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Master thesis

Energetic and economic comparison of waste incineration plants and fermentation plants for municipal solid waste in the UK

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Abstract

Energetic and economic comparison of waste incineration plants and fermentation plants for municipal solid waste in the UK

The master thesis concentrates on two different cases to generate energy from MSW. In the first case, the MSW is incinerated in an incineration plant. This approach represents the present situation in the waste treatment in large parts of the UK.
In the second case, the OFMSW is separated in a treatment facility and used in a fermentation plant. The remaining waste is again used as a feedstock in an incineration plant. The difference in the net energy yield between these two cases is investigated in this thesis.

To calculate the difference in the energy yield of case 1 and case 2, a research of the existing literature about comparisons of incineration and fermentation plants and their results are reflected and data about the MSW in the UK is collected. With the input of the literature and the researched data, a model is built which compares the two different cases of waste treatment. The results of the comparisons are then examined by varying different parameters. This step is repeated by using different input parameters. Afterwards, the results are compared and analysed.

In the next part of the thesis, an economic analysis of the incineration and fermentation combined technology plant is made. In this analysis, the investment costs, the annual profits and the annual costs of an additional fermentation plant are discussed and calculated. The result of the analysis is displayed as an amortization time calculation. The results are then analysed by varying the parameters in a sensitivity analysis.

Finally, the research question is answered and a forecast for possible plant designs with an incineration and a fermentation plant in combination are discussed.

Kurzreferat

Energetischer und wirtschaftlicher Vergleich von Abfallverbrennungsanlagen und Fermentationsanlagen für kommunalen Abfall in Großbritannien

Die Masterarbeit beschäftigt sich mit zwei verschiedenen Anwendungsfällen zur Erzeugung von Energie aus kommunalen Abfällen. Im ersten Fall wird der Abfall aus nicht getrennter kommunaler Sammlung in einer Müllverbrennungsanlage verbrannt. Dieses Verfahren findet derzeit in großen Teilen von Großbritannien statt. Im zweiten Fall wird der organische Anteil des kommunalen Abfalles in einer Aufbereitungsanlage abgetrennt und in eine Fermentationsanlage eingebracht. Der restliche kommunale Abfall wird wiederum in einer Müllverbrennungsanlage verwertet. Mit dieser Arbeit soll der Unterschied zwischen diesen zwei Fällen bezogen auf den Nettoenergieertrag untersucht werden.

Um diesen Unterschied zu berechnen, wird zuerst eine Literaturrecherche zu aktuell vorhandenen Vergleichen zwischen Verbrennungs- und Fermentationsanlagen und deren Ergebnisse durchgeführt. Außerdem werden Daten über den kommunalen Abfall in Großbritannien für die spätere Berechnung gesammelt. Mit den Erkenntnissen aus dieser Recherche wird ein Modell erstellt, welches die zwei verschiedenen Abfallbehandlungsstrategien darstellt und vergleicht. Die Ergebnisse aus dem Vergleich werden dann einer Sensitivitätsanalyse unterzogen um die Einflüsse der verschiedenen Parameter zu erkennen. Dieser Schritt wird mit weiteren Eingabeparametern wiederholt und dann mit den Ergebnissen aus dem ersten Vergleich gegenübergestellt.

Im nächsten Abschnitt der Arbeit wird eine Wirtschaftlichkeitsbetrachtung des Anwendungsfalles zwei, also dem Anlagenlayout mit Fermentations- und Verbrennungsanlage, gemacht. In dieser Betrachtung werden die Investitionskosten, die jährlichen Kosten und die jährlichen Gewinne der Fermentationsanlage analysiert und schließlich in einer Amortisationsrechnung dargestellt. Die eingesetzten Parameter für die Kosten und Gewinne werden dabei wiederum variiert und in einer Sensitivitätsanalyse analysiert.
Zum Abschluss wird die Forschungsfrage der Masterarbeit beantwortet und ein Ausblick für Anlagen mit kombinierter Fermentations- und Verbrennungsanlage gemacht.

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Glossary

MSW	Municipal solid waste
OFMSW	Organic fraction of the MSW
NOFMSW	Non-organic fraction of the MSW
HV_{MSW}	Lower heating value of MSW
HV_{OFMSW}	Lower heating of OFMSW
HV_{NOFMSW}	Lower heating of NOFMSW
HV_{kMSW}	Lower heating of MSW components
HV_{kOFMSW}	Lower heating of OFMSW components
$HV_{kNOFMSW}$	Lower heating of NOFMSW components
r_{kMSW}	Percentage share of MSW components
r_{kOFMSW}	Percentage share of OFMSW components
$r_{kNOFMSW}$	Percentage share of NOFMSW components
$S_{precision}$	Separation precision
m_{OFMSW}	Mass of OFMSW
m_{NOFMSW}	Mass of NOMFSW
$E_{el/thINC}$	Electrical/Thermal energy output of the incineration plant
η_{GFSG}	Efficiency grate firing and steam generator
$\eta_{el/thST}$	Electrical/Thermal efficiency of the steam turbine
$ED_{el/thINC}$	Electrical/Thermal energy demand of the incineration plant
ED_{elFER}	Electrical energy demand fermentation
P_{knom}	Nominal power
$Cos\varphi_{k}$	Power factor
t_{kop}	Operation factor
m_{at}	Annual throughput of the existing plant
e_{th}	Specific amount of thermal energy
c	Specific heat capacity
η_{htsDIG}	Efficiency of the digester´s heat transfer system
ED_{thM}	Amount of thermal energy demand per month depending on monthly input
m_{m}	Monthly mass input into the digester
T_{dig}	Temperature inside digester
T_{out}	Average outside temperature per month
T_{sh}	Temperature rise inside the storage facility
ED_{thFER}	Total thermal energy demand of the fermentation plant per year
E_{kthM}	Amount of thermal energy demand per

	month depending on monthly input
V_{CH4}	Volume of the resulting CH_4
m_{CH4}	Mass of the resulting CH_4
R_{CH4}	Specific gas constant
T_{SC}	Temperature at standard conditions
p_{SC}	Pressure at standard conditions
$\eta_{digester}$	Efficiency of the digester
HV_{CH4}	Heating value of the methane
$E_{el/thFER}$	Electrical/ Thermal energy output of the fermentation plant
$\eta_{el/thCHP}$	Electrical/Thermal efficiency of the CHP
$ED_{el/thFER}$	Electrical/Thermal demand of the fermentation plant
η_{FER}	Overall efficiency of the fermentation plant
$E_{evaporating}$	Evaporating Energy
$E_{evaporatingH2O}$	Evaporating energy of water
mOFMSW	Mass of OFMSW per ton MSW
Θ_{OFMSW}	Water content OFMSW
$\Theta_{s,OFMSW}$	Specific water content OFMSW
ω_{OFMSW}	Solid content of OFMSW
m_{cc}	Mass of the converted carbon
o_c	Organic content
r_C	Carbon rate
r_{cv}	Conversion rate
m_{CH4}	Mass of the resulting CH_4
m_{cc}	Mass of the converted carbon
s_{CH4}	CH_4 share of biogas
M_{CH4}	Molar mass of methane
M_C	Molar mass of carbon
$t_{Amortization}$	Amortization time
i_{costs}	Investment costs
p_{annual}	Annual profits
c_{annual}	Annual costs
$t_{operating}$	Operating time

1. Motivation

In parts of the UK, municipal waste is still collected combined or rather the willingness of separating waste is very small. In 2016, the household waste in England was recycled by 45%, the remaining waste was residual waste. In England, only 10 % of food waste is recycled. As the recycling rate for biodegradable waste is low in most parts of the UK, the waste is collected combined and brought to incineration plants. The organic fraction of municipal solid waste (MSW) is incinerated as well. (Department for Environment, Food and Rural Affairs, 2017, a)

In this thesis the following two cases are compared. In the first case, the organic waste is incinerated combined with the remaining waste. In the second case, the organic fraction of the waste is separated from the remaining MSW on site of the plant. Afterwards, the organic fraction of the municipal solid waste (OFMSW) should be treated in a fermentation plant. The energy balances of both cases shall be compared subsequently. The hypothesis is, that the water content of the biodegradable fraction reduces the heating value of the incineration plant and that if the bio waste is separated, the overall energy output will increase.

2. Theoretical framework

The following chapter describes the technology used in incineration plants and the fermentation technology. Also the efficiencies and other key figures of the processes are mentioned.

2.1 Incineration

In the following chapter, the process of waste incineration plants is analysed.

In the past, the main function of waste incineration plants was the reduction of the waste volume that goes into landfill. Since the late 1990`s, the use of waste incineration plants for the energy supply was focused more intensively. Thus, the energy efficiencies of thermal waste treatment were enhanced. (Franz Valentin, 2012)

2.1.1 Incineration process

Conventional incineration plants are composed of a weighing device, a ware house, dosing devices, an incinerator with additional facilities and heat recovery systems for the thermal use. A scheme of the process steps of an incineration plant is given in figure 1. The waste is brought to the plant with garbage trucks. The trucks are weighed to control the amount of waste in the ware house. In the ware house a bunker complex and a crane is installed. Within the bunker, the crane mixes the waste to a homogenous mass. In the next step, the crane grabs the prepared waste and feeds the incinerator continuously. The waste is applied on a grate inside the incinerator. The grate firing of waste is a complex process with several process stages. At first, the waste is dried at a temperature of about 100 °C. The water fraction of the waste is evaporating within the air flow. The next stages are the pyrolysis and the gasification. The temperatures rise to 250° C to 500° C. In this phase, the hydrocarbons are split off and a carbonized gas forms. In the following step, the remaining combustible parts of the waste incinerate on the grate. Afterwards, the gasification products oxidize with oxygen in the upper part of the combustion chamber. The temperature increases to 1000° C. In the last phase, the post combustion of unwanted substances in the flue gas takes place at around 850° C. The emerging flue gases are led to a steam boiler. The produced steam is used to drive a turbine to generate electricity in an electric generator. The electricity is used for self-consumption of the plant and transmitted to third parties. The remaining heat is either cooled in an air cooler or delivered to consumers near to the plant. (Franz Valentin, 2012)

Currently, the boiler efficiencies in incineration plants are, depending on their age, between 70 % and 85 %. The net electrical efficiency is about 21 %. In the net electrical efficiency, the own consumption of the plant is already considered. (Fehrenbach, Giegrich, & Mahmood, 2007) The cooled flue gases are then carried to the flue gas cleaning. In the flue gas cleaning, the remaining harmful substances are isolated in various treatment stages. After the cleaning, the gases are emitted to the environment by a chimney. The residues from the incineration and the flue gas cleaning are collected and are further utilised or brought to landfill. (Franz Valentin, 2012).

Figure 1 shows the process of an incineration plant.

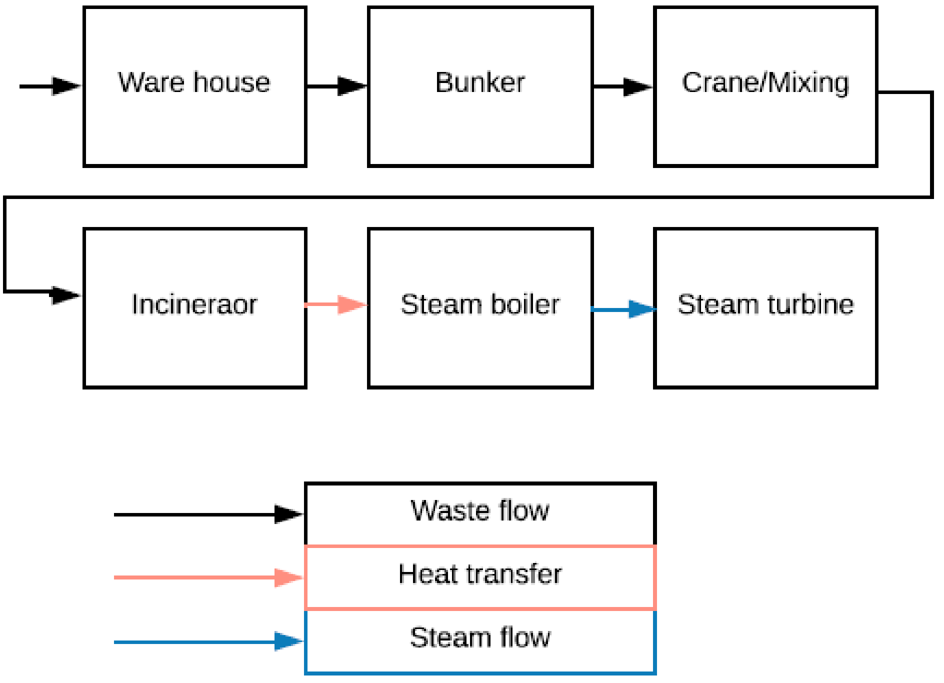

Figure 1: Process steps of an incineration plant. Modified according to (Franz Valentin, 2012)

2.2 Fermentation

The following chapter describes the fermentation technology. Especially the process of fermentation plants is investigated and explained.

2.2.1 Fermentation process

Fermentation is a bacterial process which works without oxygen. During the process, biogas, a burnable gas, consisting partly of methane, is formed. The process takes place in nature, like in marshes or digestive tracts of animals, methane formation happens. (Kaltschmitt, Hartmann, & Hofbauer, 2012) Fermentation plants are built because of the following reasons The reduction of material that goes to landfill, the reduction of environmental impacts by greenhouse gases and energy production. (Department of Biological and Agricultural Engineering, University of California, 2008)

The fermentation process can be split in four main process steps. The waste input consists of complex organic matter like carbohydrates, proteins and fats. First, the input is split in sugar, amino acids and fatty acids during the hydrolysis. Second, the acidogenesis, the products of the hydrolysis are fermented to volatile acids. Third, in the acetogenesis, acetic acid, carbon dioxide and hydrogen are generated. In the methanogenesis, methane and carbon dioxide are produced. Finally, biogas leaves the digester with following composition. The biogas exists of 45 Vol. % to 65 Vol. % methane and 35 Vol. % to 50 Vol. % carbon dioxide. The numbers depend strongly on the input material and the process. (Kaltschmitt, Hartmann, & Hofbauer, 2012)

2.2.2 Solid dry fermentation plants

There are different technologies for fermentation plants on the market. The description below relates to the solid fermentation technique. A fermentation plant includes the digester, where the main fermentation process takes place, as well as pre-treatment and the utilization of the biogas.

The fundamental facilities of the process are the weighing device, the treatment plant, the reception area, the intermediate store, the mixer system, the digester and a gas engine. The biogenic waste is delivered to the fermentation plant by waste trucks. Like in the incineration plant, the waste is weighed for monitoring purposes. After the waste is delivered into the ware house, it is picked up and brought to a treatment plant. There, the waste is shred and sieved. That step is necessary, to remove unwanted parts like plastics and metals. Afterwards, the prepared waste is convoyed to an intermediate store. With an intermediate store, the digester can be operated day and night autonomously. From there, the substrate is delivered into the mixer system. In the mixer, the waste is blend with water and biological active material from the digester. In the next step, the waste is inserted into the digester via a heat exchanger. The heat exchanger heats the substrate to a temperature of about 55° C as the process in the digester works thermophilic. The emerging biogas in the digester is then carried to a gas engine. Before the gas engine several pre-treatments of the biogas are necessary. The gas engine drives an electric generator to generate electricity. The digester residue is then separated in a liquid and a solid fraction. The solid fraction is sieved, composted and used as solid fertiliser. The liquid fraction is picked up by local farmers for organic fertilising. (Department of Biological and Agricultural Engineering, University of California, 2008)

Figure 2 depicts the dry fermentation process.

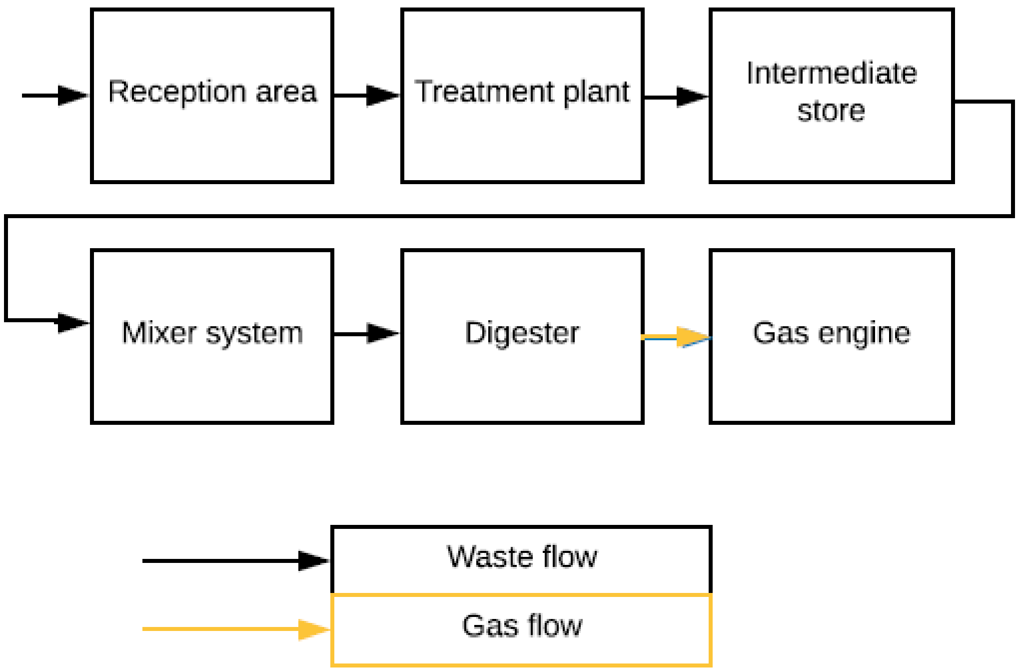

Figure 2: The dry fermentation process. Modified according to (Krismer, 2015)

3. Research question

What is the difference in the energy yield and the economic profit, if the biodegradable fraction of municipal solid waste (MSW) is separated and treated in a fermentation plant instead of treating the joint waste in an incineration plant?

The current literature does not answer this question entirely. The question has never been investigated for the UK waste specifications and the already elaborated theory does not include a satisfying consideration of the fermentation plant. The fermentation plant has been modelled in the past and never been investigated with real-life data. The thesis, "Energetic comparison of waste incineration plants and fermentation plants for municipal solid waste in the UK" is designed to fill this knowledge gap.

3.1 I-SMART Criteria

I-Innovative:

Currently there are no specific energetic comparisons between solid dry fermentation and incineration plants for the UK Especially the fermentation is not investigated in the literature. The investigation of fermentation and incineration plants and the resulting combination out of both of them has never been done before for UK waste. Furthermore, the fermentation technology used for the modelling is solid dry fermentation. This technology is unique and has never been investigated in terms of energy. The specification on energetic efficiencies is a new point of view too.

Decision makers in the UK will benefit from the thesis as the thesis gives recommendations for the best solution for the waste management. Decision makers in other countries with similar waste specifications will benefit from the thesis as well. The thesis may also make fermentation more popular in the UK and this will lead to decreasing amounts of waste going to landfill. For companies working in the field the final model of the thesis will help to calculate the energy balance of their plants.

S-Specific:

The thesis describes two technologies to produce energy from waste. Other currently used technologies are not considered. Furthermore, not the total market for waste to energy is investigated but only the UK market.

M-Measurable:

The waste data for the thesis is taken from the Department of Environment, Food and Rural Affairs from the UK government and from Thöni. Hence, the data is transparent and accessible. If data, indexes or values cannot be found in the literature, sensitivity analysis will be done.

A-Accepted:

The methods used are accepted as they are scientific comparison and thermodynamic modelling.

R-Realistic:

The data about incineration plants will be researched from the literature and the data about the fermentation will be collected from Thöni. As both data sets are already available, the success of the thesis can be termed realistic.

T-Terminable:

The timetable is described in chapter six. If there are no unexpected incidents, the thesis will be finished within the intended time.

4. Literature

The chapter Literature describes papers on the topic, that are useful for the thesis. The literature investigated is primarily used for the idea generation process and not for comparisons.

4.1 Comparison between fermentation and incineration

Tobiassen et al compare the energy yield from incineration and fermentation of biodegradable waste. The paper distinguishes between three plant designs for both technologies. These are power only plants, combined heat and power plants and combined heat and power with flue gas condensation plants. In contrast to life cycle analysis (LCA), only the energy yield is investigated. One hypothesis of the paper is that the efficiency of the incineration plant is depending heavily on the composition of the input. That means, the efficiency depends on the biodegradable waste fraction used as an input. The paper also claims that it is very difficult to determine the heating value of the biodegradable waste and that thermodynamic modelling is necessary. The two already mentioned technologies are fermentation of biodegradable waste only, followed by a biogas engine, and incineration of the biodegradable waste mixed with MSW followed by a traditional steam cycle. The energy consumption for the pre-treatment is not taken into account in this paper. (Tobiassen, Kahle, Hindsgaul, & Kamuk, 2014)

To define the composition of the biodegradable waste, samples of collected waste in Denmark were used. The heating value of the waste was calculated with Schwanecke´s formula. The lower heating value of the samples ranges from 1.4 GJ/ ton to 6.4 GJ/ ton. For the MSW with included biodegradable waste, a lower heating value of 11.5 GJ/ ton was expected. The average mass composition of the biodegradable waste was 71.1 % moisture, 13.9 % carbon, 8.1 % oxygen and small amounts of other substances. The MSW mass composition used was 30.1 % carbon, 22.9 % oxygen, 22.3 % water, 19 % ash and small parts of some other substances.

To calculate the net electrical efficiency of the incineration plant, a modern power-only plant with an air cooled condenser technology was used. The result of the calculation shows that a net electrical efficiency of 28 % is possible. The calculation also shows that the combustion of biodegradable waste lowers the energy yield due to the high water content of the fuel.

In scenario two, the power plant was enhanced with combined heat and power (CHP) production. In a CHP plant, energy which cannot be converted to electricity is used for heating. The calculation method for scenario two was similar to scenario one. But instead of a 28 % electrical efficiency, a 25 % electrical efficiency and a 60.5 % heat production can be reached. Hence, an energy plant efficiency of 85.5 % can be accomplished.

As a third scenario, waste incineration with CHP and flue gas condensation was investigated. This technology allows using the energy, which is released by condensing the vapour of the flue gas. This energy can then be used as low-temperature heat. The resulting total efficiency in that scenario was 93.8 %.

To describe the fermentation plant, pilot-scale models were used in the paper. Tobiassen et al characterize the fermentation as complex and claim a lack of available data. Furthermore, the electrical energy consumption of the fermentation is not considered.

