °C for air and -5 °C for soil. The used feedstock was chosen to be chicken manure with the loading of 45 000 kg / a, and TS of 40 %. Biogas yield for the used feedstock is assumed to be 0,184 kg $_{ch4}$ / kg $_{TS}$. Feedstock is obtained in temperature of 15 °C. The initial input values of the calculations are presented in Table *5*.

Table 5. Starting values of the plant

| Description | Value | Unit |
|---|---|---|
| Substrate | Chicken manure | |
| Mass flow | 5137 | kg / h |
| TS % | 40 | % |
| Supply temperature | 15,0 | °C |
| Specific heat capacity | 3,1 | kJ / kg K |
| Biogas yield | 0,184 | $kg_{ch4}$ / kg $_{TS}$ |

The degradation process is separated to two stages with one hydrolysis reactor and two identical fermenters. The digestate from the hydrolysis reactor is processed with solid-liquid separation, and the solid fraction is re-watered before entering to the fermenters. The liquid fraction from the solid-liquid separation is stripped and evaporated. The biogas is upgraded, and the digestate from fermenter is processed with another solid-liquid separation, where the liquid fraction is returned to process as process water and solid fraction is removed from process. The simplified flow chart is presented in Figure 21.

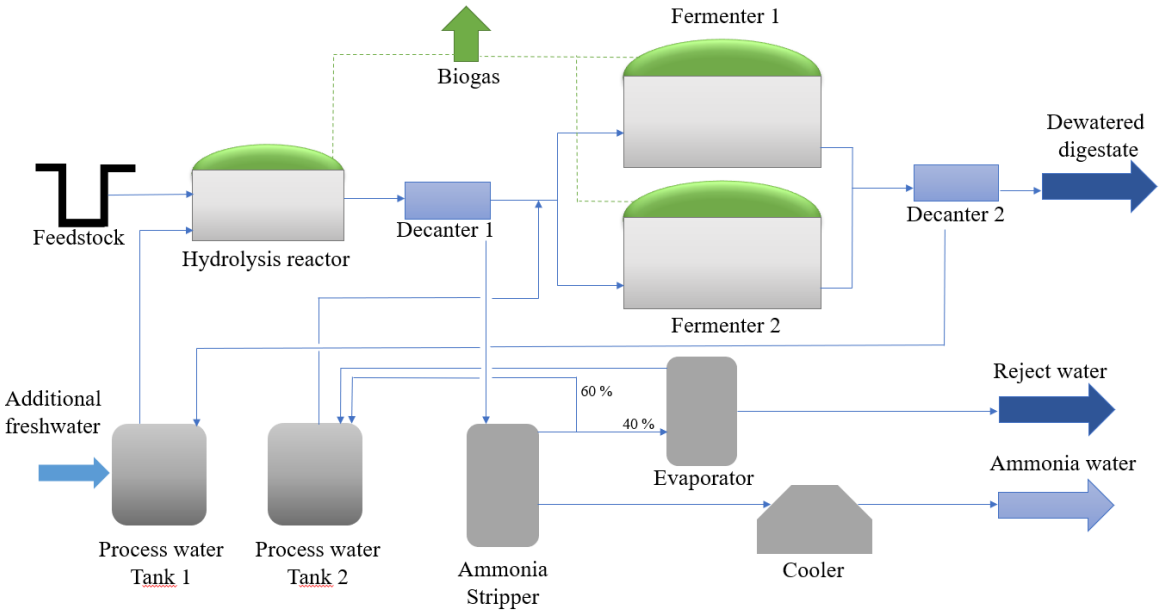



Figure 21. Flow chart of the project draft

The process is estimated to produce 378,1 kg / h bio- $CH_4$, from which 44 % is estimated to be generated in hydrolysis reactor, and the rest is produced in fermenters. The fermenters 1 and 2 are identical. The evaporation is partial, and 40 % of the ammonia stripper concentrate is fed to the evaporation process. Other 60 % is recycled to process water tank without further treatment.

### 4.1.1 Hydrolysis reactor

The feed input to the hydrolysis reactor is 5137 kg/h with the supplying temperature of 15 °C. Properties of the feed are presented in Table 5. The determined TS for the hydrolysis reactor is 12 % and degradation temperature for the process is set to 52 °C. The water added to achieve determined TS is recycled process water combined with additional freshwater and is provided in the temperature of 35 °C with the TS of 2,4 %. Water is added 20346 kg/h. The specific heat capacity of the water is 4,11 kJ / kg K. The heat demands for heating the substrate and water are calculated with the equation 4.

The hydrolysis reactor is embedded partly to the soil, and the roof is a membrane. The heat transfer coefficients, areas, and the heat losses of the different parts of the hydrolysis reactor are presented in Table 6. The heat losses are calculated with the equation 5. Used temperatures are -30 °C for air and -5 °C for soil.

Table 6. Heat losses of the hydrolysis reactor

| Reactor part | U-values [kW / $m^2$ K] | Areas [$m^2$] | Heat losses [kW] |
|---|---|---|---|
| Membrane | 0,76 | 593 | 37,0 |
| Wall (Gas - air) | 0,32 | 56 | 1,5 |
| Wall (Sludge -air) | 0,34 | 363 | 10,1 |
| Wall (Sludge - soil) | 0,30 | 140 | 2,4 |
| Bottom | 0,15 | 387 | 3,3 |

The produced $CH_4$ in the hydrolysis reactor is 166 kg / h, and power consumption of the equipment inside the reactor is 24,2 kW. The non-volatised digestate is unloaded to the solid-liquid separation with the mass flow of 24781 kg/h with TS of 7,8 % and temperature of 52 °C. The volatized fraction in the hydrolysis reactor is 471 kg/h and 231 kg/h is removed from the process in sand separation.

### 4.1.2 Fermenters

The fermentation process contains two identical fermenter reactors, which work parallel. The fermentation process conditions are in 52 °C and in the TS of 10 %. The substrate is brought from solid-liquid separation with the mass flow of 4916 kg/h and TS of 30 % in the temperature of 50 °C. The substrate is diluted with the recycled process water, which is provided in 50 °C and TS of 2,4 %. The mass flow of the additional water is 12138 kg / h. The heat demands to substrate and water heating are calculated with the equation 4.

The fermenters are embedded partly to the soil, and reactors have membrane roofs. The heat transfer coefficients, areas, and the heat losses of the different parts of the fermenter are presented in Table 7. The heat losses are calculated with the equation 5, and heat losses for both fermenters are calculated by multiplying the losses with two. Used temperatures are -30 °C for air and -5 °C for soil.

Table 7. Heat losses of the fermenter

| Reactor part | U-values [kW / $m^2$ K] | Areas [$m^2$] | Heat losses [kW] |
|---|---|---|---|
| Membrane | 0,76 | 1225 | 76,4 |
| Wall (Gas - air) | 0,32 | 83 | 2,2 |
| Wall (Sludge -air) | 0,34 | 539 | 15,0 |
| Wall (Sludge - soil) | 0,30 | 207 | 3,5 |
| Bottom | 0,15 | 855 | 7,3 |

The combined $CH_4$-production in the fermenters is 211,7 kg/h, and the power consumptions of the equipment in both fermenters individually are 53 kW. The combined mass flow of the fermenter digestate is 15744 kg/h with the TS of 6,53 % in temperature of 52 °C, and the combined mass flow of the produced biogas is 599 kg/h.

### 4.1.3 Ammonia stripper

The mass flow to the ammonia stripper is 19974 kg/h with the TS of 2,8 %. The feed is pre-heated with the concentrate to the temperature 85 °C. The enthalpy of the input flow is estimated to be 356 kJ/kg. The ammonia stripper operates at the temperature 100 °C and produces 407 kg/h ammonia-water with the concentration of 20 %. The evaporated fraction is condensed in a separate adiabatic cooler. Enthalpy of the evaporated fraction is estimated to be 2415 kJ/kg. Remainder of the flow is removed from the stripper column at temperature 100 °C. The enthalpy of the concentrate is estimated to be 419 kJ/kg. Heat losses of the stripper are estimated to be 2 % of the total losses.