Like in the calculation for the incineration plant, the fermentation was investigated for three scenarios. The first scenario was biogas combustion in a power only gas engine, the second scenario was biogas combustion with heat recovery and the third scenario was biogas combustion with heat recovery and flue gas condensation.

For the thermodynamic modelling a few assumptions were made. The district heating network for scenario two and three has a supply temperature of 85° C and a return temperature of 50° C and the biogas plant delivers the average methane yield as calculated in the pilot scale experiment. The temperatures of the district heating network were equal to the temperatures used for the scenarios with incineration.

Table 1 shows the results of the three scenarios for the two technologies. As already mentioned, the fermentation scenarios are calculated as gross figures. For the incineration an additional calculation for the efficiency of biodegradable waste incineration only is made.

Principally, the figures in table 1 are calculated by a thermodynamic model of Tobiassen et al.

Table 1: Results of the three scenarios. Data from (Tobiassen, Kahle, Hindsgaul, & Kamuk, 2014)

	Efficiency of incineration with mixed MSW	Efficiency of incineration with biodegradable waste only	Efficiency of the fermentation with biodegradable waste
Power only	27.9 % electrical efficiency	26,7 % electrical efficiency	28,1 % electrical efficiency
Combined heat and power	25.0 % electrical efficiency 60.5 % district heat Total efficiency: 85.5 %	24.0 % electrical efficiency 55.1 % district heat Total efficiency: 79.1 %	28.1 % electrical efficiency 31.2 % district heat Total efficiency: 59.3 %
Combined heat and power with flue gas condensation	24.9 % electrical efficiency 68.9 % district heat Total efficiency: 93.8 %	23.3 % electrical efficiency 100.7 % district heat Total efficiency: 124.0 %	28.1 % electrical efficiency 32.3 % district heat Total efficiency: 60.5 %

For the thesis, scenario one and two will be initial points. The efficiency of incineration with biodegradable waste is slightly lower than with mixed MSW. This is also what the hypothesis of the thesis says. Also interesting is the fact, that the efficiency in the electrical energy only scenario is higher with fermentation. Only the much lower district heat efficiency lowers the performance of the fermentation plant. For the thesis, the results of the paper can be used to investigate the incineration with biodegradable waste and municipal solid waste in the UK. Also the calculation of the heating value with

Schwanecke´s formula can be used in the thesis. The composition of the waste cannot be used, as the paper is about Denmark. Also the modelling of the fermentation is not satisfactory. For the thesis, also the energy consumption of the plant shall be investigated to get net electrical efficiencies. With that indicator, the results can be compared better.

Di Maria and Micale use LCA to compare the benefits and the downsides of incineration and fermentation followed by composting for the biodegradable fraction of MSW in their paper. The LCA approach is to include other issues like environmental influences and economic factors (Tobiassen, Kahle, Hindsgaul, & Kamuk, 2014). The paper explains, that the organic fraction of MSW can represent 15 % to 40 % of the MSW depending on the segregation at the source. The authors of the paper use source segregation as a parameter. Two scenarios are investigated. The first scenario uses a source segregation of 0 %. That means, that the MSW is collected combined and no additional bio-waste collection is necessary. Scenario 2 investigates a source segregation of 52 %. Therefore, bio-waste bins were used to collect 52 % of the biodegradable waste. For scenario 1, incineration was used as technology, for scenario 2 fermentation with composting was used. (Di Maria & Micale, 2014)

The results show, that the energy recovery in scenario 1 is higher than in scenario 2. This is because in scenario 1 also the remaining MSW is used for energy generation.

For the master thesis, the results cannot be used, as the paper compares MSW in scenario 1 with biodegradable waste only in scenario 2. But the method with using different values for segregation is interesting. In the master thesis source segregation is not considered, but segregation at the plant will be an important parameter.

Amoo and Fagbenele discuss MSW as a renewable energy source. The paper explains incineration and fermentation as possible technologies to produce renewable electricity in Nigeria. The methods used for the paper seem appropriate for the master thesis. At first, the calorific values of specific and regional MSW were estimated with data from the literature. To calculate the produced thermal energy in the incineration plant conversion efficiencies from the literature were assumed. To calculate the biogas generation per ton MSW, also assumptions from the literature were used. Afterwards, the methane fraction in the biogas is assumed to be 0.6 for a typical process. To calculate the produced electricity, the average efficiency of a steam power plant is used for the incineration and the average efficiency of a gas engine is used for the fermentation. (Amoo & Fagbenle, 2013)

For the thesis, this approach is useful. Especially the calculation for the electricity production and the incineration plant can be adopted for MSW in the UK. For the fermentation, the biogas yield and the methane concentration will be calculated with experiences of Thöni fermentation plants.

4.2 Data on waste composition

The Department for Environment, Food and Rural Affairs publish annually the digest of waste and resource statistics. The latest report is from the year 2017. The digest is an overview of statistics about waste in the UK. For the thesis, especially the statistics about the waste composition in the UK are relevant. Also other statistics like the recycling statistics or the treatments statistics are interesting. Households in the UK produced 26.7 Million tonnes of waste in 2015. 22.2 Million tonnes accrued in England, 2.4 Million tonnes in Scotland and about 1 Million tonnes in Wales and Northern Ireland. In 2015 over 15 Million tonnes of municipal solid waste was sent to landfill. About 8 Million tonnes of it were biodegradable waste. The recycling rate in England was about 44 % in 2015. In comparison, the recycling rate in the year 2000 was only 11 %. The English household waste composition in 2015 was 12.5 Million tonnes residual waste, 5.7 Million tonnes dry recycling, 4 Million tonnes other organics and 1.4 % was separately collected food waste. Residual waste is described as waste from household's regular collections, rejects from recycling and bulky waste. Dry recycling includes paper and card, plastics, electronic waste and metals. Other organics means green garden waste, mixed garden and food waste and wood. (Department for Environment, Food and Rural Affairs, 2017, a)

The Department for Environment, Food and Rural Affairs also publish regularly the report Statistics on waste managed by local authorities in England. This data set is about local authority collected waste in 2016/17. It includes household waste and non-household waste. According to the study, the total waste from households in England was 22.8 Million tonnes in 2016. 44.2 % of the waste was recycled, the remaining waste is residual waste. (Department for Environment, Food and Rural Affairs, 2017, b)

5. Methods

The research question is: What is the difference in the energy yield, if the biodegradable fraction of municipal solid waste (MSW) is separated and treated in a fermentation plant instead of treating the joint waste in an incineration plant?

In this chapter, the methods to reach the target of the thesis are explained. Figure 3 describes the two cases investigated. Case 1 has an incineration plant only layout. The collected MSW (in the UK) is delivered to the incineration plant as combined waste. The advantages of this case is that no separation neither at the source nor at the plant is necessary. The generated energy in form of electricity and heat will be used for the self-consumption of the plant and for other purposes. The disadvantage of case 1 is that the biodegradable waste is not separated. The whole waste goes into incineration. This means, that also the OFMSW is burned although it might lower the efficiency of the plant. In case 2, the delivered MSW is separated directly at the plant. The separated OFMSW is fermented in the fermentation plant and the remaining MSW is incinerated in the incineration plant. The generated energy is again used for the self-consumption of the plants and for further applications. The advantages of case 2 are that the biodegradable waste will not decrease the energy efficiency of the incineration plant and the fermentation plant will produce additional energy. The disadvantage of case 2 is the necessary separation of the waste at the plant and the extra self-consumption of the fermentation.

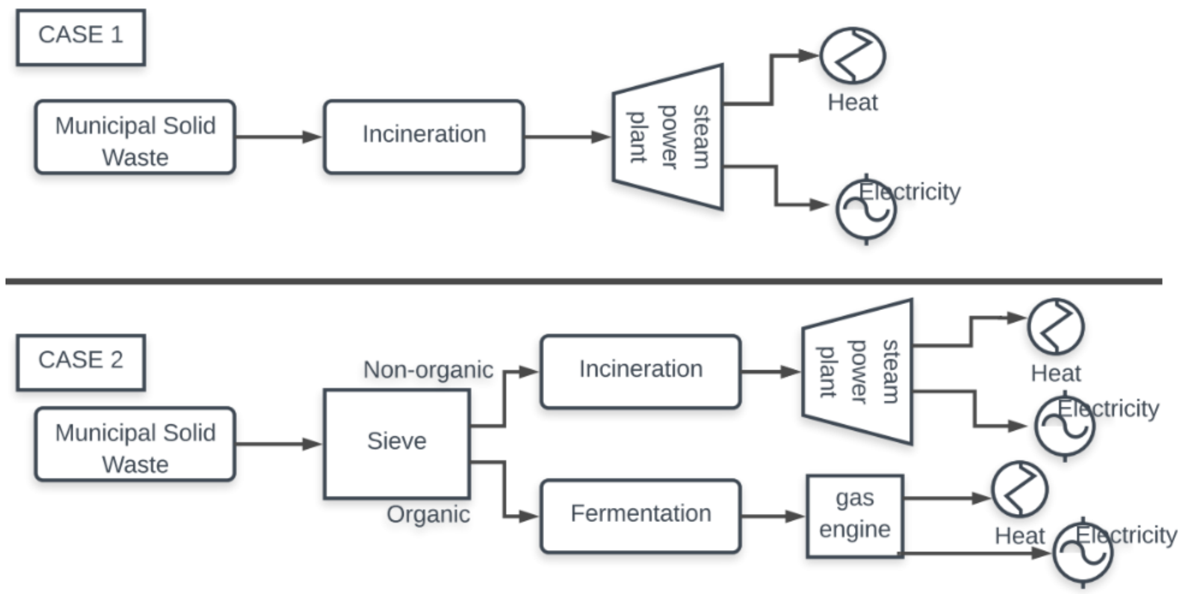

Figure 3: The two cases for the calculation.

The following section discusses the model which is used for the thesis. To calculate the energy demands and the energy generation for the two cases, a model is build. The model includes waste specifications, figures and energy consumption of different separation systems, the efficiency of the incineration and fermentation process and the efficiencies of the steam power plant and the gas engine. The target of the model is to calculate the energy yield of both cases and to compare them.

5.1 Waste input

The waste input is one of the most significant parameters to calculate the energy balance of a waste treatment plant. Waste composition varies a lot in the UK. Not only regional but also seasonal differences appear. Therefore, the model includes different waste compositions to calculate an average energy balance and various energy balances for specific cases. Specific waste compositions in the analysis will be the winter or summer compositions and some regional compositions. The waste compositions will be multiplied with calorific values from the literature to calculate the energy content of the wastes.

The data about the waste in the UK are from an UK based company working in the biogas and waste business that have access to specific UK waste data. With the specific UK waste data, the calorific values are calculated.

5.2 Separation process

For case 2, the separation of MSW in an OFMSW and in a NOFMSW fraction is necessary. Currently, there are different technologies to segregate waste on the market. The energy consumptions of the following procedure will be used for the model.

The MSW is brought to a single shaft operating bag opener. There, the MSW is cut into smaller sizes and homogenized. Afterwards, the MSW is forwarded to the drum sieve via conveying belt. The drum sieve is installed in a slanting position. The MSW moves from the higher input position to the lower output position. The sieve-hole dimension on the sieve is 80 mm. The small sized particles of the MSW fall through the drum sieve and the inert fraction moves on the screen. On the rear side of the sieve, the coarse fraction drops off. The fine fraction drops beneath the machine. (Masias Recycling, 2018)

5.3 Efficiency of incineration plants

The efficiency of incineration plants depends on a lot of parameters. The most important parameters are the age of the plant, the technology used and the way of energy recovery. All of these parameters should be implemented in the model. For the model, two plant layouts are considered. One layout is a waste incineration plant with power only output. The remaining heat is emitted to a cooling system. The second layout is an incineration plant with combined heat and power production. Similar to the power only plant, the steam drives a generator to produce electrical energy. But instead of a cooling device, the heat is delivered to a consumer like a district heating network. This technology improves the overall efficiency of the plant, but lowers the electric efficiency because the condensation temperature of the steam in generally higher.

To calculate the energy output of the incineration plant, efficiencies from the literature are used. Literature researches show electrical efficiencies about 21 % (Fehrenbach, Giegrich, & Mahmood, 2007).

5.4 Efficiency of fermentation plants

As for the incineration plant, a lot of parameters determine the efficiency of a fermentation plant. Especially the energy recovery technologies used are interesting for the model. In a first plant layout, a power only production will be discussed. The biogas is burned in a gas engine and the engine drives a generator. For an advanced model, also a waste heat utilization is considered. The heat recovery from the flue gas after the engine is used to supply consumers with heat and for self-consumption purposes. (Tobiassen, Kahle, Hindsgaul, & Kamuk, 2014)

To determine the efficiency of the fermentation plant, experiences of consisting Thöni fermentation plants are applied (Thoeni Industriebetriebe GmbH, 2018, a).

5.5 Model environment summary

The model is created with the spreadsheet computer application Microsoft Excel. Figure 4 and figure 5 show the model parameters for case 1 and case 2.

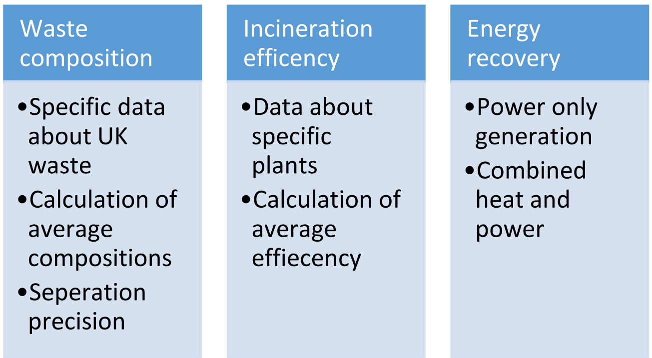

Figure 4: Model parameters for case 1

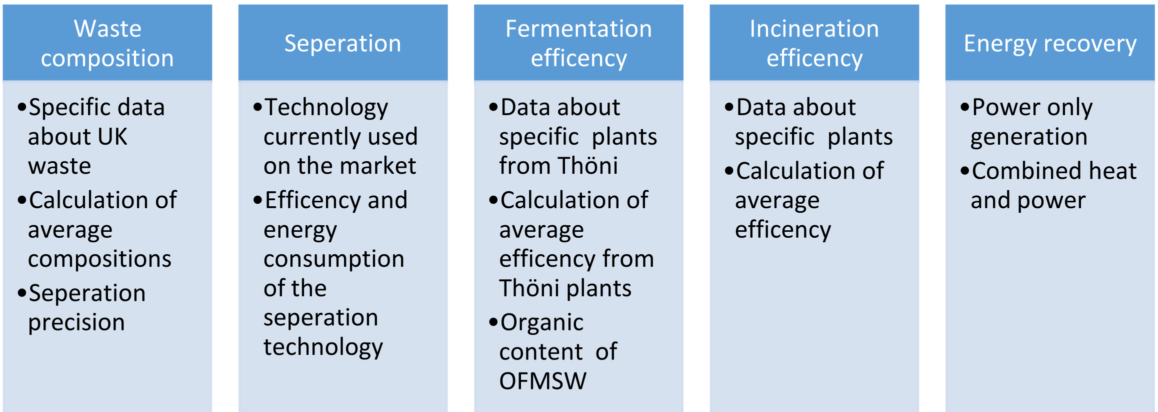

Figure 5: Model parameters for case 2

The system boundaries are defined as following:

Principally the difference in the energy yield is investigated and facilities that are necessary in both cases are neglected.

The model starts with the waste being in the ware house of the incineration plant. For case 2, the model starts with the waste being in the pre-treatment aka separation. The modelling finishes with the energy recovery. For power only plants with the produced electricity in the generator, for combined heat and power plants with the produced electricity and the produced heat, that goes to district heating. The energy used for waste collection is not part of the model. Also the efficiencies of voltage transformation substations and district heating are not considered.

6. Timetable

Table 2 shows the timetable for the master thesis. The milestones are the building of a first simple model until the beginning of April. Therefore, all the necessary data must be collected beforehand. After evaluating the first model, an advanced model should be established. In the period from early May to Mid-June, the model should be evaluated again and the main sections of the thesis should be written. Afterwards the thesis will be proof read. Finally, the thesis will be printed and submitted.

Table 2: Timetable for the master thesis

From:	To:	Task:
26.01.18	19.02.18	Pre-version of the master thesis
19.02.18	11.03.18	Collecting data for the model
11.03.18	01.04.18	Building a first model
01.04.18	22.04.18	Evaluation of the first model
22.04.18	06.05.18	Building of an advanced model
06.05.18	20.05.18	Evaluation of the second model
20.05.18	17.06.18	Creating main section of the thesis
17.06.18	08.07.18	Writing remaining section of the thesis
08.07.18	29.07.18	Proofreading of the thesis
29.07.18	19.08.18	Rework of the thesis
19.08.18	27.08.18	Printing and binding of the thesis
28.08.18	28.08.18	Submission of the thesis
11.09.18	12.09.18	Master´s examination

7. Calculations for the model

Chapter 7 describes the calculation of the model and the formulas used. To create the model, empirical data from existing fermentation and incineration plants were used. Furthermore, process engineering calculations were made to complete the model. Some values are specific for different plants and different locations. Therefore, sensitivity analyses were made. All electrical and heat energy consumptions were calculated for one ton of waste, which allows comparisons between different plants.

7.1 Waste composition

The MSW is a mix of different waste types. These waste types for example are plastics, paper and card, organics, textiles etc. The different waste types also have different heating values. To calculate the heating value of one ton of MSW, the amounts of the waste types are split up in percentages and multiplied by the specific heating value of each waste type. The heating value for one ton of MSW is calculated by formula 1.

$$HV_{MSW} = \sum_{i=1}^{k} HV_{kMSW} * r_k$$

(1)

- HV_{MSW} = Lower heating value of MSW [kWh/ t MSW]
- HV_{kMSW} = Lower heating value of MSW components on wet basis [kWh/ t]
- r_{kMSW} = Percentage share of MSW components [-]

To calculate the heating value of the OFMSW separated from the MSW, the organic waste types are summed up together and multiplied by the heating value of the organic waste types. As it is practically not possible to separate 100% of the organic fraction from the MSW the separation precision needs to be considered. Therefore, the heating value of the OFMSW has to be multiplied by the separation precision.

Formula 2 shows how the eating value of the OFMSW is calculated.

$$HV_{OFMSW} = \left(\sum_{i=1}^{k} HV_{kOFMSW} * r_{kOFMSW} \right) * s_{precision}$$

(2)

- HV_{OFMSW} = Lower heating value of OFMSW [kWh/ t MSW]
- HV_{kOFMSW} = Lower heating value of OFMSW components on wet basis [kWh/ t]
- r_{kOFMSW} = Percentage share of OFMSW components per ton MSW [-]
- $s_{precision}$ = Separation precision [-]

The OFMSW mass of one ton MSW is calculated by multiplying the mass of MSW with the percentage share of OFMSW components per ton MSW and the separation precision. Formula 3 shows the calculation.

$$m_{OFMSW} = \left(m_{MSW} * \sum_{i=1}^{k} r_{kOFMSW} \right) * s_{precision}$$

(3)

- m_{OFMSW} = Mass of OFMSW [t OFMSW/ t MSW]
- m_{MSW} = Mass of MSW [t MSW]
- r_{kOFMSW} = Percentage share of OFMSW components per ton MSW [-]
- $s_{precision}$ = Separation precision [-]

For case 2, the heating value of the MSW without the organic fraction is important as well. Therefore, all non-organic waste types are summed up and multiplied by the different heating values of each waste type. The resulting heating value is then multiplied by 100 %-separation precision.

Formula 4 shows the calculation of the energy content of the MSW without the organic fraction.

$$HV_{NOFMSW} = \left(\sum_{i=1}^{k} HV_{kNOFMSW} * r_{kNOFMSW} \right) * (100\% - s_{precision})$$

(4)

- HV_{NOFMSW} = Lower heating value of NOFMSW [kWh/ t MSW]
- $HV_{kNOFMSW}$ = Lower heating value of NOFMSW components on wet basis [kWh/ t]
- $r_{kNOFMSW}$ = Percentage share of NOFMSW components per ton MSW [-]
- $s_{precision}$ = Separation precision [-]

The mass of the NOFMSW per ton MSW is calculated similar to Formula 3. But instead of using the OFMSW components the NOFMSW are used and the separation precision needs to be subtracted from 100%. The final calculation is shown in formula 5.

$$m_{NOFMSW} = \left(m_{MSW} * \sum_{i=1}^{k} r_{kNOFMSW} \right) * (100\% - s_{precision})$$

(5)

- m_{NOFMSW} = Mass of NOFMSW [t NOFMSW/ t MSW]
- m_{MSW} = Mass of MSW [t MSW]
- $r_{kNOFMSW}$ = Percentage share of NOFMSW components per ton MSW [-]
- $s_{precision}$ = Separation precision [-]

7.2 Calculations for case 1

Chapter 7.2 concentrates on the calculations of case 1 with an incineration plant only layout.

7.2.1 Efficiency of the incineration plant for case 1

The calculations for case 1 are consisting of a multiplication of different efficiencies and additions of the incineration plants own consumptions. The initial value is the heating value of the MSW which is used as a feedstock for the incineration plant. That value is multiplied by the efficiencies of the plant. In formula 6 the heating value of the MSW is multiplied by the efficiency of the grate firing and steam generator and the electrical efficiency of the steam turbine to calculate the electrical energy output of the plant. For the calculation of the thermal energy output, the same multiplications are made but instead of the electrical efficiency, the thermal efficiency of the steam turbine is used. Finally, the electrical and thermal energy demands of the incineration plant are subtracted. Therefore, formula 6 shows the calculation of the electrical and thermal energy output of the incineration plant.

$$E_{el/thINC1} = HV_{MSW} * \eta_{GFSG} * \eta_{el/th\,ST} - ED_{el/thINC}$$

(6)

- $E_{el/thINC1}$ = Electrical/Thermal energy output of the incineration plant [kWh/ t MSW]
- HV_{MSW} = Lower heating value of MSW [kWh/ t MSW]
- η_{GFSG} = Efficiency grate firing and steam generator [-]
- $\eta_{el/thINC}$ = Electrical/Thermal efficiency of the steam turbine [-]
- $ED_{el/thINC}$ = Electrical/Thermal energy demand of the incineration plant for 1 t MSW [kWh/ t MSW]

To calculate the total, the electrical and the thermal efficiency of the incineration plant, the energy outputs are divided by the heating value of the MSW (HV_{MSW}). This calculation step is shown in formula 7.

$$\eta_{el/th\,INC1} = \frac{E_{el/thINC1}}{HV_{MSW}}$$

(7)

- $\eta_{el/thINC1}$ = Electrical/Thermal efficiency of the incineration plant [-]
- $E_{el/thINC1}$ = Electrical/Thermal energy output of the incineration plant [kWh/ t MSW]
- HV_{MSW} = Lower heating value of MSW [kWh/ t MSW]

7.3 Calculations for case 2

To calculate the efficiency of case 2, the efficiency of the fermentation plant and the efficiency of the incineration plant are considered. To calculate the efficiency of the fermentation plant, the electrical and thermal consumers need to be considered beforehand. The energy consumptions of the fermentation plant are all calculated for a throughput of the organic part of one ton MSW (m_{OFMSW}).