The concentrate exits the pre-heater at temperature 62 °C with TS of 2,4 %. The evaporated fraction is cooled with the adiabatic cooler to the temperature of 20 °C.

### 4.1.4 Evaporator

The evaporator receives 40 % of the concentrate from ammonia stripper, 7827 kg/h. The flow is received in temperature of 62 °C and with the TS of 2,4 %. In the following are considered the alternative options for single-stage evaporator and multi-stage evaporator.

Single-effect evaporator

The energy balance of the single-effect evaporator is presented in the equation 11. The evaporated fraction is 5971 kg/h, and the operating temperature of the evaporator is 90 °C. The heat losses of the evaporator are assumed to be 2 % of the total heat demand. The evaporator uses 100 °C steam with the enthalpy of 2675 kJ/kg as the heating medium and the condensed steam is used to pre-heat the input feed. The condensate has enthalpy of 293 kJ/kg, and the pre-heated input feed has the enthalpy of 327 kJ/kg.

The evaporated fraction exits the evaporator as 90 °C vapor, and the concentrate is removed from the process without further treatment. The enthalpy of the evaporated fraction is 2659 kJ/kg, enthalpy of the concentrate is 285 kJ/kg. The energy demand of the evaporator can then be calculated with the equation 12.

MVR-evaporator

The MVR-evaporator requires the same energy for building up the process as single-effect evaporator, but the operating power demand can be calculated with the equation 15. The efficiency of the compressor is estimated to be 80 %. The energy flows of the heating medium and vaporized fraction are calculated at single-effect evaporator calculations.

Multiple-effect evaporator

The energy balance of the multiple-effect evaporator is presented in the equation 14. The considered evaporator has four stages, with the operating temperature levels of 78 °C, 70 °C, 60 °C, and 45 °C. Total evaporated mass flow is 5971 kg/h, and the evaporated fractions per stage are assumed equal, 25 % in each. The first three evaporated fractions are condensed in the next stage to provide heat, and the last fraction is condensed in a separate cooler.

The condensates of the vaporized fractions from each stage outflow in 2 °C lower temperature than the operating temperature in the previous stage. The condensed fractions are mostly water, and the enthalpies of the saturated water in the considered temperatures are used. The evaporated fraction from the last stage is considered as steam enthalpy in the same temperature as the operating temperature of the last stage. In the Table 8 are presented the mass flows, temperatures, and enthalpies of each evaporated fractions.

Table 8. Flow properties of the multiple-effect evaporator

| | Mass flow [kg/h] | Temperature [°C] | Enthalpy [kJ/kg] | Energy flow [kJ/h] | Energy flow [kW] |
|---|---|---|---|---|---|
| Input feed $M_f$ | 7281,0 | 80,0 | 335,0 | 2439208 | 677,6 |
| Cond. 1 $M_{c1}$ | 1492,8 | 76,0 | 318,2 | 475044 | 132,0 |
| Cond. 2 $M_{c2}$ | 1492,8 | 68,0 | 284,7 | 424974 | 118,0 |
| Cond. 3 $M_{c3}$ | 1492,8 | 58,0 | 242,8 | 362458 | 100,7 |
| Vapor. 4 $M_{v4}$ | 1492,8 | 45,0 | 2585,0 | 3858759 | 1071,9 |
| Product $M_{p4}$ | 1310,0 | 43,0 | 180,1 | 235905 | 65,5 |

The condensates from the different stages of evaporator are collected and recycled to process water tank. The concentrate is removed from the process as reject water.

The heating energy required for pre-heating the feed to the input temperature can be calculated with the equation 4. The specific heat capacity for the feed is estimated to be 4,1 kJ / kg K.

## 4.2 Methods

The heat demands of the different processes are calculated for the minimal outside temperature at the target area. Due to the variety of selections, four different scenarios with different technological selections are created. The scenarios have different options for evaporator technology and reactor heating system.

The properties of the heat generation methods are presented in Table 4. Based on the table, the most suitable heat supply technology for each scenario is considered. The selection concentrates on the end-product of the heat supply technologies and its suitability to initial scenario.