7.3.1 Calculation of the electrical energy demand of the fermentation plant

All electrical consumers of the fermentation plant which are not necessary for case 1, with an incineration only plant layout, were considered in the model. For the pre-treatment of the waste different technologies were considered. The, for the calculation used operation time factors, are taken from existing plants. In existing plants, the electrical energy demand for each electrical consumer is calculated in specific electrical energy demand per annual throughput of OFMSW (kWh/m_{at}).

To calculate the energy demand of each electrical consumer, the nominal power of the consumer is multiplied by its power factor and its operation time and then multiplied by the hours per year. To calculate the energy demand per ton OFMSW, the multiplication is divided by the annual throughput of the existing plant. Finally, the result is multiplied by the mass of the organic part of the MSW (m_{OFMSW}), as it is important for the comparison in chapter 8, that the electrical energy demand is calculated for a throughput of the organic part of one ton MSW (m_{OFMSW}). Formula 7 shows the calculation of the electrical energy demand of the fermentation plant for a throughput of the organic part of one ton MSW.

$$ED_{elFER} = \left(\frac{\left(\sum_{i=1}^{k} P_{k,nom} * cos\varphi_k * t_{kop}\right) * 8760}{m_{at}}\right) * m_{OFMSW}$$

(7)

- ED_{elFER} = Electrical energy demand of the fermentation plant [kWh/ t MSW]
- P_{nom} = Nominal Power [kW]
- $\cos\varphi$ = Power factor [-]
- t_{op} = Operation factor [-]
- 8760 = Hours per year [h/a]
- m_{at} = Annual throughput of the existing plant [t OFMSW/ a]
- m_{OFMSW} = Mass of OFMSW per ton MSW [t OFMSW/ t MSW]
- k = Number of electric consumers

The nominal power and the power factor are taken from the manufacturer information of each electrical device. The power factor is a dimensionless number between 0 and 1 which describes the relation between effective power and apparent power. (Steffen & Bausch, 2007) The operation factor provides information about how long an electrical consumer is used.

7.3.2 Calculation of the thermal energy demand of the fermentation plant

The thermal energy demand of the fermentation plant depends on the outside temperatures of the plants location. To calculate the thermal energy demand, the average temperatures of a city have to be considered. Like for the calculation of the electrical energy demand of the fermentation plant, the thermal energy demand of the fermentation plant is calculated for the OFMSW part of one ton MSW (m_{OFMSW}).

Per ton MSW and 1 Kelvin a specific amount of thermal energy is necessary. The amount of thermal energy is calculated with formula 8.

$$e_{th} = \frac{c * m_{OFMSW}}{\eta_{htsDIG}}$$

(8)

- e_{th} = specific amount of thermal energy per Kelvin and ton MSW [kWh/ t MSW*K]
- c = specific heat capacity of the waste [kWh/ (t OFMSW*K)]
- m_{OFMSW} = Mass of OFMSW per ton MSW [t OFMSW/ t MSW]
- η_{htsDIG} = efficiency of the digester´s heat transfer system [-]

To calculate the total energy demand of the fermentation plant, the average outside temperatures at the location of the plant and the self-heating of the OFMSW in the storage are essential. Formula 9 takes these values in account.

$$ED_{thM} = (m_m * e_{th}) * (T_{dig} - T_{out} - \Delta T_{sh})$$

(9)

- ED_{thM} = amount of thermal energy demand per month depending on monthly input [kWh]
- m_m = Monthly mass input into the digester [t MSW]
- e_{th} = Amount of thermal energy demand from formula 6 [kWh/ t MSW*K]
- T_{dig} = Temperature inside digester [K]
- T_{out} = Average outside temperature per month [K]
- ΔT_{sh} = Temperature rise inside the storage facility [K]

Formula 10 finally calculates the thermal energy demand for the fermentation plant for one year by adding all monthly thermal energy demands.

$$ED_{thFER} = \frac{\sum_{k=1}^{12} \mathrm{E}_{kthM}}{m_{at}}$$

(10)

- ED_{thFer} = Total thermal energy demand of the fermentation plant per year [kWh]
- E_{kthM} = Amount of thermal energy demand per month depending on monthly input, calculated with formula 9 [kWh]
- m_{at} = Annual throughput of the existing plant [t OFMSW/ a]

7.3.3 Efficiency of the digester

The efficiency of the digester is defined as the heating value of the OFMSW compared to the energy value of the resulting biogas. The calculation is split up in various calculation steps.

Firstly, the water content of the OFMSW by figure number 11. The solid content of the OFMSW is calculated by formula number 12.

$$\theta_{OFMSW} = \theta_{s,OFMSW} * m_{OFMSW}$$

(11)

- Θ_{OFMSW} = Water content OFMSW [t H_2O/ t MSW]
- $\Theta_{s,OFMSW}$ = Specific water content OFMSW [t H_2O/ t OFMSW]
- $_{mOFMSW}$=Mass of OFMSW per ton MSW [t OFMSW/ t MSW]

Consequently, the solid content of the OFMSW is:

$$\omega_{OFMSW} = m_{OFMSW} - \theta_{OFMSW}$$

(12)

- ω_{OFMSW} = Solid content of OFMSW [t/ t MSW]
- Θ_{OFMSW} = Water content OFMSW [t H_2O/ t MSW]
- $_{mOFMSW}$=Mass of OFMSW per ton MSW [t OFMSW/ t MSW]

In the next step of the calculation, the mass of the converted carbon is determined by multiplying the mass of the solid content of the OFMSW with the proportionally organic content, the carbon rate of the organic content, the conversion rate

$$m_{cc} = \omega_{OFMSW} * o_c * r_c * r_{cv}$$

(13)

- m_{cc} = Mass of the converted carbon [t/ t MSW]
- ω_{OFMSW} = Solid content of OFMSW [t/ t MSW]
- o_c = Organic content [-]
- r_C = Carbon rate [-]
- r_{cv} = Conversion rate [-]

Biogas exists of CH_4 and CO_2 mainly. To calculate the mass of the resulting CH_4, the mass of the converted carbon is multiplied with the CH_4 share of biogas and the molar mass relation of CH_4 to C.

$$m_{CH4} = m_{cc} * s_{CH4} * \left(\frac{M_{CH4}}{M_C}\right)$$

(14)

- m_{CH4} = Mass of the resulting CH_4 [t/ t MSW]
- m_{cc} = Mass of the converted carbon [t/ t MSW]
- s_{CH4} = CH_4 share of biogas [-]
- M_{CH4} = Molar mass of methane [kg/ kmol]
- M_C = Molar mass of carbon [kg/ kmol]

In the next step, the mass of the resulting CH_4 is converted to the volume of the resulting CH_4 at standard reference pressure and temperature.

Formula 15 shows how this calculation step is done.

$$V_{CH4} = \frac{m_{CH4} * R_{CH4} * T_{SC}}{p_{SC}}$$

(15)

- V_{CH4} = Volume of the resulting CH_4 [m^3/ t MSW]
- m_{CH4} = Mass of the resulting CH_4 [t/ t MSW]
- R_{CH4} = Specific gas constant [J/ t*K]
- T_{SC} = Temperature at standard conditions [K]
- p_{SC} = Pressure at standard conditions [Pa]

The volume of the resulting CH_4 can be multiplied by the specific energy content of methane at standard reference conditions. The result of this calculation is the heating value of the digester output in form of methane.

To calculate the efficiency of the digester, the heating value of the OFMSW at the digester input and the heating value of the methane at the digester output are compared.

This last calculation step is shown in Formula 16.

$$\eta_{digester} = \frac{HV_{CH4}}{HV_{OFMSW}}$$

(16)

- $\eta_{digester}$ = Efficiency of the digester [-]
- HV_{CH4} = Lower heating value of the methane from one ton MSW [kWh/ t MSW]
- HV_{OFMSW} = Lower heating value of OFMSW [kWh/ t MSW]

7.3.4 Efficiency of the fermentation plant

Chapter 7.4.4 shows how to calculate the efficiency of the fermentation plant. After calculating the efficiency of the digester, the efficiency of the whole plant including the CHP has to be calculated. Therefore, the efficiencies of the CHP are multiplied by the heating value of the methane. CHP manufacturers specify the electrical, the thermal and the overall efficiencies in their data sheets. Furthermore, the electrical and thermal consumptions of the plant have to be considered. Formula 17 shows the calculation of the electrical energy output of the fermentation plant well as the calculation of the thermal energy output of the fermentation plant

$$E_{el/thFER} = HV_{CH4} * \eta_{el/thCHP} - ED_{el/thFER}$$

(17)

- $E_{el/thFER}$ = Electrical/ Thermal energy output of the fermentation plant [kWh/ t MSW]
- HV_{CH4} = Lower heating value of the methane [kWh/ t MSW]
- $\eta_{el/thCHP}$ = Electrical/ Thermal efficiency of the CHP [-]
- $ED_{el/thFER}$ = Electrical/Thermal demand of the fermentation plant [kWh/ t MSW]

The overall efficiency of the fermentation plant is calculated with formula 18. It compares the heating value of the OFMSW with the total energy output of the fermentation plant.

$$\eta_{FER} = \frac{E_{elFER} + E_{thFER}}{HV_{OFMSW}}$$

(18)

- η_{FER} = Overall efficiency of the fermentation plant [-]
- E_{elFER} = Electrical energy output of the fermentation plant [kWh/ t MSW
- E_{thFER} = Thermal energy output of the fermentation plant [kWh/ t MSW]
- HV_{OFMSW} = Lower heating value of OFMSW per ton MSW [kWh/ t MSW]

7.3.5 Efficiency of the incineration plant in case 2

For the calculation of the incineration plant for case 2, the evaporating energy of the water content of the OFMSW has to be considered. In contrast to case 1, the OFMSW goes to fermentation instead of incineration. The calculation of the efficiency of the incineration plant for case 2 is principally the same as the calculation of the efficiency for the incineration plant in case 1. But in addition, also the evaporating energy is taken into account. As the organic fraction is segregated in the pre-treatment, the water content of the OFMSW has not to be vaporised. This means, less energy needs to be considered for the grate firing process. Formula 19 shows the calculation of the evaporating energy.

$$E_{evaporating} = E_{evaporatingH2O} * (m_{OFMSW} * \theta_{OFMSW})$$

(19)

- $E_{evaporating}$= Evaporating Energy [kWh/ t MSW]
- $E_{evaporatingH2O}$= Evaporating energy of water [kWh/ t H_2O]
- $_{mOFMSW}$= Mass of OFMSW per ton MSW [t OFMSW/ t MSW]
- Θ_{OFMSW}= Water content OFMSW [t H_2O/ t OFMSW]

Afterwards, the evaporating energy is added to the heating value of the NOFMSW and multiplied by the different efficiencies as seen in chapter 7.3.

7.4 Summary of the calculation steps

Figure number 6 displays the calculation steps graphically. The blue arrows show the energy outputs and the red arrows show the energy input.

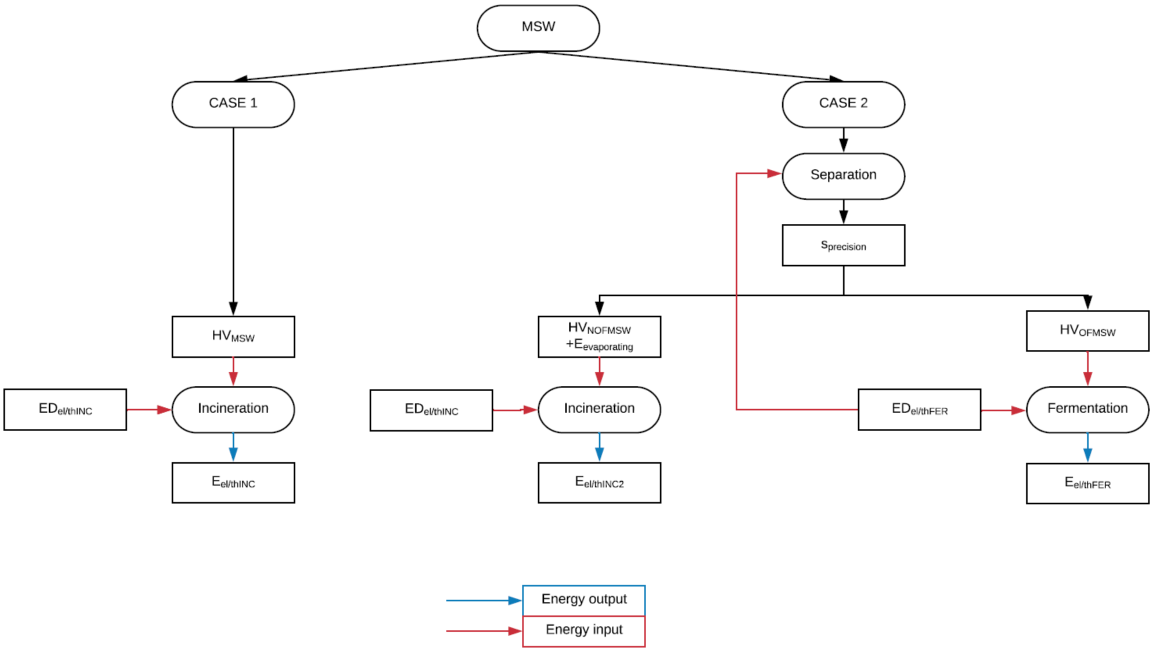

Figure 6: Graphical display of the calculation steps

8. Baseline scenarios

The calculations of chapter 7 are used to create two baseline scenarios. The two scenarios differ in the waste composition, the location, and in the efficiencies of the incineration plant, as two different incineration plants are used. The used parameters, assumptions and values have been selected, because specific data for these baseline scenarios is available. For baseline scenario 1, the average waste composition of England, incineration plant efficiencies of existing MSW incineration plants and a standard fermentation plant with composting facilities has been chosen. For baseline scenario two, the waste composition of Scotland, the plant efficiency of an incineration plant in construction and also a standard fermentation plant with composting facilities has been chosen. For better comparison afterwards, the not location depending parameters of the fermentation plant are unmodified. Typical location depending parameters of the fermentation plant are the waste composition and the thermal energy consumption. In table number 3, the parameters that are valid for both baseline scenarios are evident.

Table 3: Parameters used for both baseline scenarios

Parameter	**Value**
Total throughput	100.000 t MSW / year
$S_{precision}$	95 %
Organic content of the solid content of the OFMSW	65 %
Carbon rate of the organic content	50 %
Conversion rate	60 %
Biogas composition	55 % CH_4, 45 % CO_2
Water content OFMSW	48 %
Solid content OFMSW	52 %
η_{elCHP}	42.5 %
η_{thCHP}	41.6 %

8.1 Baseline scenario 1

For the baseline scenario 1, the values of table number 4 for the different parameters were used.

Table 4: Parameter values used for scenario 1

Parameter	**Value**
η_{GFSG}	83 %
η_{elST}	18 %
η_{thST}	26 %
ED_{elINC}	42 %
ED_{thINC}	0 %

8.1.1 Waste composition for scenario 1

For scenario 1, the average MSW composition of England for the year 2007 was used. The data was published by the Department for Environment, Food and Rural Affairs in 2009.

Figure number 7 shows the waste composition for England in 2007. The percentage share of the different waste types is shown on the Y-axis. The different waste types are plotted on the X-axis.

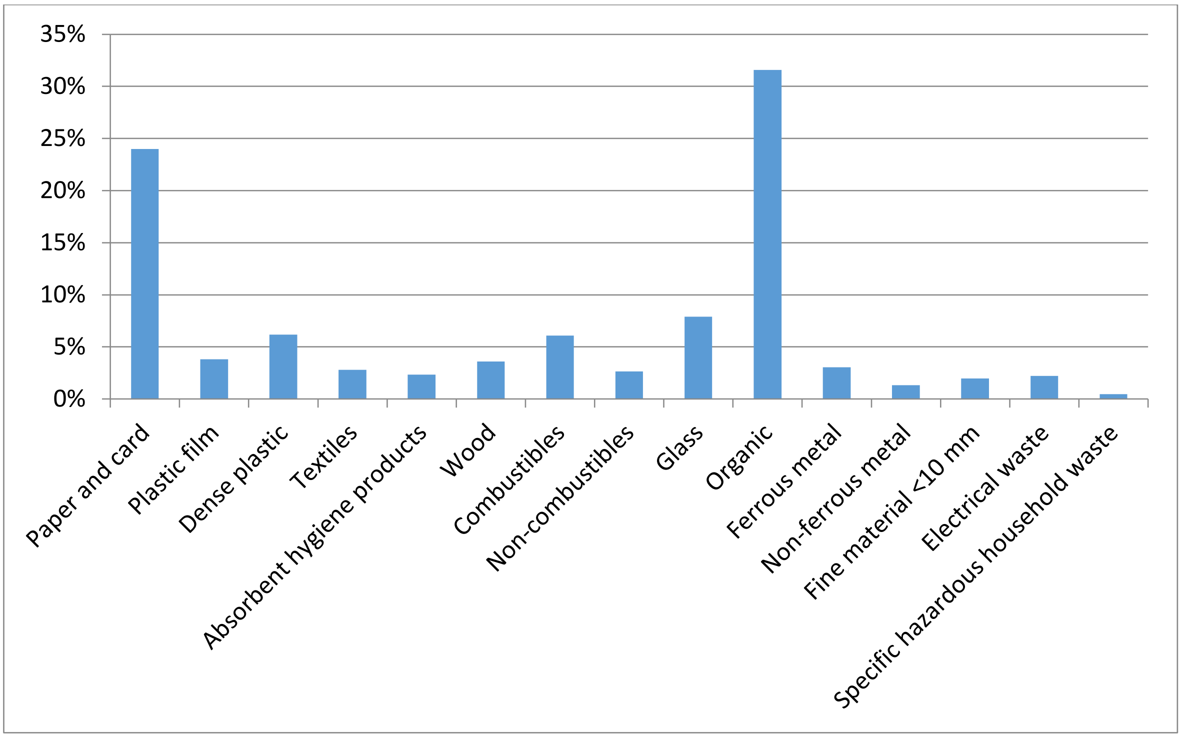

Figure 7: MSW composition of England in 2007. Modified according to (Department for Environment, Food and Rural Affairs, 2009, c)

With the annual input of 100,000 t of MSW, the heating value of the MSW is 238.59 GWh (HV_{MSW}). The NOFMSW that goes to incineration in case 2 has a heating value of 190.96 GWh (HV_{NOFMSW}) and the heating value of the OFMSW that goes to fermentation is 47.64 GWh (HV_{OFMSW}). The non-organic substances which pass through the digester without contributing to the biogas generation were not considered in the calculation. These numbers are calculated according to chapter 7. The calculated values of case 2 are also regarding the separation precision of the pre-treatment which is 95 % for scenario 1. Experiences with existing pre-treatment facilities show a range in the separation precision from 93 % to 98 % (Canas, 2018).The mass of the OFMSW is 33,430.5 t and the mass of NOFMSW is 66,596.5 t.

8.1.2 Calculation of case 1 for scenario 1

For the calculation of case 1, the assumptions shown in table 3 are used. The data for the assumptions is taken from (Institut für Energie- und Umweltforschung, 2007). The data was chosen because publically available and the efficiencies are explained into detail. In the publication they were investigating different incineration plants and potentials for the future. The thermal own consumption of the plant is zero, as it is already considered in the thermal efficiency of the steam turbine.

The calculation of case 1 shows, that the electrical efficiency of the incineration plant is 8.6 % and the thermal efficiency is 21.2 %. The produced electrical energy is 20.5 GWh and the produced thermal energy is 50.6 GWh.

8.1.3 Calculation of case 2 for scenario 1

8.1.3.1 Electrical energy consumers of the fermentation plant

The pre-treatment installation for scenario 1 is a combination of a bag opener and a sieve drum. To split the MSW in an OFMSW and a NOFMSW fraction, the waste has to be crushed into smaller parts. Therefore, the bag opener cuts the waste into smaller sizes. A belt conveyor forwards the MSW to the sieve drum. The pre-treatment system is driven by multiple electrical motors with a total installed power of 600 kW at 400 V and 50 Hz. The power factor is 0.8. According to experiences of currently operating fermentation plants the operation time of the pre-treatment system is about 50 % of the year (Masias Recycling, 2018). The sieve drum separates the waste by its particle size. The waste is split into a fine and a coarse fraction. The fine fraction with particle sizes smaller than 80 mm is used for the fermentation plant as the fine fraction contains most of the organic material of the waste. For the separation a limit of 80 mm is used, as anaerobic fermentation plants with plug flow technology can handle particle sizes up to that size (Krismer, 2018). The fine fraction of the waste is brought to the mixer system by a conveyor belt. The belt has an installed power of 15 kW. The mixer system consists of a mixer and a hydraulically operated piston pump system, which conveyors the blended organic material to the digester via a substrate heat exchanger. The mixer has two stirring shafts. Each shaft is working with an installed power of 7.5 kW. The hydraulic unit for the piston pump and the hydraulically valves has an installed power of 15 kW. The voltage, frequency and power factor comply with the specifications of the shredder. The operation time of the mixer shifts is 80 % and the operation time of the hydraulic unit is 75 %.

The energy demand of the digester itself consists of the paddle agitator, different pumping systems for the heating of the digester and some lightning installations. The discharge of the digester is performed by a hydraulically working piston pump. The pump delivers the digester output to the dewatering area, where presses are installed to segregate the fermentation residues into a fine and coarse fraction. The coarse fraction is brought to the composting by a conveyor belt and the fine fraction is pumped to storage. The composting is done in an aerobic environment and has to be supported by artificial air supply.

The exhaust air system of the fermentation plant exists of an air fan and an exhaust air scrubber. The biogas system has an energy demand for the support air blower of the gas storage and the compressor and chiller of the biogas treatment facility.

Table number 5 summarizes all electrical consumers of the fermentation plant for scenario 1.

Table 5: Energy consumption of the fermentation plant split into 7 sectors

Sectors	**Energy demand [MWh/ a]**
Pre-Treatment	1,956
Charge	151
Digester	99
Discharge and dewatering	263
Composting	195
Exhaust air system	390
Biogas-system	41
Sum	**3,095**

8.1.3.2 Thermal energy consumers of the fermentation plant

As already mentioned in chapter 7, the thermal energy demand of the digester depends on the outside temperatures of the location of the plant. For scenario 1, London will be used as the plants location. The average temperatures of London spreads from 4.9° C in January to 18.7° C in July (AM Online Projects, 2018, a). Therefore, the digester has an annual thermal energy demand of 1.46 GWh. Figure 8 shows the thermal energy consumption and the outside temperature over a period of one year for the fermentation plant in London.

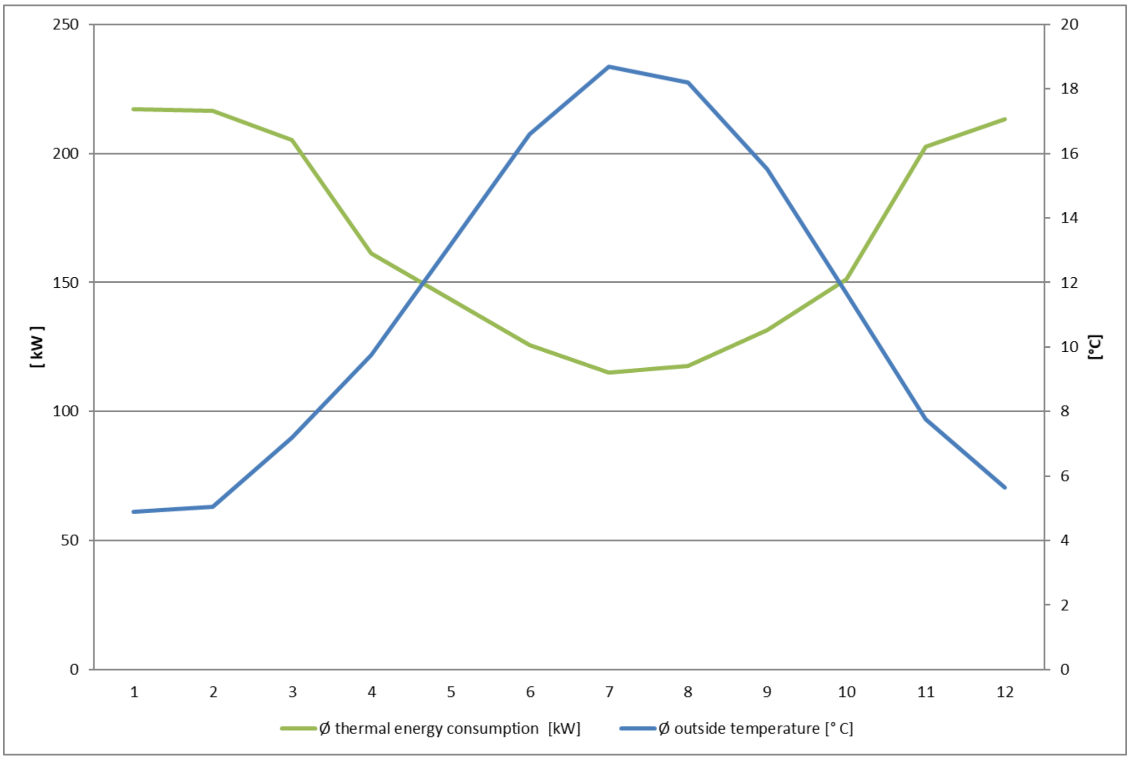

Figure 8: Thermal energy demand of the digester, calculated for the outside temperatures of London

8.1.3.3 Calculation of the fermentation plant

To calculate the efficiency of the digester for scenario 1, the assumptions shown in table 3 were made.

The biogas composition for scenario 1 is 55 % CH_4 and 45 % CO_2. The composition may vary between 50 to 75 % CH_4 and 25 to 45 % CO_2 (Fachagentur Nachwachsende Rohstoffe e.V. (FNR), 2013).

The water content of the OFMSW for scenario 1 is 48 %, hence the solids content is 52 %. The water content in the OFMSW is not steady and changing for different areas. The (FhG-IBP, 2014) estimates the average water content of the OFMSW between 42 and 52 %.

For scenario 1, the organic content of the solid content is 65 % with a carbon rate of 50 %. Empirical data of existing fermentation plants show a range of the organic content between 55 and 70 %. The carbon rate ranges from 45 to 59 %. (Krismer, 2018).

The conversion rate of the carbon in the OFMSW to gas is 60 % for scenario 1. According to (Koch, 2015), the conversion rate depends on the digester input and on the mode of operation. Conversion rates in existing fermentation plants show a range from 55 % to 85 %.

Table 6 shows the results of the calculation for an annual throughput of 100,000 t MSW with the assumptions of table 3.

Table 6: Results of the calculation of the fermentation plant for scenario 1

Water content OFMSW [t]	16,047
Solid content OFMSW [t]	17,384
Organic content of the solid content [t]	11,300
Carbon content [t]	5,650
Converted carbon [t]	3,390
Mass of the resulting methane [t]	2,486
Volume of the resulting methane (VCH_4) [m³]	3,474,000
Heating value of the digester output [GWh]	34.5
Electrical energy output fermentation plant [GWh]	11.58
Thermal energy output fermentation plant [GWh]	12.9
Total energy output fermentation plant [GWh]	24.48

The results of the calculations show, that the fermentation of the OFMSW generates an annual volume of 3,474,000 m³ methane with a heating value of 34.5 GWh.

For scenario 1, a CHP is used to transform the energy within the methane to electrical and thermal energy. The CHP used has an electrical efficiency of 41.6 % and a thermal efficiency of 42.5 % (2G energy AG, 2018). By using the formulas described in chapter 7, the annual energy generated is 24.48 GWh. The electrical energy generated is 11.58 GWh and the thermal energy generated is 12.9 GWh.

8.1.3.4 Calculation of the incineration plant of case 2

For the calculation of the incineration plant for case 2, the same assumptions as for the incineration plant for case 1 were made. In addition, also the evaporating energy was considered as explained in chapter 7. The annual energy generated is 60.5 GWh. The electrical energy generated is 17.5 GWh, the thermal energy generated is 43 GWh.

8.1.3.5 Combined energy output from incineration and fermentation

As case 2 considers the fermentation and the incineration of the MSW, the results of the individual plants need to be combined. Table number 7 gives an overview of the combined generated energy for case 2.

Table 7: Energy generated in case 2 for scenario 1

	Electrical energy produced [GWh]	Thermal energy produced [GWh]	Total energy produced [GWh]
Fermentation	11.58	12.9	24.48
Incineration	17.5	43	60.5
Combined	**29.08**	**55.9**	**84.98**

8.1.4 Specific results of baseline scenario 1

Table number 8 shows the specific results of the two cases used for baseline scenario 1. The results are all calculated as net energy generated with an input amount of 1 t MSW.

Table 8: Specific results of baseline scenario 1

Calculated component	**Value [kWh/ t MSW]**
Case 1	
Energy generated case 1	711.41
Electrical energy generated case 1	205.2
Thermal energy generated case 1	506.21
Case 2 Fermentation	
Energy generated fermentation plant	244.87
Electrical energy generated fermentation plant	115.80
Thermal energy generated fermentation plant	129.07
Case 2 Incineration	
Energy generated incineration plant case 2	605.42
Electrical energy generated incineration plant case 2	174.63
Thermal energy generated incineration plant case 2	430.79
Case 2	
Total energy generated case 2	850.29
Electrical energy generated case 2	290.43
Thermal energy generated case 2	559.86

8.1.5 Comparisons for scenario 1

Chapter 8.1.4 describes the results of scenario 1 by comparing the two cases. Figure number 9 shows the result of the calculation for both cases. On the X-axis, the cases are applied. On the Y-axis, the annual produced energy of the two different variants is shown. The bar of case 2 is apparently higher than the bar of case 1. The difference between both cases is 13.88 GWh.

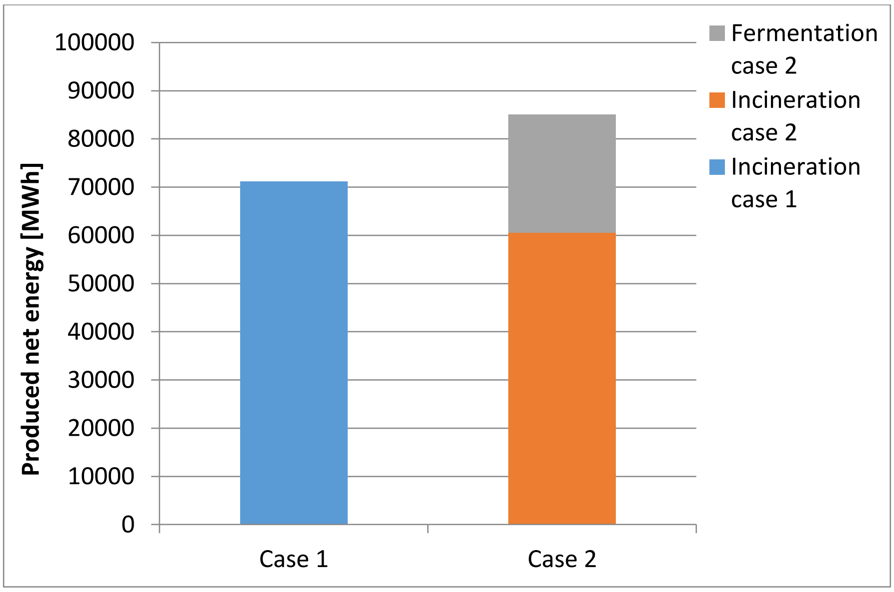

Figure 9: Energetic comparison of case 1 and case 2 for scenario 1

Figure number 10 compares the produced electrical energy of both cases. Like in figure number 9, the two cases are applied on the X-axis and on the Y-axis the annual produced electrical energy is shown.

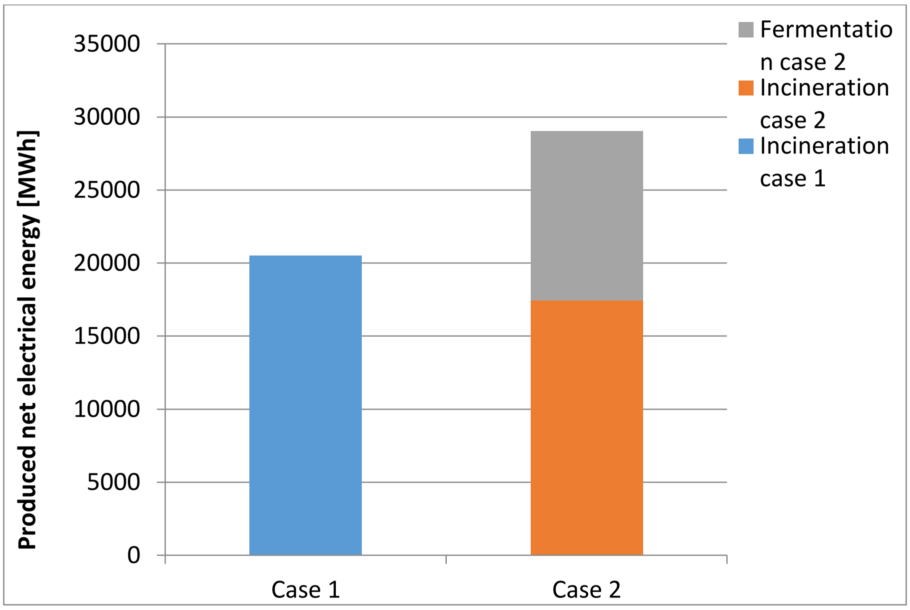

Figure 10: Comparison of case 1 and case 2 with regard to the annual net electrical energy production

It is apparent, that the bar of case 2 is higher than the bar of case 1. The exact difference between both cases is 8.52 GWh.

Figure number 11 shows the same comparison but instead of the electrical energy, the thermal energy is observed. The difference between both cases is 5.36 GWh.

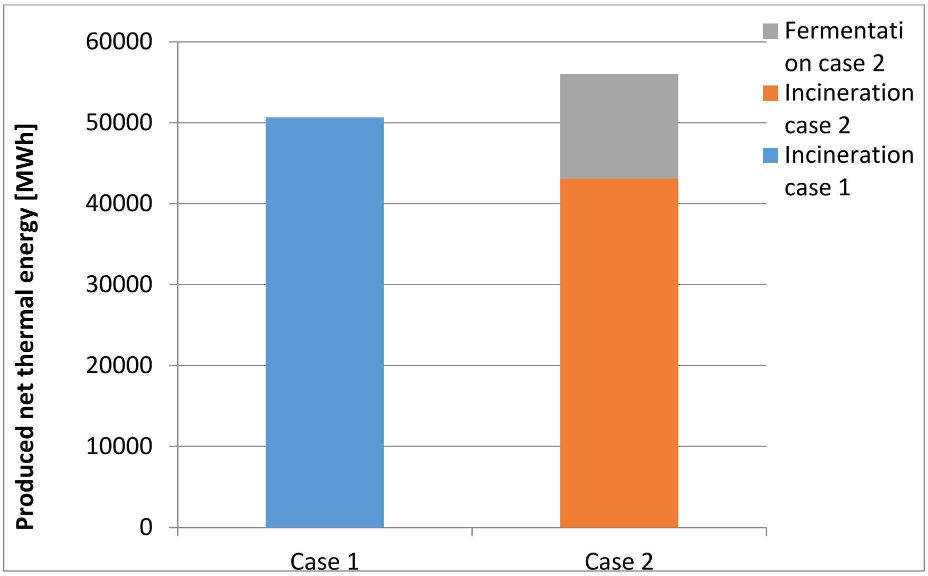

Figure 11 Comparison of case 1 and case 2 with regard to the annual net thermal energy production

It is obvious, that the relative difference in figure 10 is higher than in figure 9 and in figure 11. The reason therefore, is the difference of the thermal and electrical efficiencies of both cases. The incineration plant has an electrical efficiency of 8.6 % and a thermal efficiency of 21.2 %, whereas the fermentation plant has an electrical efficiency of 24.3 % and a thermal efficiency of 27.1 %.

In figure 12, the total energy produced is split up in an electrical energy and a thermal energy part. In the fermentation plant, the share of the produced electrical energy is significantly higher than the share of produced electrical energy in the incineration plant.

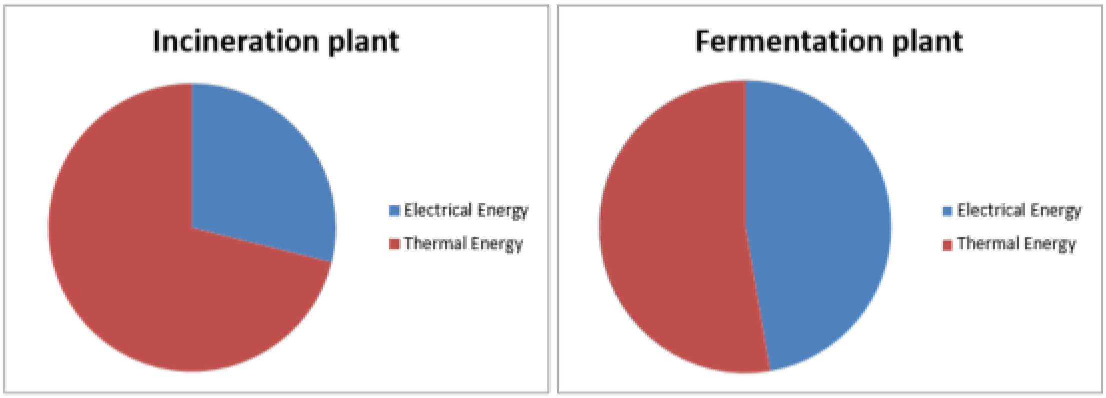

Figure 12: Share of produced energy for the incineration and the fermentation plant

8.2 Parameter analysis for baseline scenario 1

The in chapter 8.1 calculated values are depending on the parameters used. To generalize the statements of chapter 8.1, the most important parameters used are varied and compared.

8.2.1 Variation of the separation precision

The separation precision depends on the applied technology for the separation of the MSW. For the calculations in chapter 8.1, a separation precision of 95 % was used. This means, 95 % of the within the MSW contained OFMSW goes to fermentation. By using simpler technologies than described in chapter 8.1, the separation precision declines. The declining separation precision also means less amount of OFMSW goes to fermentation and the difference in the energy yield between case 1 and case 2 drops. By using for example a separation precision of zero, the difference in the energy generation between case 1 and case 2 is also zero as the total amount of MSW goes to incineration in both cases. On the other side, the highest energy yield can be achieved with a separation precision of 100 %. Figure number 13 shows the difference in the energy yield for the totally generated energy, the generated electrical energy and the generated thermal energy depending on the separation precision. Figure number 13 shows that with increasing separation precision, the difference in the energy yield between case 1 and case 2 rises.

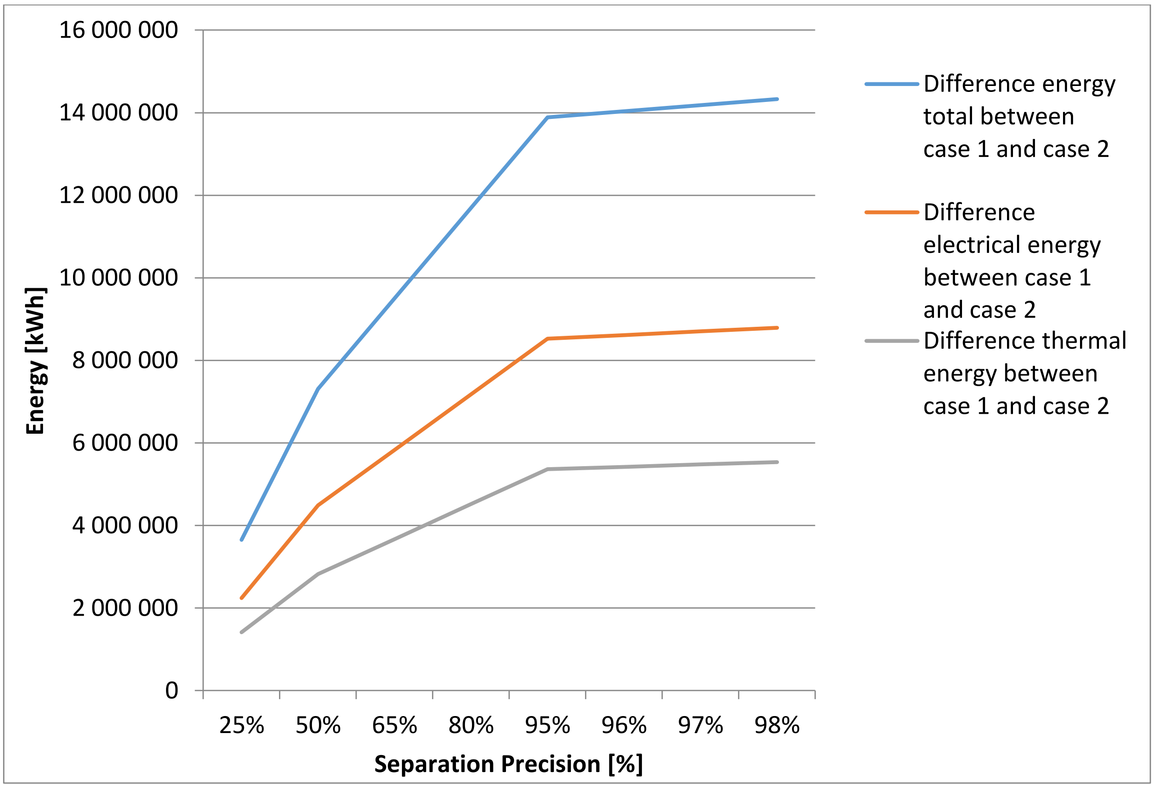

Figure 13: Difference in the energy yield of case 1 and case 2 depending on the separation precision

Figure number 14 shows the total, the electrical and the thermal energy generated in case 2 depending on the separation precision. The energy yield of case 1 does not depend on the separation precision, as no separation is done in case 1. It is well recognisable, that the combined energy yield grows with increasing separation precision. The reason therefore, is the superior efficiency of the fermentation plant. It is also recognisable, that the thermal and electrical energy generation of the fermentation plant rises due to a larger amount of feedstock that goes to the fermentation plant. Conversely, the energy generation of the incineration plant reduces with the growing separation precision.