# 5 Results and Discussion

This chapter presents the calculated heat flows of a fertilizer producing biogas plant. The flow chart of the process is presented in Figure 21. The used equations and assumptions are presented in chapter 3.1. The values for the calculations are presented in chapter 4.1. The results of the heat demand calculations are presented in section 5.1. In the section 5.2 is generated 4 different scenarios from the results and considered the most suitable heat supply technology.

## 5.1 Results

The results are presented in separate tables for each subprocess. The calculated heat losses, energy demands for substrate heating, microbiological heat production, heat produced in the equipment, and the total heat demand of the reactors are presented in Table *9*. The table includes all the reactors in the process. The positive values present heat flows that require heat and negative values present heat flows brought to the process.

Table 9. Energy flows of the reactors

| Reactor | Substrate [kW] | Heat losses [kW] | Heat from microbiological processes [kW] | Heat from equipment [kW] | Total heat demand [kW] |
|---|---|---|---|---|---|
| Hydrolysis reactor | 557,0 | 54,3 | -53,2 | -24,2 | 533,9 |
| Fermenter 1 | 18,4 | 104,4 | -33,8 | -53,0 | 36,0 |
| Fermenter 2 | 18,4 | 104,4 | -33,8 | -53,0 | 36,0 |
| Reactors total | | | | | 605,8 |

The calculations for ammonia steam stripper are done for steam stripper. The heat flows regarding the energy balance and the heat demand of the ammonia stripper are presented in Table *10*.

Table 10. Energy flows of the ammonia stripper

| Flow | Mass flow [kg / h] | Enthalpy [kJ / kg] | Energy flow [kW] |
|---|---|---|---|
| Feed | 19974 | 356,0 | -1975,3 |
| Concentrate | 19566 | 419,2 | 2278,2 |
| Distillate | 407 | 2414,6 | 273,1 |
| Heat losses | | | 11,8 |
| Heat demand | | | 587,8 |

The evaporators are calculated for two different types: single-effect, and multi-effect evaporator. The energy flows of the single-effect evaporator energy balance are presented in Table *11*.

Table 11. Energy flows of the single-effect evaporator

| Flow name | Mass flow [kg / h] | Enthalpy [kJ / kg] | Energy flow [kW] |
|---|---|---|---|
| Feed | 7281,0 | 327 | 660,6 |
| Evaporated | 5971,0 | 2659 | -4410,1 |
| Concentrate | 1310,0 | 285 | -103,6 |
| Condensate | 6258,5 | 405 | -704,2 |
| Heat losses | | | -93,0 |
| Heating steam (100 °C) | 6258,5 | 2675 | 4650,4 |

The energy flows of the multi-effect evaporator energy balance are presented in Table *12*. The numberings in the flow names reference to the effect in order.

Table 12. Energy flows of the multiple-effect evaporator

| Flow name | Mass flow [kg / h] | Enthalpy [kJ / kg] | Energy flow [kW] |
|---|---|---|---|
| Input feed | 7281,0 | 335 | -677,6 |
| Cond. 1 | 1492,8 | 318 | 132,0 |
| Cond. 2 | 1492,8 | 285 | 118,0 |
| Cond. 3 | 1492,8 | 243 | 100,7 |
| Vapor. 4 | 1492,8 | 2585 | 1071,9 |
| Product | 1310,0 | 180 | 65,5 |
| Heat losses | | | 16,5 |
| Pre-heating heat demand | | | 149,7 |
| Heat demand (kW) | | | 951,9 |

The operating power demand of the MVR-evaporator is calculated with the equation 15 resulting 300,4 kW. The energy demands, supply methods, and temperature levels of the

different subprocesses are gathered in Table *13*. The energy demands and temperature levels present the minimal requirements for operating the process.

Table 13. Summary of the heat demands of the processes (*,** Alternative options)

| Process | Operating temperature [°C] | Heat demand [kW] | Commonly used heat sources | Mentions |
|---|---|---|---|---|
| Reactors - Hydrolysis reactor | 52 | 534 | Heating water circulation, Electric coil | Dependent on outside temperature |
| - Fermenters | 52 | 72 | Heating water circulation, Electric coil | Dependent on outside temperature |
| Stripper | 100 | 588 | Steam | Distillate cause waste heat flow |
| Evaporator - multiple-effect* | 80 | 952 | Hot water, steam | |
| -MVR evaporator** | 90 | 300 | Electricity | Start-up steam not included |
| Other losses | | 43 | Electric coil | Dependent on outside temperature |

The MVR-evaporator does not include the start-up steam for evaporating process. The required start-up steam is the same as calculated in the single-effect evaporator, which is presented in Table *11*.

## 5.2 Discussion

In the Table 13 are presented the heat demands and the temperature levels of the different processes in fertilizer producing biogas plant. The operating temperature and heat demand of each subprocess are the minimum requirements, that should be received from the heat recovery of a residual heat flow. The shares of the calculated total heat energy demand in fertilizer producing biogas plants are presented in the Figure 22 and Figure 23. Figure 22 presents process with multiple-effect evaporator with the total heat demand of 2189 kW.

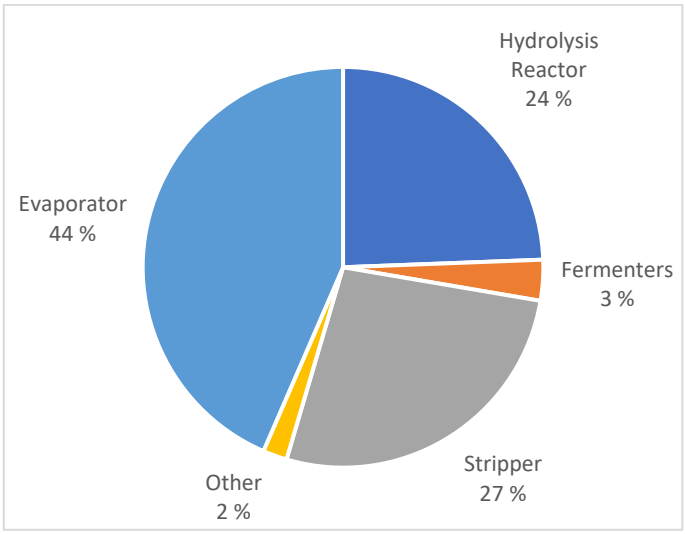



Figure 22. Share of energy demand with the multiple-effect evaporator

Figure 23 presents the energy demand of process with the operating MVR-evaporator. The total energy demand is 1537 kW, electricity demand to MVR evaporator being 300 kW and other processes heat demand being 1237 kW.

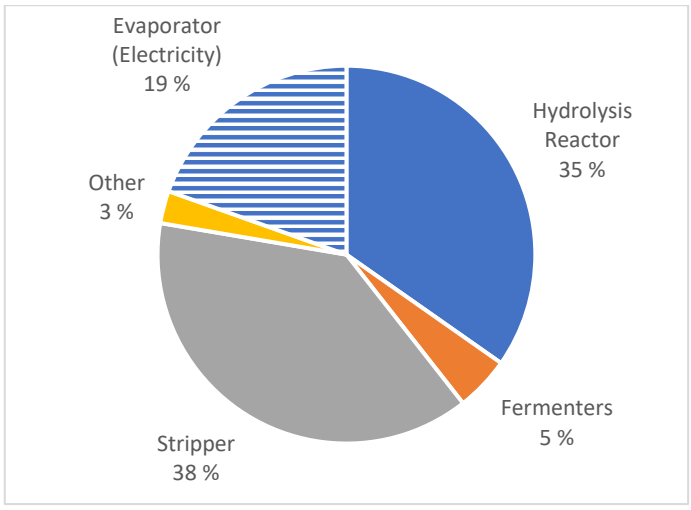



Figure 23. Share of energy demand with the MVR evaporator. MVR evaporator does not require heat for operating, but requires electricity

The figures 22 and 23 show, that both evaporator options have remarkable share, 44 % and 19 %, from the total heat demand. It should also be noted that the calculations assume only 40 % of the ammonia stripper concentrate to be evaporated, and with different evaporation rate the shares vary. In the chapter 3.1.1 is stated that the reactors typically cover 5 – 15 % of the total heat demand. (IEA Bioenergy 2013 p. 215) The calculated process stated that reactors covered together 27 % and 40 % of the total heat demand. The calculated process

contained together 3 reactors (1 hydrolysis reactor and 2 fermenter), which can explain the larger share of demand.