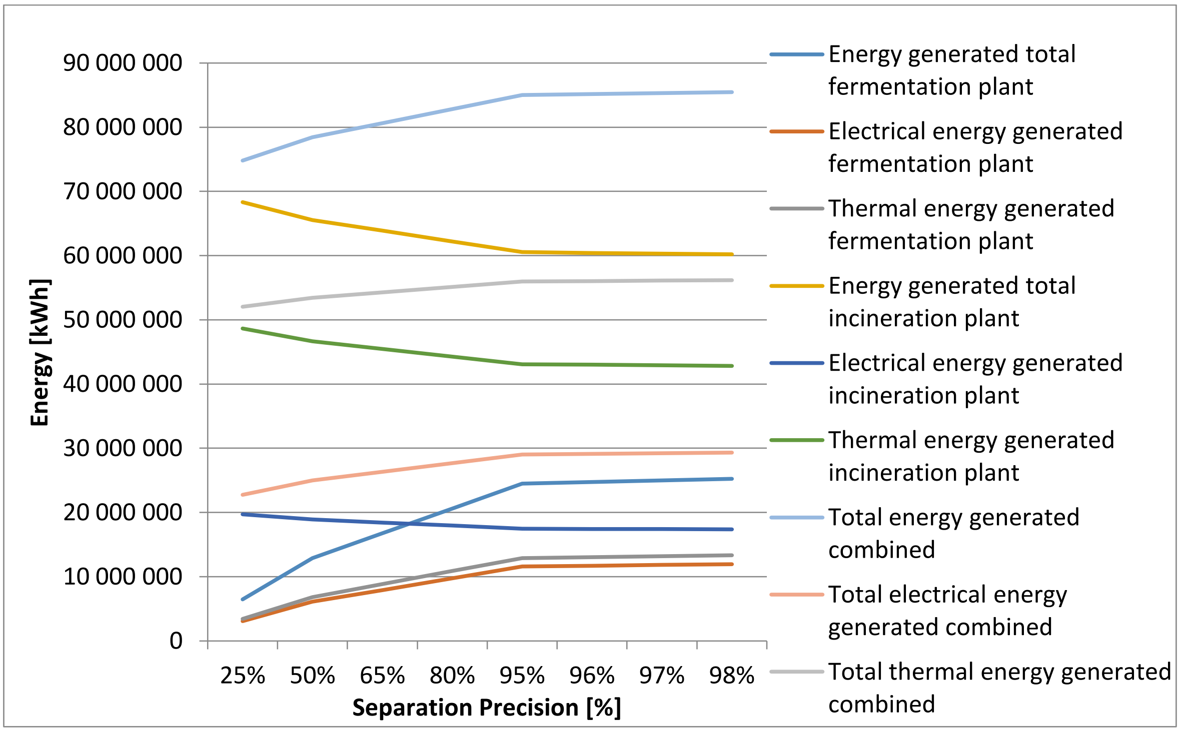

Figure 14: Energy-, electrical energy-, thermal energy- yield of the incineration and fermentation plant depending on the separation precision

8.2.2 Variation of the efficiency of the grate firing and steam generation and the carbon rate

Figure number 15 shows the difference in the net energy generation between case 1 and case 2 by varying the efficiency of the grate firing and steam generation and the carbon rate between 5 and 100 %. These two parameters were used, as the electrical energy generation and the thermal energy generation depend on them. The efficiency of the grate firing and the steam generation is layed on the X-axis. The carbon rate is plot on the Z-axis and the difference in the energy generation is shown on the Y-axis. The negative values beneath the X-axis reveal that under the circumstances of the corresponding parameters, an incineration plant layout produces more energy than a plant layout with fermentation plant and incineration plant. In brief, that case 1 has a better energy yield than case 2. Conversely, the bars with a positive value describe that case 2 generates more energy than case 1. In the top left corner, the difference in the energy yield between case 1 and case 2 is 56.28 GWh/ a. The carbon rate is 100 % and the efficiency of grate firing and steam generation 0 %. The bar at the bottom right corner has a value of -15.12

GWh/ a with a carbon rate of 5 % and an efficiency of grate firing and steam generation of 100 %. The values around zero, thus the area where the energy yield of both cases is similar, describe the transition zone between case 1 and case 2. This zone occurs at a carbon rate of about 10 to 25 % and an efficiency of grate firing and steam generation of around 25 to 45 %. For scenario 1, an efficiency of grate firing and steam generation of 83 % and a carbon rate of 50 % was used. The net difference in the energy generation there is 13.88 GWh/ a. This value is located in the centre of the graphic.

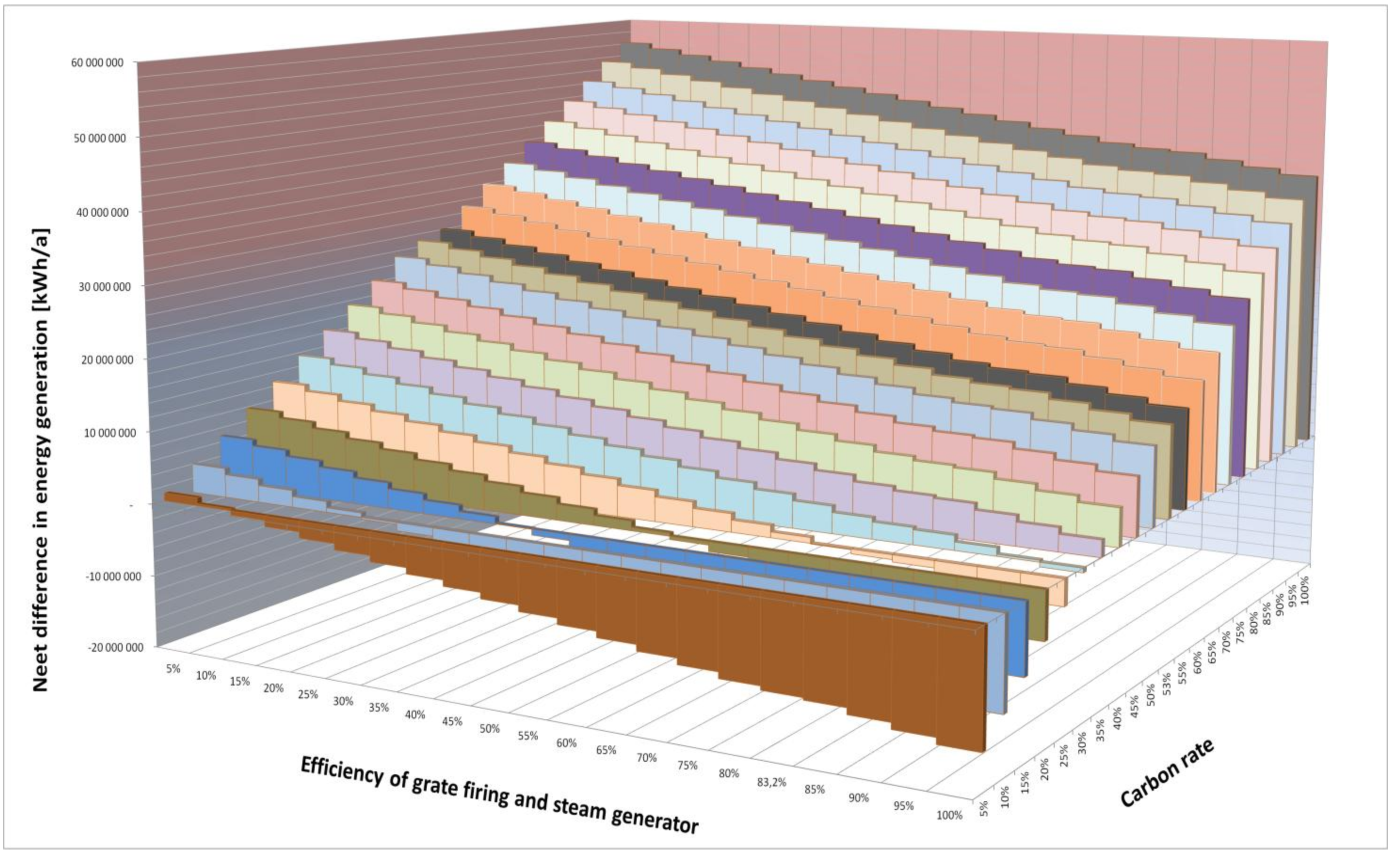

Figure 15: Net difference in the energy generation between case 1 and case 2 depending on the carbon rate and the efficiency of the grate firing and the steam generator

8.2.3 Variation of the evaporating energy

In chapter 7, the calculation of the evaporating energy was explained. The evaporating energy was considered for the calculation of the incineration plant of case 2. Because of process-engineering designs of different incineration plants, the amount of evaporating energy can vary for different structured incineration plants. Therefore, the generated energy in the incineration plant of scenario 1 is varied from 0 kWh/ t MSW to 120 kWh/ t MSW. For baseline scenario 1, 100.6 kWh/ t MSW was used. In figure number 16, the energy yield of the incineration plant and the fermentation plant of case 1 are shown. Additionally, the difference in the energy generation of case 1 and case 2 is displayed in the graphic.

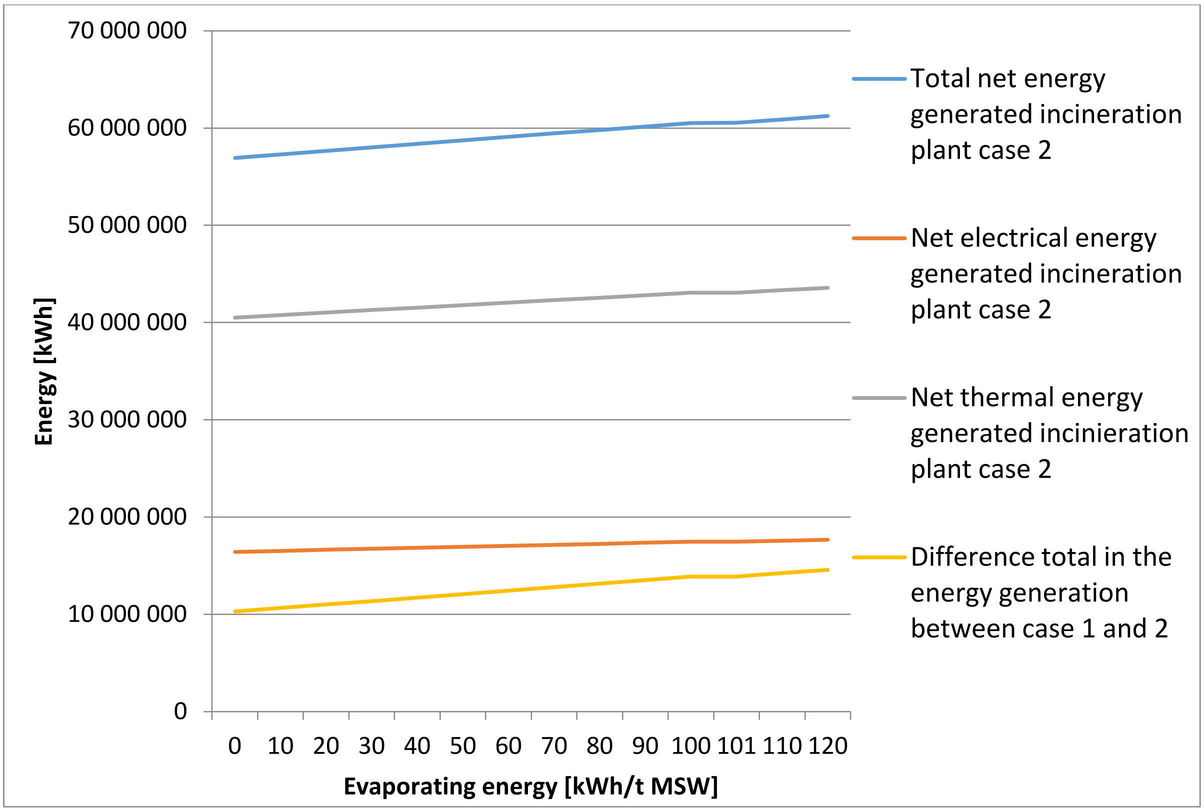

Figure 16: Energy yield of the incineration plant of case 2 and the difference in the energy generation between case 1 and case 2 depending on the amount of evaporating energy

The total net energy generated, the net thermal energy generated and the difference in the energy generation between case 1 and case 2 increases with a similar incline. The net electrical energy generation on the contrary enhances only slightly. The reason therefore is the much lower energy yield in comparison to the thermal energy generation. Therefore, the change of the evaporating energy is not as strong affected from the variation of the evaporating energy.

8.2.4 Comparison of the most important parameters

In chapter 8.2.4, the separation precision, the solid content of the OFMSW, the carbon rate, the electrical and thermal efficiency of the CHP, the efficiency of the grate firing and steam generation and the electrical and thermal efficiency of the steam turbine are compared regarding the difference in the net energy generation between case 1 and case 2. In figure 17, these parameters are varied in a range from -25 % to +25 % from the initial value on the X-axis. On the Y-axis, the difference in the net energy generation between case 1 and case 2 is applied.

The separation precision and the efficiency of the grate firing and steam generation cannot be varied in the full range, as the physical limit for the efficiency and the precision is 100 %. The electrical and thermal efficiency of the CHP and the separation precision have almost the same slope. The carbon rate and the solid content of the OFMSW have the steepest gradient. That means, these parameters are the most influential factors.

Whereas, the thermal and electrical efficiency of the steam turbine have the least influence on the difference in the net energy generation between case 1 and case 2.

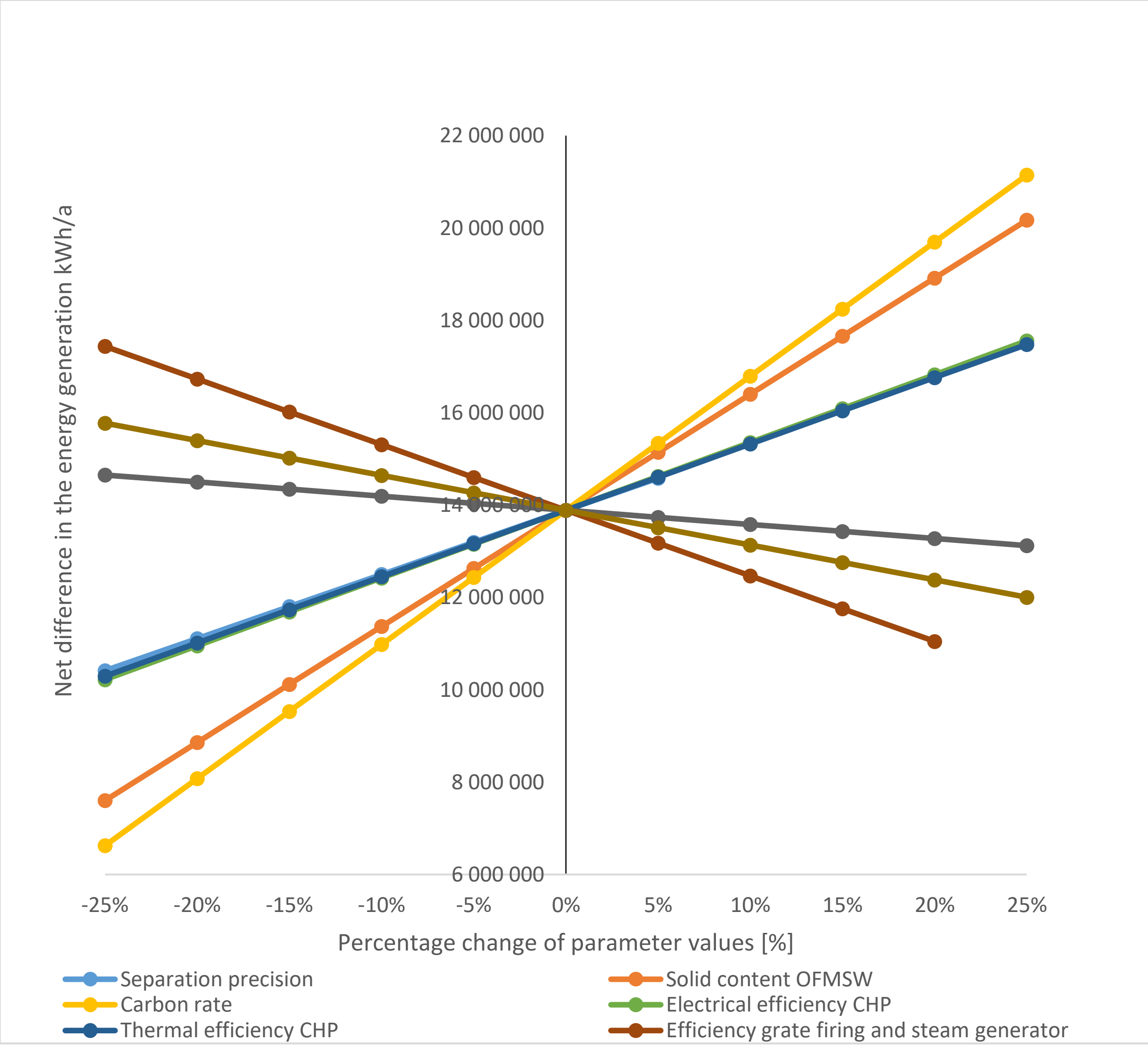

Figure 17: Comparison of the parameters regarding the difference in the net energy generation between case 1 and case 2

8.3 Baseline scenario 2

For the calculation of baseline scenario 2, the parameters in table 9 were used. Scenario 2 differs from scenario 1 in the waste composition, the location of the plant and the efficiencies of the incineration plant.

Table 9: Parameter values used for scenario 2

Parameter	Value
$\eta_{GFSG} * \eta_{elST}$	28 %
ED_{elINC}	13 %

8.3.1 Waste composition for scenario 2

The data for the waste composition is taken from (Zero Waste Scotland, 2010). In their report, the MSW composition of Scotland was analysed by representative samples of local authorities in Scotland. Figure number 18 shows the MSW composition.

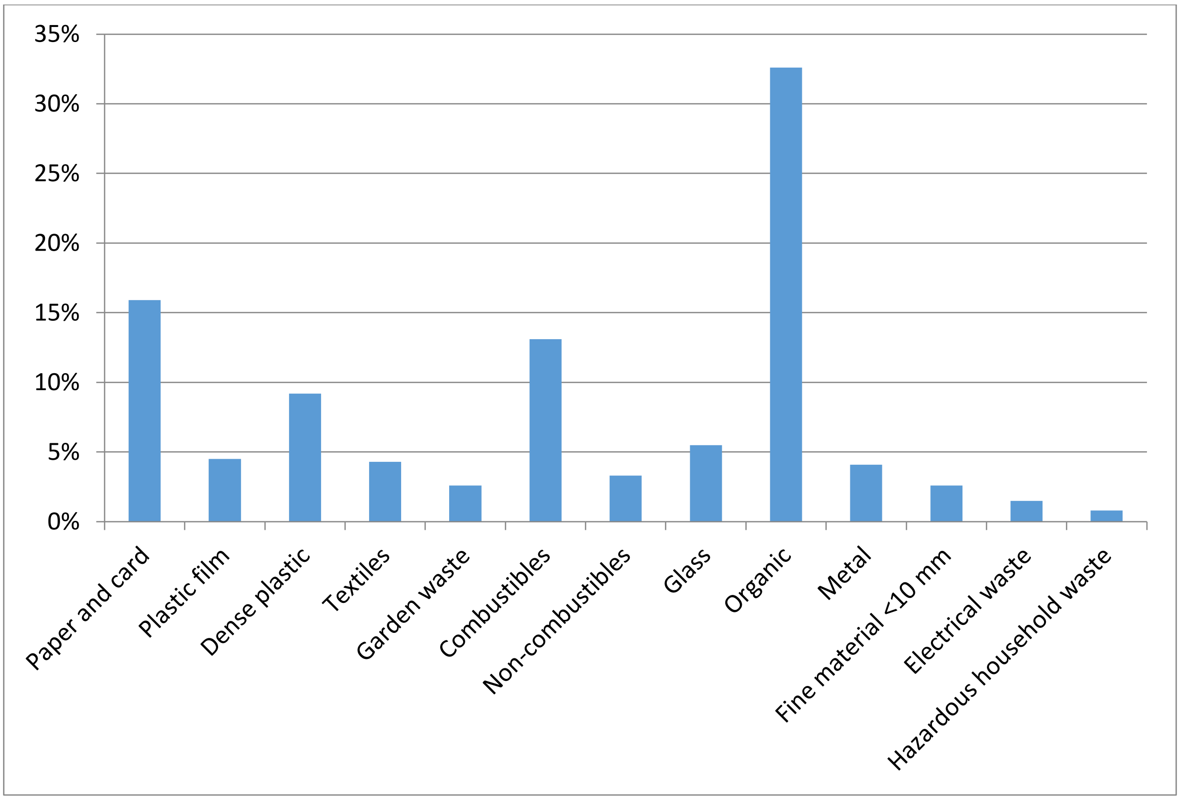

Figure 18: MSW composition of Scotland in 2009. Modified according to (Zero Waste Scotland, 2010)

With the annual input of 100,000 t of MSW, the heating value of the MSW is 265.8 GWh (HV_{MSW}). The NOFMSW that goes to incineration in case 2 has a heating value of 221.6 GWh (HV_{NOFMSW}) and the heating value of the OFMSW that goes to fermentation is 44.2 GWh (HV_{OFMSW}). These numbers are calculated according to chapter 7. The mass of the OFMSW is 33,440 t and the mass of NOFMSW is 66,560 t.

8.3.2 Calculation of case 1 for scenario 2

For the calculation of case 1, the assumptions shown in table 3 are used. The data comes from a plant under construction from Martin GmbH (Huber, 2018). The thermal energy is only used for the plants own consumption. The remaining thermal energy is cooled in an air cooler. Therefore, the useable thermal energy is zero. The plants layout is for generation of electrical energy only. The overall electrical efficiency, which is the efficiency of the grate firing and steam generator multiplied with electrical efficiency of the steam turbine, is 28 %. The electrical energy demand of the plant is 13 %. Therefore, the net produced electrical energy is 64.7 GWh with a net electrical efficiency of 24.3 %.

8.3.3 Calculation of case 2 for scenario 2

8.3.3.1 Electrical energy consumers of the fermentation plant

As the layout of the fermentation plant is the same and the waste composition of scenario 2 is analogical to the waste composition of scenario 1, the electrical energy demand of the fermentation plant only slightly increases compared to scenario 1. Table number 10 gives an overview of the electrical energy demand.

Table 10: Energy consumption of the fermentation plant split into 7 sectors

Sectors	**Energy demand [MWh/ a]**
Pre-Treatment	1,956
Charge	152
Digester	99
Discharge and dewatering	263
Composting	195
Exhaust air system	390
Biogas-system	41
Sum	**3,097**

8.3.3.2 Thermal energy consumers of the fermentation plant

As the incineration plant is built in Edinburgh, the outside temperatures of this location will be used to calculate the thermal energy demand of the fermentation plant. The average temperatures of Edinburgh spreads from -0.1° C in January to 19.1° C in July (AM Online Projects, 2018, b). Therefore, the digester has an annual thermal energy demand of 1.57 GWh. Figure 19 shows the thermal energy consumption and the outside temperature over a period of one year for the fermentation plant in Edinburgh.

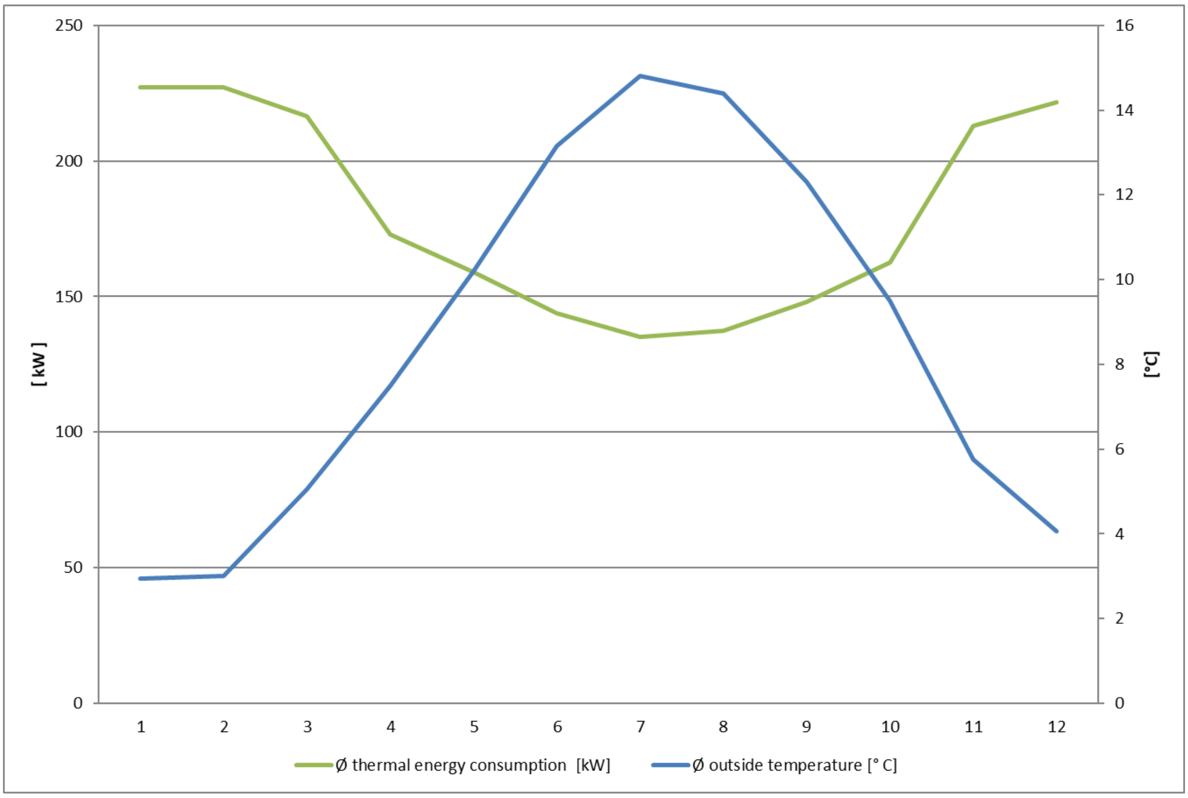

Figure 19: Thermal energy demand of the digester, calculated for the outside temperatures of Edinburgh

8.3.3.3 Calculation of the fermentation plant

For the calculation of the efficiency of the fermentation plant, the same assumptions were made as seen in scenario 1. The energy output differs from scenario 1, as the waste composition and the energy demands of the fermentation plant are different. In table number 11, the results of the calculations for scenario 2 are shown.

Table 11: Results of the calculation of the fermentation plant for scenario 2

Water content OFMSW [t]	16,051
Solid content OFMSW [t]	17,389
Organic content of the solid content [t]	11,303
Carbon content [t]	5,651
Converted carbon [t]	3,391
Mass of the resulting methane [t]	2,487
Volume of the resulting methane (VCH_4) [m³]	3,475,000
Heating value of the digester output [GWh]	34.54
Electrical energy output fermentation plant [kWh]	11.58
Thermal energy output fermentation plant [kWh]	12.8
Total energy output fermentation plant [kWh]	24.38

The results of the calculations show, that the fermentation of the OFMSW generates an annual volume of 3,475,000 m³ methane with a heating value of 34.54 GWh.

The CHP used for scenario 2 is the same as used for scenario 1. The total net energy generated is 24.38 GWh. This number can be split up in 12.8 GWh of thermal energy and 11.58 GWh of electrical energy.

In comparison with the calculation of the fermentation plant in scenario 1, the net energy generated has decreased. This is related to the fact, that the thermal and electrical own demands of the fermentation plant in scenario 2 are higher than in scenario 1.

8.3.3.4 Calculation of the incineration plant of case 2

The procedure of calculation of the incineration plant for case 2 is identical to procedure of the calculation in scenario 1. The net electrical energy generated is 56.74 GWh. As the thermal energy is not used for further applications, this number complies with the total energy generated.

8.3.3.5 Combined energy output from incineration and fermentation

In table number 12, the in the incineration and fermentation plant generated energy is combined. The total energy output of case 2 in scenario 2 is 81.11 GWh.

Table 12: Energy generated in case 2 for scenario 2

	Electrical energy produced [GWh]	Thermal energy produced [GWh]	Total energy produced [GWh]
Fermentation	11.58	12.8	24.38
Incineration	56.74	0	56.74
Combined	**68.32**	**12,8**	**81.12**

8.3.4 Comparisons for scenario 2

Chapter 8.2.4 compares the results of scenario 2. Figure number 20 shows the result of the calculation for both cases. Like for scenario 1, on the X-axis, the cases are shown and on the Y-axis, the annual produced energy of the two different variants is applied. Again, the bar of case 2 is higher than the bar of case 1. The difference between both cases is 16.39 GWh.

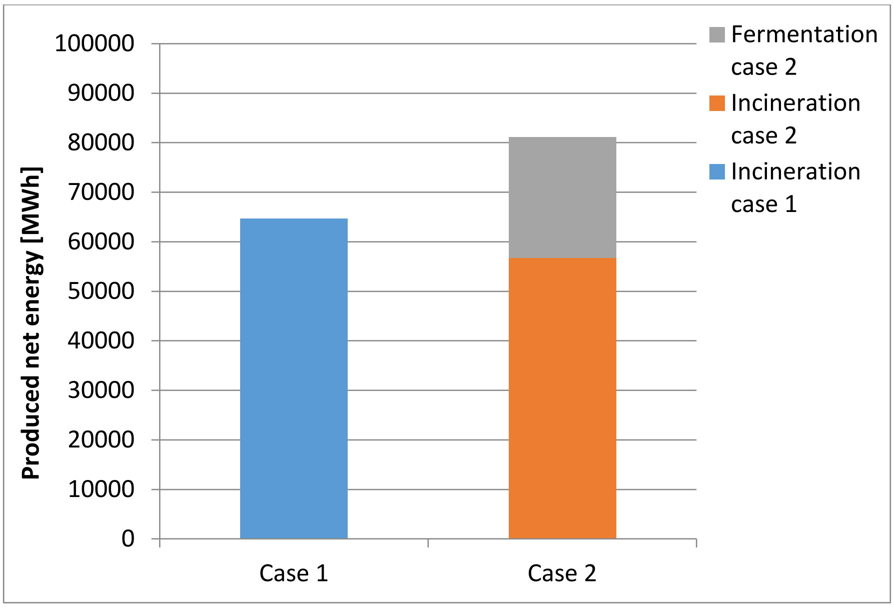

Figure 20: Energetic comparison of case 1 and case 2 for scenario 2

In figure 21, the comparison of the electrical energy generated is shown. The difference between case 1 and case 2 is 3.6 GWh.

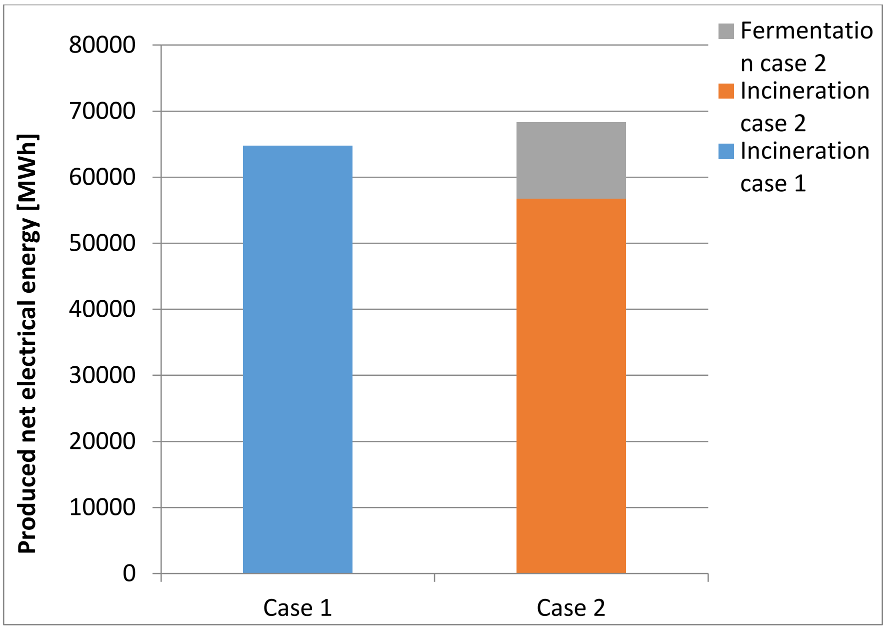

Figure 21: Comparison of case 1 and case 2 with regard to the annual net electrical energy production

The thermal energy in the incineration plant is not used. Therefore, the produced thermal energy for case 1 is zero. The produced thermal energy for case 2 complies with the produced thermal energy of the fermentation plant. Therefore, the difference between case 1 and case 2 regarding the thermal energy production is 12.8 GWh.

8.4 Specific comparison of baseline scenario 2

Table number 13 shows the calculated net energy generated for the two cases of baseline scenario 2. The results are calculated for an input amount of 1 t MSW.

Table 13: Specific results of baseline scenario 2

Calculated component	Value [kWh/ t MSW]
Case 1	
Energy generated case 1	647.2
Electrical energy generated case 1	647.2
Thermal energy generated case 1	0
Case 2 Fermentation	
Energy generated fermentation plant	243.75
Electrical energy generated fermentation plant	115.84
Thermal energy generated fermentation plant	127.92
Case 2 Incineration	
Energy generated incineration plant case 2	567.39
Electrical energy generated incineration plant case 2	567.39
Thermal energy generated incineration plant case 2	0
Case 2	
Total energy generated case 2	811.14
Electrical energy generated case 2	683.22
Thermal energy generated case 2	127.92

8.5 Comparisons between baseline scenario 1 and baseline scenario 2

The most significant differences in baseline scenario 2 compared to baseline scenario 1 are the efficiencies of the incineration plant and the energy demand of the fermentation plant. Table number 14 sums up the different annual results of the calculations. The values for the generated energy are all calculated as net energy generated. That means, the own consumption of the incineration and fermentation plant have already been considered. To show the exact difference between both scenarios, the results are shown in kWh.

Table 14: Comparison of baseline scenario one and two

Comparative value	Scenario 1	Scenario 2
Total energy generated case 1 [kWh]	71,140,584	64,719,996
Electrical energy generated case 1 [kWh]	20,519,856	64,719,996
Thermal energy generated case 1 [kWh]	50,620,728	0
Electrical energy demand fermentation plant [kWh]	3,095,714	3,096,593
Thermal energy demand fermentation [kWh]	1,458,362	1,577,411
Energy generated fermentation plant [kWh]	24,487,102	24,375,425
Electrical energy generated fermentation plant [kWh]	11,580,268	11,583,559
Thermal energy generated fermentation plant [kWh]	12,906,834	12,791,867
Energy generated incineration plant case 2 [kWh]	60,541,862	56,738,726
Electrical energy generated incineration plant case 2 [kWh]	17,462,751	56,738,726
Thermal energy generated incineration plant case 2 [kWh]	43,079,111	0
Total energy generated case 2 [kWh]	85,028,964	81,114,152

Electrical energy generated case 2 [kWh]	29,043,019	68,322,285
Thermal energy generated case 2 [kWh]	55,985,945	12,791,867
Difference in the energy generation between case 1 and case 2 [kWh]	13,888,380	16,394,156

Figure number 23 displays the values of table number 14 graphically. The biggest differences between scenario 1 and scenario 2 occur at the thermal energy generated in the incineration plant in case 1 and case 2 and the electrical energy generated in the incineration plant of case 1 and case 2. The huge difference in the thermal energy generation of the incineration plants between both baseline scenarios is because in baseline scenario 2, the thermal energy of the incineration plant is not used for any further applications as for example district heating. The incineration plant layout of baseline scenario 2 is designed to cool the thermal energy in a cooling device instead of using it. The differences in the electrical energy generated of the incineration plant appear, due to the better electrical efficiency of the steam turbine in scenario 2.

The energy yield and the electrical energy demand of the fermentation plant is almost the same in both cases. The thermal energy demand of the fermentation plant is slightly higher for baseline scenario 2 because of the colder outside temperatures of the plants location.

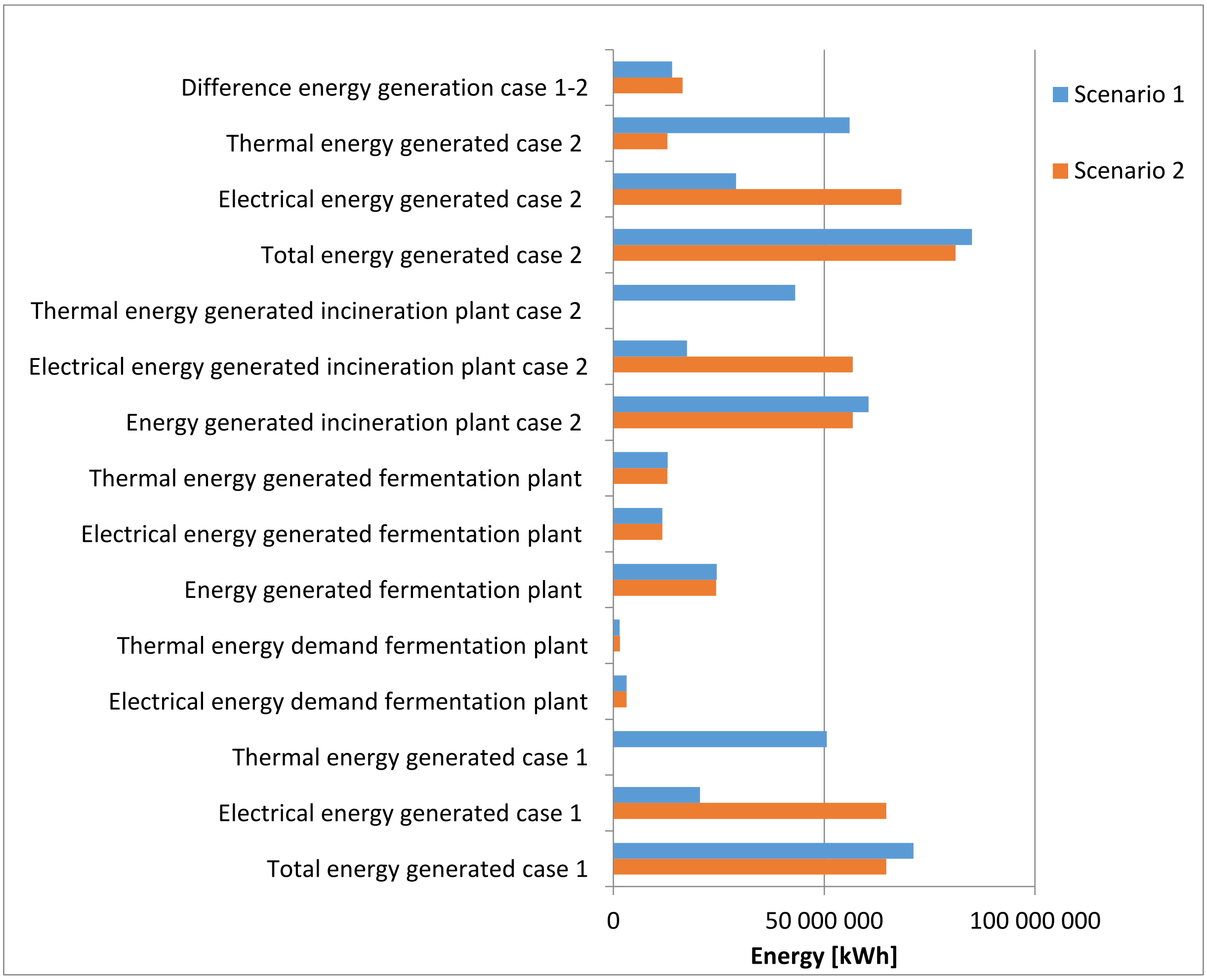

Figure 22: Energetic comparison between baseline scenario 1 and 2

9. Economic analysis

In chapter 9, the economic approach is investigated. The investment costs for the fermentation plant are calculated and the additional economic gains of the fermentation plant are considered. For the economic approach, the results and assumptions of baseline scenario 1 are used.

9.1 Investment costs for the fermentation plant

The investment costs are calculated for a fermentation plant size of 100,000 t/ MSW per year. Referring to baseline scenario 1, the annually processed 100,000 t of MSW comply with 33,430.5 t of OFMSW. The pre-treatment, the construction technology, the conveying system, the charge of the digester, the digester, the discharge of the digester, the dewatering, the exhaust air system, the gas treatment and the composting are considered for the calculation of the investment costs.

Not considered are plant components which already exist in incineration plants, like for example wheel loaders, receiving scales or traffic routes.

Table number 15 shows the investment costs in Euro and British Pound Sterling. The used exchange rate is 1.13 Euro per Pound. The data about the investment costs come from (Thöni Industriebetriebe GmbH, 2018, b) and the data about the investment costs of the pre-treatment come from (Bianna Recycling, 2018). The fermentation plant is designed for an annual amount of 33.000 t of OFMSW.

Table 15: Investment costs of the fermentation plant

Trade	**Costs [€]**	**Costs [£]**
Pre-treatment fermentation	817,600	723,539
Civilian building	672,000	594,690
Composting hall	840,000	743,362
Charge	638,416	564,970
Digester	5,809,417	5,141,077
Discharge	344,691	305,037
Conveying system	160,334	141,889
Exhaust air treatment	876,645	775,792
Dewatering	235,200	208,141
Gas treatment	1,162,461	1,028,727
Composting	3,796,380	3,359,628
Total	**15,353,144**	**13,586,852**

9.2 Annual costs

The annual operating costs of the fermentation plant are summed up in table number 16. The values of the different sectors are explained in the chapters 9.2.1 to 9.2.4.

Table 16: Annual operating costs of the fermentation plant

Cost centre	Annual costs [€]	Annual costs [£]
Labour costs	180,371.80	159,530
Maintenance costs	422,794,44	374,154.37
Costs for chemicals	8,357.63	7,396.13
Disposal costs	1,425,111.93	1,261,161
Sum	**2,036,635.80**	**1,802,241.50**

9.2.1 Labour costs

According to (Krismer, 2018) fermentation plants with a CHP for gas treatment can be operated by six employees. The employees are split up in one plant manager, one engineer and four workmen. The annual labour costs for the employers exist of the employee's salary and the national insurance costs, which are 13.8 % of the employees' salary (UK Government, 2018). The data about the annual salary of the different fermentation plant employees comes from (PayScale, 2018). The final annual labour costs are shown in table number 17.

Table 17: Annual labour costs of the fermentation plant

Professional title	Quantity	Annual costs [€]	Annual costs [£]
Plant manager	1	44,909.22	39,720
Engineer	1	38.701.98	34,230
Workmen	4	96,760.60	85,580
Sum		**180,371.80**	**159,530**

9.2.2 Maintenance costs

Experiences of existing fermentation plants show, that the annual maintenance costs of the civil constructions are 0.5 % of the investment costs and the annual maintenance costs of the mechanical machines are 3 % of the investment costs (Krismer, 2018). The annual maintenance costs are shown in table number 18.

Table 18: Annual operation costs of the fermentation plant

Plant section	Annual costs [€]	Annual costs [£]
Civil constructions	7,560	6,690.27
Mechanical machines	415,234.44	367,154.37
Sum	**422,794,44**	**374,154.37**

9.2.3 Costs for chemicals

The demand of chemicals on fermentation plants depends on the input material. Therefore, the annual costs of the chemicals are estimated with 0.25 € per ton OFMSW. The 0.25 € per ton OFMSW is an average number of existing fermentation plants

(Krismer, 2018). With the mass of the OFMSW in baseline scenario one annual costs for the chemicals of **8,357.63 €** or **7396.13 £** arise.

9.2.4 Costs for the disposal of the fermentation residue

To calculate the amount of liquid and solid fermentation residues after the dewatering and composting of the digester output, a mass balance according to the experiences of (Thoeni Industriebetriebe GmbH, 2018, a) is done. The digester input is 33,430.5 t of OFMSW per year. The mass of the OFMSW at the digester input reduces about 15 % during the fermentation process in the digester. The digester output is 28,438 t of fermentation residue. The fermentation residue is then split into a solid and a liquid fraction in the dewatering press. The solid fraction is 9,441 t and the liquid fraction is 18,997 t. The liquid fraction is stored and disposed. The solid fraction is brought to the composting facility, where it is dried with artificial ventilation. During the composting procedure, the mass of the solid fraction can be reduced for another 22 % due to artificial ventilation. At the output of the composting, the solid fraction has a mass of 7,348 t.

The remaining liquid and solid fermentation residues need to be disposed. The solid fraction is brought to landfill. The average landfill costs of the UK are 120.91 €/ t or 107 £/ t (Anthesis Consulting Group, 2017). Consequentially the annual costs for the disposal of the solid fermentation residues are 888,446.68 € or 786,263 £. The liquid fraction is disposed in a sewage treatment plant. The costs for the disposal of the liquid fermentation residues is 28.25 €/ t or 25 £/ t (Szmidt, 2018). Hence, the annual costs for the disposal of the liquid fraction of the fermentation residues are 536,665.25 € or 474,925 £. The annual sum of the disposal costs is **1,425,111.93 €** or **1,261,161 £**.

9.3 Economic profits of the fermentation plant

In chapter 9.3, the economic profits of the fermentation plant are described. The profits are split up in a fermentation plant layout with electrical energy use only and one layout with electrical and thermal energy use.

9.3.1 Profits of the plant expansion

With the fermentation plant, the amount of annual accepted waste of the plant can be increased. For baseline scenario one this means that annually 33,430.50 t of additional quantity can be accepted. The average gate fee in the UK for MSW that goes into incineration is 83 £/ t or 93.8 €/ t (Anthesis Consulting Group, 2017). Therefore, annual profits of **3,135,446.60 €** or **2,774,731.50 £** can be gained by the increased plant capacity.

With the separation of the MSW to a NOFMSW fraction and an OFMSW fraction, the energy output of the incineration plant is increased. As explained in the results of scenario 1 in chapter 8, the difference between the energy output of one ton MSW and one ton NOFMSW is 57.13 kWh per ton for the electrical energy output and 140.92 kWh per ton for the thermal energy output. This means, the energy output of the incineration plant can be increased for the mass of the NOFMSW fraction input. The annual mass of the

NOFMSW input into the incineration plant is 66,569.5 t. The revenue from electrical energy from incineration plants is 0.032 €/ kWh or 0.028 £/ kWh according to (Eunomia Research & Consutling Ltd., 2018). For the revenue from thermal energy, 0.017 €/ kWh or 0.015 £/ kWh are taken into account (Eunomia Research & Consutling Ltd., 2018). Therefore, the annual profit from energy of the additional energy output of the NOFMSW fraction is **121,689.13 €** or **107,689.49 £** for the electrical energy and **159,479.47 €** or **141,132.27 £** for the thermal energy. The profit earned by the thermal energy sales are not considered for plant layout one. Figure number 24 describes the mass inputs to the incineration and fermentation plant. The total reception capacity of the plant was increased from 100.000 t waste per year to 133,430.5 t waste per year with the new fermentation plant. Of the 133,430.5 t, 33.430,5 t OFMSW are treated in the fermentation plant. In the incineration plant, 66,569.5 t NOFMSW and 33.430.5 t MSW are used as a feedstock.