MVR-evaporator does not consume heat while operating (Chapter 3.1.3), and the electricity power demand (300 kW) is remarkably lower than the heat demand of multiple-effect evaporator (952 kW), which means that MVR-evaporator consumes less energy. The start-up of a MVR-evaporator consumes lot of heat energy (Table 11). Thus it requires additional capacity from the heat generation technology. Multiple-effect evaporator consumes more energy than MVR evaporator (652 kW higher demand). However, multiple-effect evaporator can operate with either hot water or steam, which widens the variety of applicable heat generation technologies. The heat load of multiple-effect evaporator does not vary, which makes it easier to operate.

In Table 9 are presented the heat demands of the reactors. The biggest heat demanding subdivision in the table is substrate heating, which covers approximately 75 % of all heat demand in the reactors together. The result seems reasonable, as the feed and additional water are heated from ambient temperatures. The heat demand of the reactors could be reduced with the pre-heating of both substrate and additional water if excessive heat is available. The remaining 25 % of the reactor heat demand is resulted from heat losses, which are dependent on the outside temperature. The heat losses could be reduced with better insulation. Alternatively, the process could be changed to mesophilic digestion, which would reduce the heating demand of the substrate.

According to the Table 9, around 85 % of the fermenters' heat demand is caused by the heat losses. The calculations are done for the coldest temperature at the target area. According to the equation 5, the heat losses are dependent on the outside temperature, and at the warmer temperatures the heat losses are reduced. This could lead to a situation, where fermenters' are energy-positive. In chapter 2.1.3 is mentioned that +/- 2 °C temperature changes cause damage to microbiological activity, and the cooling options of fermenters should be investigated. (Suomen biokaasuyhdistys ry. 2015 p. 64)

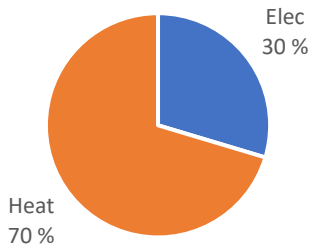
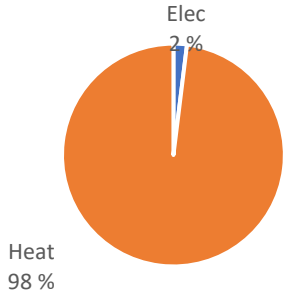
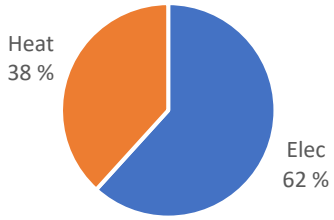
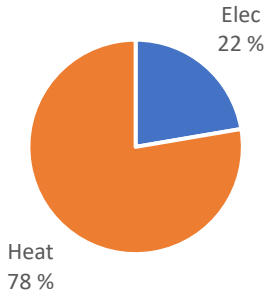
The process has three main outflows: solid-fraction from solid-liquid separation after the fermenters, ammonia stripper distillate, and evaporator concentrate. The solid-fraction exits the solid-liquid separation at 50 °C and TS of 30 %. Ammonia stripper distillate is removed at 100 °C to a separate cooler, and according to Table 10 has energy flow of 273 kW. The

evaporator concentrate in the MVR evaporator is removed at 90 °C, and according to the Table 11 causes 104 kW waste heat flow. The multiple-effect evaporator produces concentrate at 45 °C and heat flow of 66 kW (Table 12). The processes in the calculated plant operate at the minimum on 52 °C, and from the outflows only ammonia stripper distillate appears as an attractive flow for heat recovery.