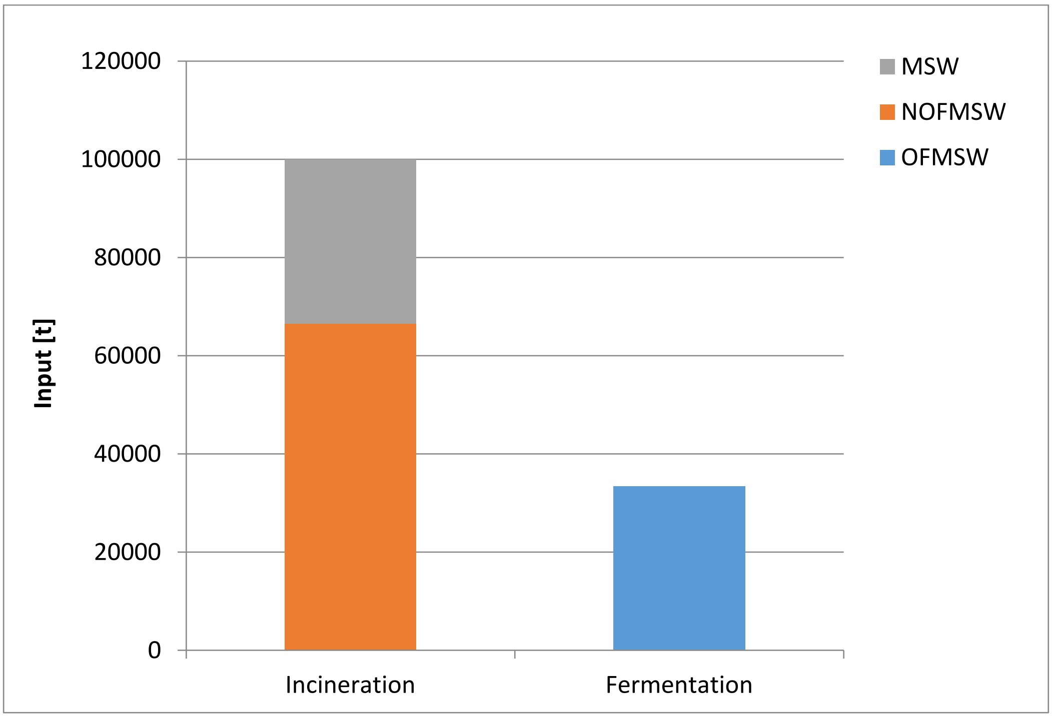

Figure 23: Mass inputs of the incineration and the fermentation plant

9.3.2 Profits for fermentation plant layout 1

The fermentation plant layout number one describes a layout with electrical energy use only. The results in chapter 9 have shown that the net electrical energy output of the fermentation plant is 11,58 GWh for baseline scenario 1. The feed in tariff in the UK for electrical energy from fermentation is 0.0436 £/ kWh or 0.0493 €/ kWh for the second quarter of 2018, according to (Office of Gas and Electricity Markets, 2018). Therefore, the annual profit of **570,536.64 €** or **504,899.68 £** is generated.

9.3.3 Total economic profits for plant layout 1

By adding all profits described in chapter 9.3.1 and 9.3.2, the annual profits of plant layout one are **3,827,672.36 €** or **3,387,320.67 £**. Table number 19 shows an overview of the annual profits of plant layout one.

Table 19: Annual profits of fermentation plant layout 1

Earning potential	Annual profits [€]	Annual profits [£]
Electrical energy sale from fermentation plant	570,536.64	504,899.68
Electrical energy sale from additional MSW amounts of the incineration plant	121,689.13	107,689.49
Profit of accepting additional amount of MSW	3,135,446.60	2,774,731.50
Sum	**3,827,672.36**	**3,387,320.67**

9.3.4 Profits for fermentation plant layout 2

For the fermentation plant layout number 2, additionally the generated thermal energy is used for further applications. In chapter number 8, the net thermal energy output of the fermentation plant was calculated as 12.9 GWh. The revenue for thermal energy is again 0.017 €/ kWh or 0.015 £/ kWh (Eunomia Research & Consutling Ltd., 2018). Multiplied by the generated thermal energy, the annual profit from the sale of thermal energy is **219,416.18 €** or **194,173.61 £**. By adding the profits of the sale of electrical energy, the total profit for the fermentation plant of layout number 2 is **789,952.82 €** or **699,073.29 £**. In table number 20, the annual profits of plant layout 2 are summarized.

Table 20: Annual profits of plant layout 2

Earning potential	Annual profits [€]	Annual profits [£]
Electrical energy sale from fermentation plant	570,536.64	504,899.68
Thermal energy sale from fermentation plant	219,416.18	194,173.61
Electrical energy sale from additional MSW amounts of the incineration plant	121,689.13	107,689.49
Thermal energy sale from additional MSW amounts of the incineration plant	159,479.47	141,432.27
Profit of accepting additional amount of MSW	3,135,446.60	2,774,731.50
Sum	**4,206,568**	**3,722,626.55**

9.4 Amortization calculation

To calculate the amortization time of the fermentation plant, a static amortization calculation has been done. The calculation of the amortization time is shown in formula number 20.

$$t_{Amortization} = \frac{i_{costs}}{(p_{annual} - c_{annual}) + \frac{i_{costs}}{t_{operating}}}$$

(20)

- $t_{Amortization}$ = Amortization time [a]
- i_{costs} = Investment costs [€]
- p_{annual} = Annual profits [€/ a]
- c_{annual} = Annual costs [€/ a]
- $t_{operating}$ = Operating time [a]

With the calculated values of the chapters 9.1 to 9.3 and an operating time of the fermentation plant of 20 years, the amortization time is 6 years for plant layout one and 5.23 years for plant layout two.

9.4.1 Sensitivity analysis for the amortization time

The amortization time of the fermentation plants depends on many parameters. The most important parameters are used for a sensitivity analysis.

9.4.1.1 Variation of the gate fee

In figure number 25, the gate fees are varied. The gate fees depend on the plants location and on legal issues. The average UK gate fee for OFMSW that goes into fermentation is 32.77 €/ t or 29 £ /t (Anthesis Consulting Group, 2017). If for legal considerations, the separated OFMSW has to be classified as anaerobic digestion input at the gate already, the amortization time changes drastically. Therefore, the calculation of the amortization time is made with changes of the gate fee from 35 % to 165 % of the primary value of 93.79 €/ t. In absolute numbers, the gate fee ranges from 32.77 €/ t to 154.75 €/ t MSW. The result of the analysis is shown in figure number 25.

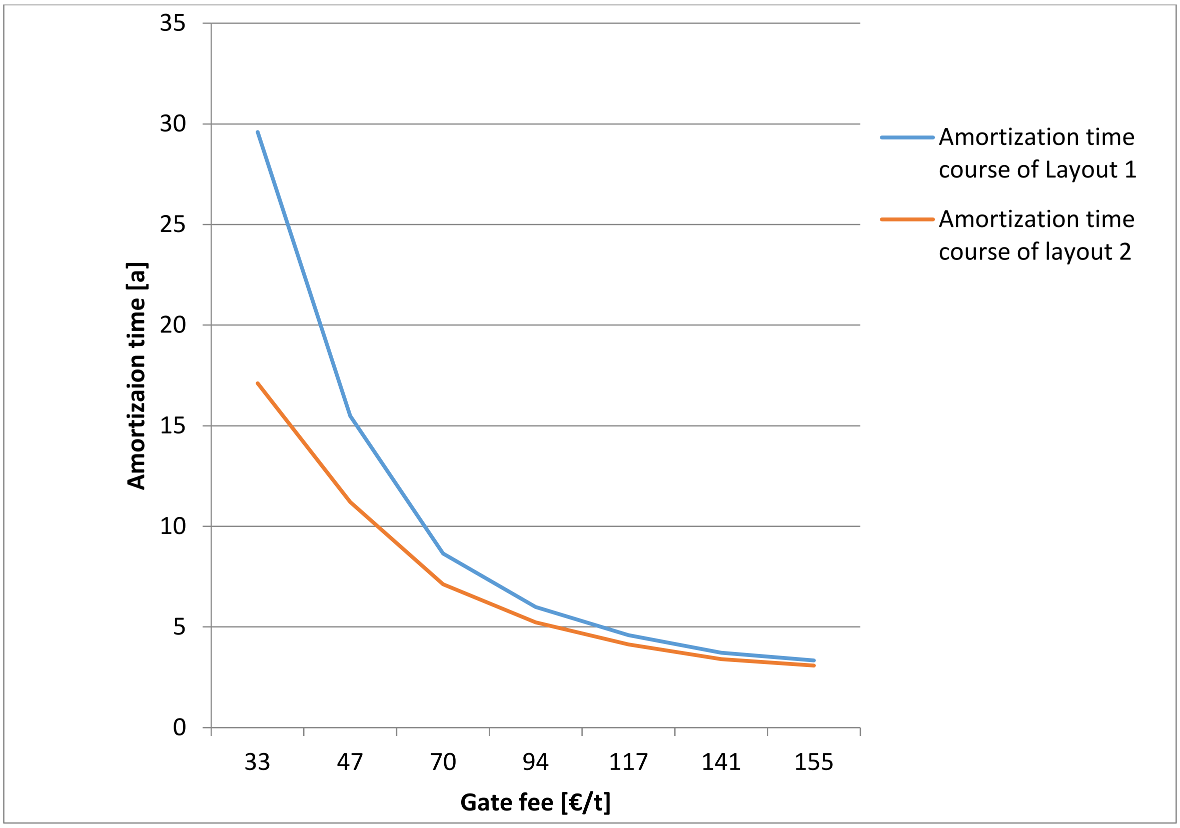

Figure 24: Amortization time depending on the gate fee

The graphic shows the importance of the gate fee for the amortization time as the profit from the additional waste acceptance is 82 % of the total profit of plant layout 1 and 75 % for plant layout 2. With a gate fee of 32.77 €/ t the fermentation plant is profitable after 17.1 years for plant layout 2 and 29.6 years for plant layout 1. This means, that amortization time exceeds the 20-year operation time for plant layout 1. On the opposite side, an amortization time of less than five years can be achieved for both plant layouts with a gate fee of 154.75 €/ t.

9.4.1.2 Variation of the feed in tariffs for electrical energy from fermentation

The electrical energy feed in tariffs in the UK for electrical energy from renewable energies change quarterly. For electricity from fermentation plants, the feed in tariff changed from 0.1789 €/ kWh in 2013 to 0.0493 €/ kWh in 2018 (Office of Gas and Electricity Markets, 2018). The feed in tariff from 2013 corresponds to 362.8 % of the feed in tariff of 2018. As new state subsidies for electricity from fermentation plants may be established, as well as the drop in prices may continue, the sensitivity analysis for the feed in tariffs was made for a range from 25 % to 362.8 % from the current tariff of 0.0493 €/ kWh. In absolute numbers, the feed in tariff ranges from 0.012 €/ kWh to 0.179 €/ kWh. Figure number 26 shows the result of the analysis for plant layout one and two.

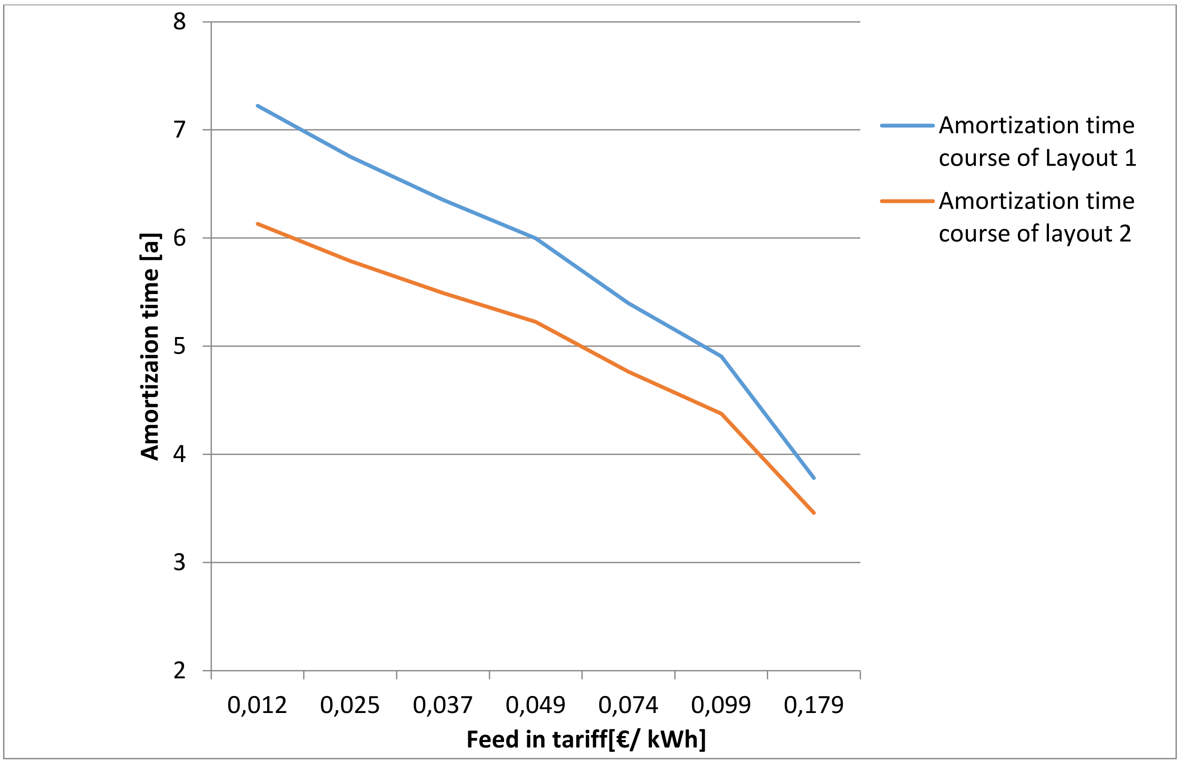

Figure 25: Amortization time depending on the feed in tariff

It is apparent, that the amortization time for both layouts is under five years with the feed in tariff of 2013. If the feed in tariff is further on declining, the amortization time is rising up to 7 years. The profits gained by the feed in of electricity from fermentation represent only 15 % for layout one and 14 % for layout two of the total obtained profit. Therefore, the change in the amortization time is much slighter than it was the case with the changed gate fees.

9.4.1.3 Variation of the disposal costs of the solid fermentation residues

By evaluating the annual costs of the fermentation plant it is obvious, that the disposal of the fermentation residues represents the lion´s share of the costs. Around 44 % of the annual costs are caused by the expenses for the disposal of the solid fermentation residues. The calculation of the amortization time has been done with disposal costs of the solid fraction of 120.91 € /t. This amount consists of 80 % tax and 20 % disposal fee (Anthesis Consulting Group, 2017). If it is possible to prove that the solid fermentation residue exists of stabilized organic material, the disposal is tax free (Szmidt, 2018). This means that the price for the disposal of the solid fermentation residue decreases from 120.91 €/ t to 24.18 €/ t. Therefore, the disposal costs of the solid fraction are varied in a range from 24.18 €/ t to 217.64 €/ t in figure number 27.

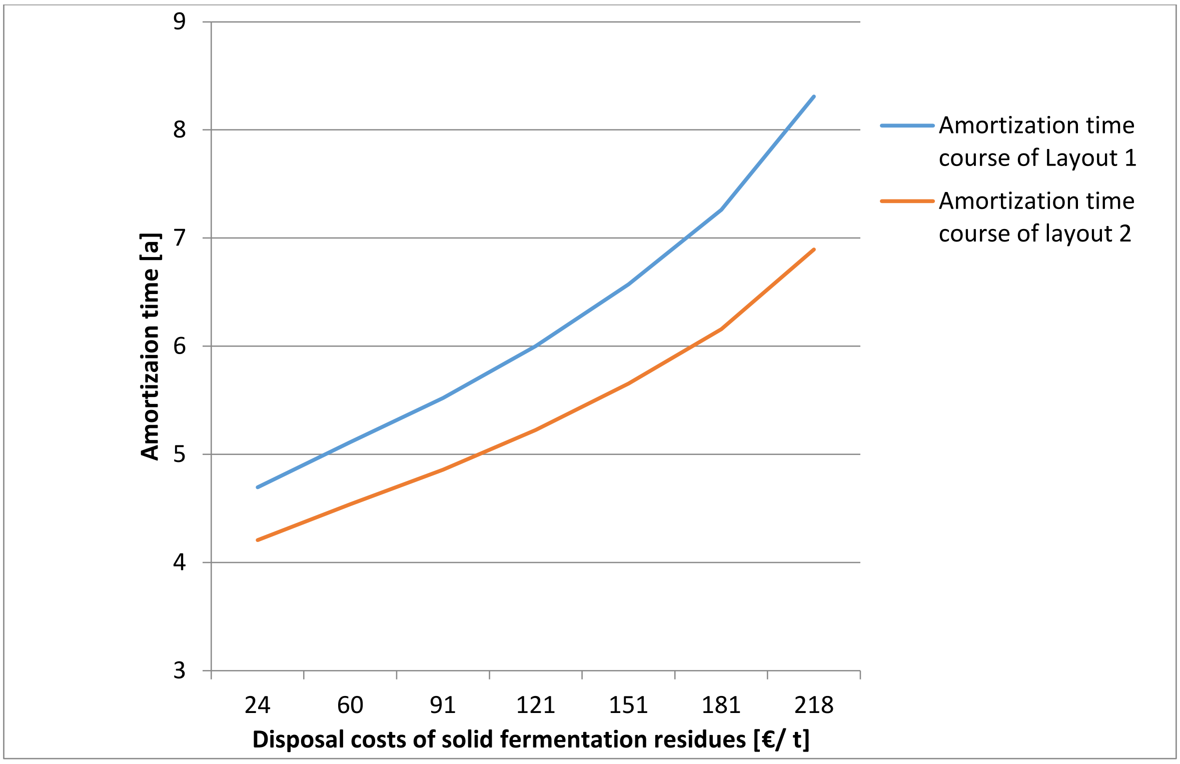

Figure 26: Amortization time depending on the disposal costs of solid fermentation residues

With a tax-free disposal of the solid fermentation residues, the amortization time of the fermentation plant can be reduced to less than 5 years for both plant layouts. By increasing the disposal costs, the amortization time raises to over 8 years for plant layout 1 and to about 7 years for plant layout 2.

9.4.1.4 Variation of the disposal costs of the liquid fermentation residues

It is possible to classify the liquid fermentation residue as a product if certain standards are fulfilled (Szmidt, 2018). The standards include regulations about the pasteurization of the input material, documentation of the input material, sampling of the fermentation residues and limits for ingredients of the liquid fermentation residues like for example nitrogen or phosphorus (Wrap, 2014). If the liquid fermentation residue fulfils the standards it can be classified as a product. This product can be used as a fertilizer in the agricultural business. In most cases farmers will take the solid fermentation residue for free and pay for the transport (Szmidt, 2018). Therefore, figure number 28 shows the amortization time for layout 1 and layout 2 for disposal costs from 0 €/ t to 28.25 €/ t. With a cost neutral disposal of the liquid fermentation residues, the amortization time of layout 1 drops to fewer than 5 years, and the amortization time of layout 2 declines to 4.4 years.

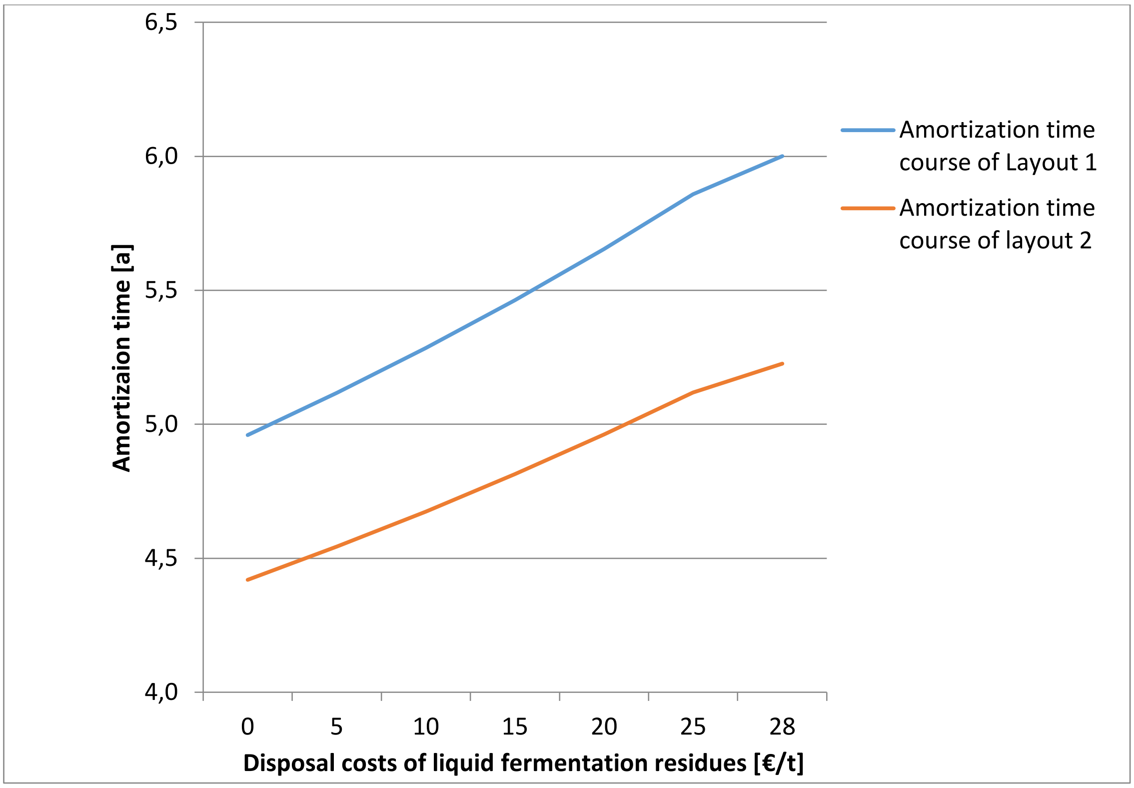

Figure 27: Amortization time depending on the disposal costs of liquid fermentation residues

9.4.1.5 Variation of the separation precision and pre-treatment investment costs

In chapter 8.2.1, the energy yield depending on the separation precision is described. The graphic shows that the compared energy yield of case 2 declines with shrinking separation precision. The declining separation precision comes with smaller investment costs for the separation facilities. Figure number 29 shows the course of the amortization time with different investments for different separation precisions. The in baseline scenario 1 and baseline scenario 2 used separation precision is 95 % with an investment of 817.600 € for the separation facility. It is assumed, that the investment cost for the separation facility declines with the separation precision. For example, the investment for a separation facility with a separation precision of 60 % is only 516.379 €. The energy consumption of the separation facility is also assumed to decline with the separation facility. The investment costs of the remaining plant compositions like the digester is not varied.