Only clear optimization target is the waste heat flow from ammonia distillate, which could be used for example to pre-heat the substrate. According to the Table *13*, the lowest operating temperatures are at the reactors with 52 °C, while evaporators and stripper operate at significantly higher temperatures. The stripper concentrate pre-heats the input feed from 52 °C to 85 °C (Figure *5* and values from 4.1.3), and the temperature of the concentrate is reduced close to 52 °C. The multiple-effect evaporator provides the output flows at 45 °C (Table *8*), and MVR-evaporator recycles the condensate in own system.

The alternative methods to cover heat demands of the different processes, are summarized in Table 13. According to the Table 13, the reactors can be heated with either electric coil or hot water circulation, and the heat losses of the tanks and pipes can be covered with electric heating coils in the containers. The steam stripper requires steam supply, and evaporator heat demand can be covered with either electricity, hot water, or steam, depending on the selected technology. In the following Table 14 are presented 4 scenarios for the heat supply for more precise assessment. The scenarios are done for electric heating and water circulation heating of the reactors, for both considered evaporator types. The heat demand shares are based on data presented in Table 13.

Table 14. Alternative scenarios for evaporator types and reactor heating

| Scenario | Properties | Energy demand, electricity + heat [kW] | Figurative presentation |
|---|---|---|---|
| 1 – Expensive electricity, cheap heat available | Multiple-effect evaporator + electric reactor heating | 649 $kW_{el}$ 1540 $kW_{heat}$ |   |
| 2 – Scarce electricity, heat supply surplus | Multiple-effect evaporator + water circulating reactor heating | 43 $kW_{el}$ 2146 $kW_{heat}$ |   |
| 3 – Cheap and excessive electricity | MVR-evaporator + electric reactor heating | 949 $kW_{el}$ 588 $kW_{heat}$ |   |
| 4 – Expensive electricity, restricted area for heat production | MVR-evaporator + water circulating reactor heating | 343 $kW_{el}$ 1194 $kW_{heat}$ |   |

The heat generation technologies are presented in Table 4. According to the table, the only technologies that produce both heat and power are CHP boiler and gas turbines. The other technologies produce only heat, and the electricity must be bought from the retailer. Steam

required in steam stripping, can be generated in electric boiler and both combustion boilers. Additionally, the heat from gas turbine fume gas can be recovered to produce steam. Hot water required for multiple-effect evaporator can be produced with all the previously mentioned technologies and heat pumps. In the following are considered the best heat generation technologies for the scenarios presented in Table 14.

**Scenario 1**

First scenario uses water or steam for multiple-effect evaporation and stripping processes. The reactors are heated with electric heaters. This scenario requires approximately ¾ of the heat supply as heat, and the remainder as electricity. The scenario is suitable for situation where electricity is not available, or prices are high, or heat production is cheap.

The share of heat and electricity in scenario 1 corresponds very well to the CHP boiler production rates, where the heat efficiency is 60 % and electrical efficiency 20 %. At the warmer outside temperatures, the electric heating demand for the reactors decrease, while the heating demands of stripper and evaporator remains mainly the same. The produced excessing electricity could then be sold to the distributors.

CHP boiler requires large investments with the Rankine cycle processes, water pre-treatment, and fume gas treatment, but investing to a CHP boiler, the plant would become self-sufficient. Other alternative would be investing to a gas turbine, where the heat-electricity ratio is close to 1:1. Gas turbines would provide excessive electricity that could be used to the pumps and agitators, which are not considered in this report, or sold to the distributors. The fuel for gas turbine would be produced biogas, which makes the plant self-sufficient, but it consumes valuable product.

**Scenario 2**

In the second scenario the reactors contain water circulation system for heating, and multiple-effect evaporator is in use. Only electric heating is required for process water tanks which require 2 % of the heat demand. Remaining 98 % is covered with heat supply. The scenario is for the situation where electricity is not available, or price is extremely high.

Suitable technology for this scenario is condensing boiler, which produces steam at high efficiency. The condensing boiler requires construction work for high temperature combustion boiler and steam circulation, as well as water pre-treatment and fume gas

treatment. Other alternatives could be heat pumps which consume less electricity than electric heaters, or CHP boiler which would produce excessive electricity that could be sold to distributors.

**Scenario 3**

Third scenario has MVR-evaporator, electric heating for reactors, and steam stripping. In this scenario, from the heat demand 62 % is supplied as electricity and the remaining 38 % with heat supply. This scenario is for situations where excessive electricity is available, or heat production is not profitable.

The most suitable option to heat supply for this scenario is an electric boiler and electric heaters, which converts electricity to heat with close to 100 % efficiency (Chapters 3.2.6 and 3.2.7). Electric boiler provides the steam for stripping process, and it can also provide the start-up-steam if operated in higher power during the start-ups.

Another alternative for this scenario could be gas turbines, which produce electricity with 30 % efficiency and heat with 30 % efficiency. This technology would produce excessive heat, which could be consumed for example to dry the fertilizer and reduce logistical costs.

**Scenario 4**

The last scenario has a MVR-evaporator and hot water circulation in the reactors. The stripping process requires steam. This scenario is for the situation where electricity is expensive, but the area for the plant is restricted. The scenario has 22 % of the heat demand supplied through electricity and remaining 78 % with heat supply.

The most suitable solution for this is electric boiler for steam supply and heat pumps for heat supply. Heat pumps can produce low temperature heat supply required in the reactors with higher efficiency than electric heaters, and electric boiler is compact steam producing technology. Additionally, the electric boiler can provide the start-up-steam for MVR evaporator.

Other alternative would be to produce everything through the electric boiler if suitable heat source for heat pumps is not available. The electric consumption would be close to the heat demand.

# 6 Conclusions

The objective in this thesis was to create a study regarding the heat demand and heat flows in a fertilizer producing biogas plant. Based on the initial heat flows the objectives were to observe if the process contained any recoverable heat flows or if the heat flows could be optimized. Another objective was to search possible heat supply technologies, and based on the received heat demand, objective was to initialize the most suitable one. Other studies were found regarding the energy balance of biogas plant, but not regarding the digestate treatment. The calculations were done based on a project draft of a company operating in the biogas and fertilizer industry in the Nordic countries.

For the objectives regarding the heat flows, the subprocesses in the plant were initialized and the energy flows in each subprocess were calculated. One outflow, ammonia stripper distillate, was found, which had unutilized waste heat flow. Other outflows were not considered as profitable for heat recovery due to the low energy flow. The heat flows entering and exiting the subprocesses appeared to be close to same temperature level, and significant possibility for heat flow optimization was not observed.

Objective regarding the heat demand was succeeded, and the heat demands of the subprocesses were found in both volume-vice and temperature-vice. The heat demands of the subprocesses are presented in Table *13* and the share of the heat demands with the alternative evaporator-options in Figure 22 and Figure 23. The calculations included two alternative options for evaporation, and both options appeared to have remarkable share to the total demand.

The heat supply technology objective was not achieved as expected. This thesis considered only heat demand, instead of heat and electricity, which affected to the heat supply technology selection. The calculations had two alternative evaporators, from which one consumed heat and the other electricity. Additionally, some other subprocesses had option for electrical heating, which distorted the selection. Due to the problems in objective comparison, several different scenarios were created, and initial heat supply technology selection was done for each scenario.

The report results in several key findings. The key finding from the heat flows is the distillate from ammonia steam stripper, which has unrecovered energy flow of 273 kW. The key findings from the heat demands are the selection of the evaporator type, which affects to the total demand by 650 kW, reducing the heat demand but increasing electricity demand. On top of that, the possible need for cooling in the reactors at warmer outside temperatures is a point to be considered in the further development of the project. The key finding regarding the heat supply is the variety of options in the heat supply technologies and process selections. The heating methods should be tailored initially in each project, based on the available resources in the target area.

This thesis provides an insight to the heat flows in the fertilizer producing biogas plant, but more comprehensive picture could be obtained by calculating the electricity demands of the subprocesses. Additionally, these calculations are done for the coldest outside temperatures at the target area, and the fluctuation in the heat demand around the year should be considered for selecting the most suitable heat supply technology.

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