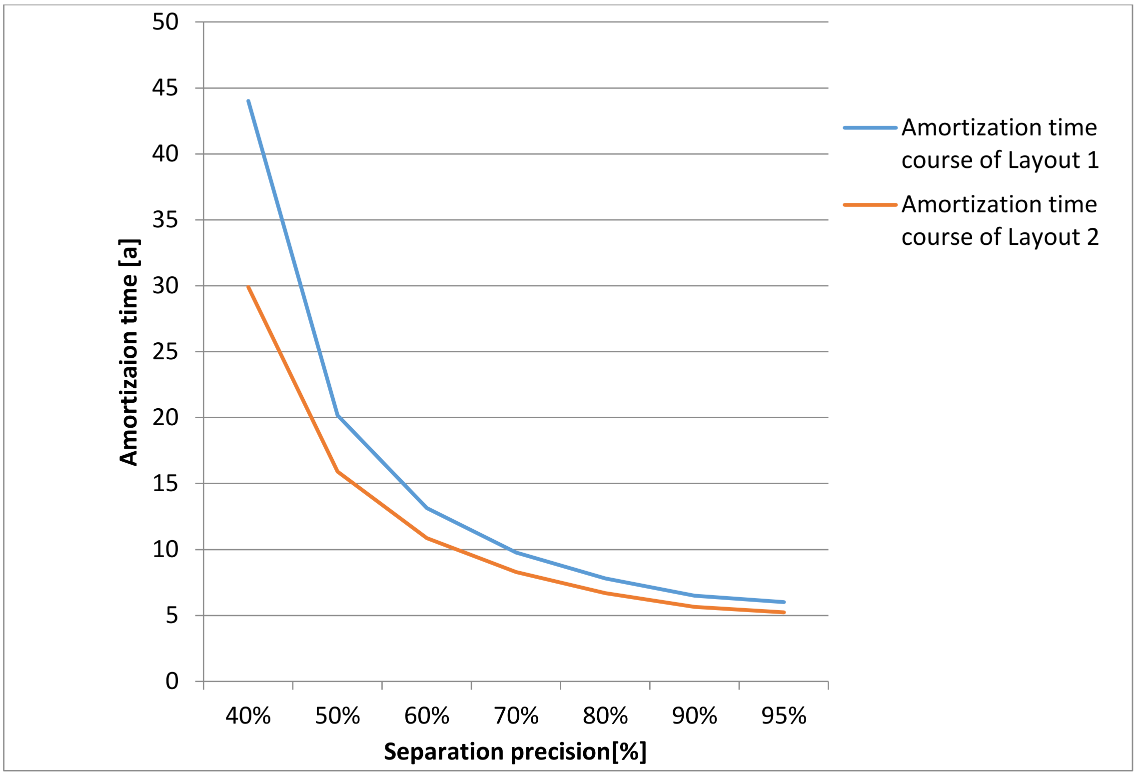

Figure 28: Amortization time depending on the separation precision

As evident in figure number 29, the amortization time rises with declining separation precision, although the reduced investment costs and energy consumptions are considered. The reason for this is, that on the one hand the investment cots reduce by 8,606.32 € and the electrical energy demand of separation facility reduces for 20,589 kWh/ a per 1 % lower separation precision. But on the other hand the annual net electrical energy generation reduces for 89,718 kWh and the annual net thermal energy generation reduces for 56,476 kWh. This is equivalent to revenue shortfalls of 88,404.5 € for plant layout 1 and 107,606.37 € for plant layout 2 for the operation time of 20 years.

9.4.1.6 Variation of the evaporating energy

Like explained in chapter 8.2.3, the evaporating energy depends on the design of the incineration plant. In figure number 30, the course of the amortization time depending on the amount of evaporating energy is pictured. It is apparent, that the change of the evaporation energy does not influence the amortization time drastically. For plant layout 1, the amortization time drops from around 6.08 years without consideration of the evaporating energy to 5.99 years with an evaporating energy of 120 kWh/ t MSW. The amortization time of plant layout 2 behaves similar to the amortization time of plant layout 1. Without consideration of the evaporating energy the amortization time is 5.37 years, with the evaporating energy of 130 kWh/ t MSW, the amortization time is 5.20 years. Figure number 30 describes the discussed matter graphically.

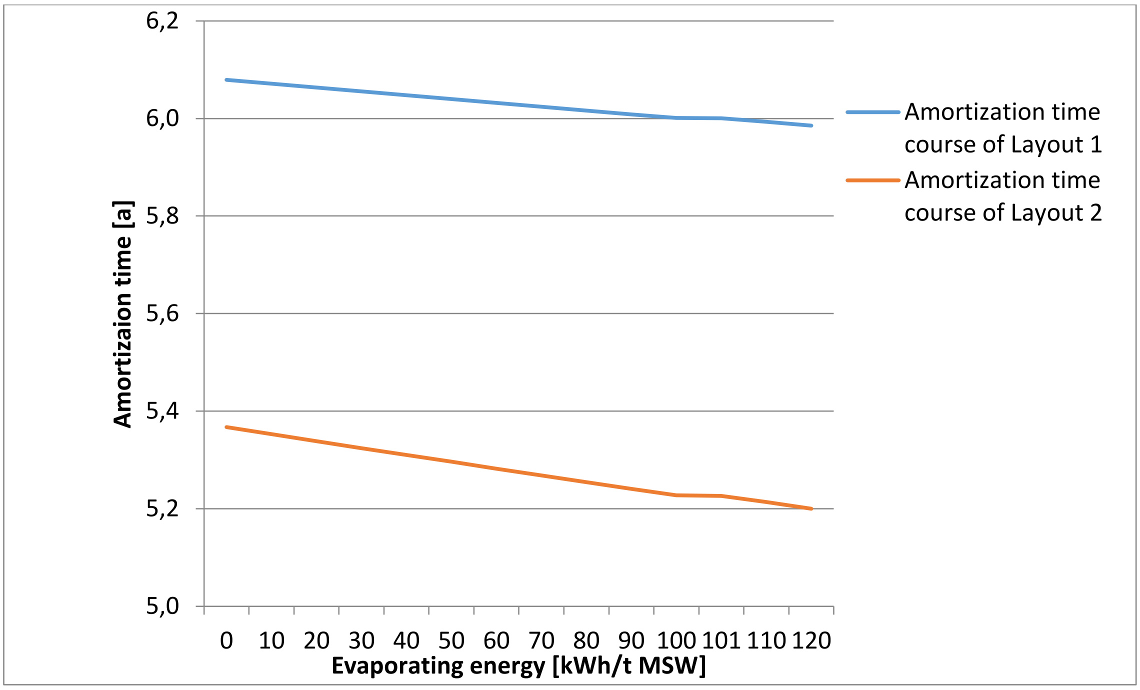

Figure 29: Amortization time depending on the evaporating energy

9.4.1.7 Comparison of the most important amortization time- parameters

To compare the influence of the above-mentioned parameters, the change of the amortization time is shown in figure number 31 for plant layout 1 and in figure number 32 for plant layout two. For plant layout 1, the disposal costs for the solid and the liquid fermentation residues, the revenue from the gate fee and the revenue from the feed in of the electrical energy are taken in account. For plant layout 2, the same parameters were taken in account and additionally, the revenue from the feed in of the thermal energy was included.

For the importance of the influence of each parameter on the amortization time it applies that the steeper the course, the higher is the influence. The parameters were changed in a range from -25 % to +25 % from the initial size. It is obvious, that for both layouts, the revenue from the gate fee is the most important parameter. The amortization time changes from 8.65 years to 4.59 years for plant layout 1 and from 7.13 to 4.13 years for plant layout 2 by changing the parameter from -25 % to +25 % from the initial value.

In contrast, the disposal costs of the fermentation residues have only a small influence on the amortization time.

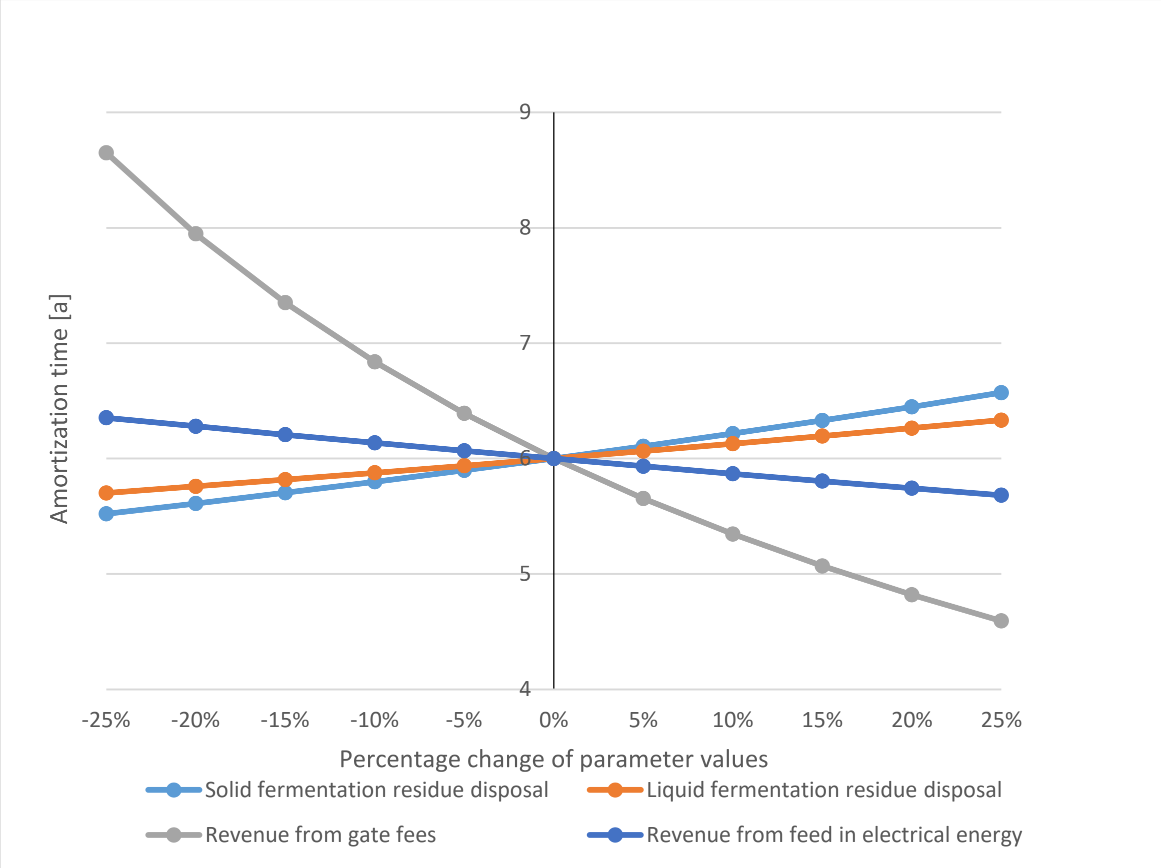

Figure 30: Comparison of the parameters for plant layout 1

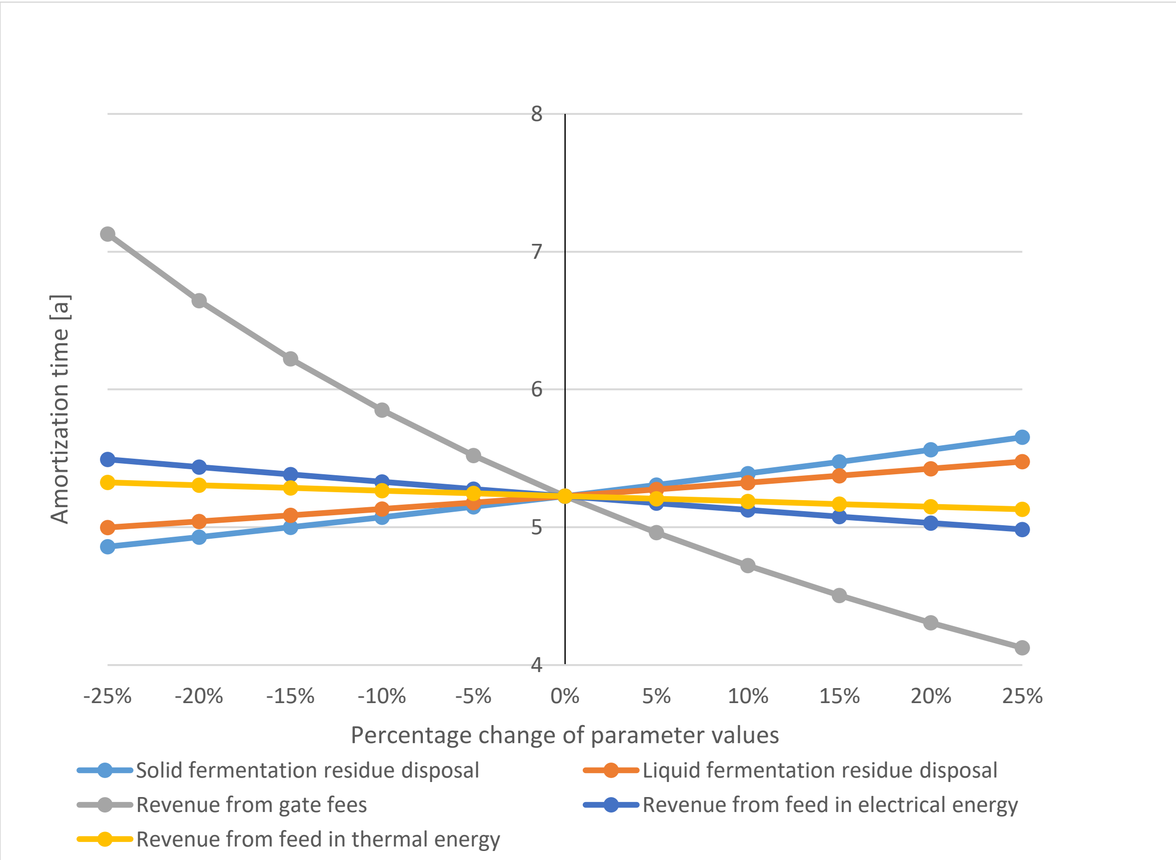

Figure 31: Comparison of the parameters for plant layout 2

10. Conclusion

In the last chapter of the master thesis, the results of the calculations are compared with the research question and the assumptions of the research question. And the end of the chapter, an outlook about the combined incineration and fermentation technology on the UK market is shown.

10.1 Answering the research question

To answer the research question, the following terminologies were established. Case 1 and case 2 describe the two different technologies for waste treatment which were used for the thesis. In case 1, the waste is incinerated completely in an incineration plant, in case 2, the OFMSW is separated from the remaining MSW and used in a fermentation plant. The remaining waste is again incinerated. Baseline scenario 1 and 2 characterise two different scenarios with different parameters like the different waste composition or different efficiencies of the incineration plant. For the economic analysis, the terminology of plant layout 1 and 2 was introduced. Plant layout 1 only considers the net electrical energy produced, plant layout 2 also includes the net thermal energy produced.

The research question was formed in chapter number 3 as:

What is the difference in the energy yield and the economic profit, if the biodegradable fraction of municipal solid waste (MSW) is separated and treated in a fermentation plant instead of treating the joint waste in an incineration plant?

The assumption behind this research question was that the OFMSW has a high share of moisture which decreases the efficiency of the incineration plant.

The difference in the energy generation between case 1 and case 2 in chapter 8 describes this difference in the energy yield between those 2 scenarios. In baseline scenario 1, the difference in the annual energy yield between case 1 and case 2 is 13.88 GWh or 138.88 kWh/ t MSW. For baseline scenario 2, the difference is 16.4 GWh or 163.94 kWh / t MSW. The difference of the net electrical energy yield between an incineration plant layout with separate treatment of the OFMSW in a fermentation plant to a joint waste incineration plant is 8.5 GWh with a feedstock of 100,000 t MSW or 85.2 kWh/ t MSW for baseline scenario 1 and 3.6 GWh with a feedstock of 100,000 t MSW or 36 kWh / t MSW for baseline scenario 2.

The economic profit has been investigated in an amortization time calculation. The calculation shows an amortization time of 6 years for plant layout 1 and an amortization time of 5.23 years for plant layout 2. The annual average profit of the additional fermentation plant is 1,791,000 € for plant layout 1 and 2,170,000 € for plant layout 2.

The sensitivity analyses in chapter 9.4.1 show, under which circumstances an additional fermentation plant is economically viable. The analyses show, that the revenues from the gate fees are the most important parameters in respect of the amortization time. The change of the parameters from -25 % to 25 % of the initial value shows, that parameters like the revenue from energy sales and the disposal costs change the amortization time only for less than 1 year. The variation of the gate fees though change the amortization time in a range of around 4 years.

The assumption, that the high share of moisture in the OFMSW decreases the energy yield has been confirmed. But with the addition, that the evaporating energy only has a limited influence to the improved energy yield. The correlation between evaporating energy and difference in the energy yield of case 1 and case 2 is shown in chapter 8.2.3. The variation of the evaporating energy from 0 to 120 kWh/ t MSW changes the difference of the energy yield between case 1 and case 2 for scenario 1 for annually 4.3 GWh or 43 kWh/ t MSW.

The major part of the difference in the energy yield is caused by the superior efficiency of the digester and CHP combination in comparison to the incinerator and steam turbine set-up.

In chapter 9.4.16 also the influence of the evaporating energy on the amortization time of the fermentation plant is discussed. Both plant layouts only slightly decrease in the amortization time with enhanced evaporating energy. Relating to the amortization time, the biggest influence factor is the revenue from the gate fee. This is shown clearly in chapter 9.4.1.7. The revenue from the generation of electrical and thermal energy only plays a subordinate role.

10.2 Potential assessment for fermentation plants in the UK

In chapter 10.2, the potential of fermentation plants with the conditions of the UK are analysed and associated with the results of chapter 8. The analysis of the practically possible energy yield shows, that there is quite big potential for plants with the technology of case 2.

10.2.1 Current market situation in the UK

In 2015, 26.7 Million tonnes of MSW were produced in UK households. That is about the same as in 2014, where 26.8 Million tonnes of MSW were produced. 22.2 Million tonnes accrued in England, 2.4 Million tonnes were generated in Scotland, 1.3 Million tonnes occurred in Wales and 0.8 Million tonnes were produced in Northern Ireland.

With consideration of the MSW composition in chapter 8.1.1 around 32 % of the UK MSW from households is OFMSW. That corresponds to an annual amount of 8.54 Million tonnes of OFMSW. 7.7 Million tonnes of the OFMSW were sent to landfill in 2015.

In 2015, 9,271 GWh of electrical energy were produced from OFMSW. Around 52 % of the produced electrical energy came from landfill gas and about 16 % from anaerobic digestion. The remaining electrical energy from OFMSW was produced in incineration plants and a small part of the produced electrical energy came from co-firing with fossil fuels.

10.2.2 Theoretically possible energy yield with the technology of case 2

The theoretically possible energy yield of case 2 is calculated with the total generated MSW in the UK. Therefore, the feedstock of 26.7 Million tonnes of MSW with a total amount of 8.54 Million tonnes of OFMSW was used. Table number 21 shows the results of the calculation.

Table 21: Theoretically possible energy yield of case 2

Calculated component	Value [GWh/ a]
Net electrical energy generation of incineration plant	4,663
Net thermal energy generation of incineration plant	11,502
Net electrical energy generation of fermentation plant	3,092
Net thermal energy generation of fermentation plant	3,446
Total net electrical energy generation	7,754
Total net thermal energy generation	14,948
Total net energy generation	**22,703**

The total net energy generation of 22,703 GWh complies with 1.4 % of the total energy demand of the UK which is 1,635,969 GWh per year (Department for Business, Energy & Industrial Strategy, 2017). In 2017, 98,900 GWh of renewable electricity was generated in the UK (Department for Business, Energy & Industrial Strategy, 2018). The calculated electrical energy from MSW with the technology of case 2 is 7,754 GWh. This is 7.8 % of the renewable generated electrical energy.

10.2.3 Practically possible energy yield with the technology of case 2

As it is practically not possible to use the total annual amount of MSW as a feedstock for plants that use the technology of case 2, minor amounts of MSW needs to be appropriated. The anaerobic digestion market outlook presumes an availability of 2.2 million tonnes of OFMSW from households per year (Eunomia Research & Consulting Ltd., 2011). For these 2.2 Million tonnes treatment facilities with a capacity of 412,500 tonnes per year already exist. This means that 1,787,500 tonnes of OFMSW per year are still available. With regard to the waste composition in chapter 8.1.1 about 5,585,937 tonnes of MSW can be used as a feedstock. Table number 22 shows the results of the calculation with a feedstock of 5,585,937 tonnes of MSW.

Table 22: Practically possible energy yield of case 2

Calculated component	Value [GWh/ a]
Net electrical energy generation of incineration plant	975
Net thermal energy generation of incineration plant	2,406
Net electrical energy generation of fermentation plant	647
Net thermal energy generation of fermentation plant	721
Total net electrical energy generation	1,622
Total net thermal energy generation	3,127
Total net energy generation	**4,750**

With the total net energy generation of 4,750 GWh/ a, about 0.3 % of the total energy demand of the UK can be covered. The total net electrical energy generation of 1,622 GWh/ a, that is practically possible is equal to 1.6 % of the total generated renewable energy in the UK.

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Statement of Affirmation

I hereby declare that all parts of this thesis were exclusively prepared by me, without using resources other than those stated above. The thoughts taken directly or indirectly from external sources are appropriately annotated. This thesis or parts of it were not previously submitted to any other academic institution and have not yet been published.

Dornbirn,………………………… ………..…………………

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