Incineration or pyrolysis for processing un-separated household waste?

An exploration of pyrolysis for non-recyclable but flammable household waste within a case study

Ricardo Blees

Student number: S2203243

Supervisors:

Dr. Maarten Arentsen

Prof. Dr. Joy Clancy

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Extra information:

Student:	Ricardo Blees
Master program:	Master of Environmental and Energy Management
Specialization:	Energy Management
Student Number:	S2203243
E-mail address:	Ricardo.blees@hvhl.nl
University:	University of Twente
Department:	Department of Governance and Technology for Sustainability
Faculty:	Faculty of Behavioural, Management and Social Sciences
Address:	Drienerlolaan 57552 NB Enschede
First Supervisor:	Maarten Arentsen
E-mail address:	m.j.arentsen@utwente.nl
Second Supervisor:	Joy Clancy
E-mail address:	j.s.clancy@utwente.nl

ABSRACT

The target for CO_2 neutral electricity production for 2050 is an important step by the Netherlands to fight global warming. This will have a major impact on the current electricity production sectors that have to find innovative alternatives. One of those sectors is waste to electricity through incineration of flammable waste.

Within this research, the aim is to analyze two alternative approaches for processing flammable household waste, which is currently incinerated in Friesland. The two approaches are slow & fast pyrolysis and will be analyzed based on their environmental and product value. The structure of this report begins with a short introduction regarding the topic, research questions and overview of the methodology. Secondly, the current household waste composition that is incinerated is determined and approximated. Thirdly, the incinerator, slow and fast pyrolysis are in depth analyzed, based on their current market value and emission concentrations. Thereafter, the data is compared to each other, based on global warming, environmental effects and the product value. Finally, the results are concluded in a clear overview and recommendations are made.

Within this research, it was found that 132.647 ton household waste was incinerated in 2018 in Friesland, whereas 81,9-91,3 % consisted of flammable waste. Here, bio-organic material and paper are the main components that is incinerated. Furthermore, the remaining significant part consisted of incontinence waste material, fermentation residue and textile. When this waste portion is incinerated, electricity is produced from the heat (142.397 MWh) and the product value is 0,07 euro/kg waste, excluding production and construction costs. On the other hand, slow and fast pyrolysis for the production of electricity significant lower value was calculated and was respectively 0,032 euro/kg waste and 0,041 euro/kg waste. However, when the pyrolysis products were sold as a chemical feedstock or fertilizer, the value was found to be significant higher (0,16-0,20 euro/kg waste) for slow pyrolysis.

With respect to the emission levels, it was found that slow and fast pyrolysis of household waste emits significant lower global warming potential gases than incineration. This is mainly due the decrease of the CO_2 emission, as for methane and hydrogen significant higher amounts are produced during the pyrolysis process. As for the acidification potential, the gases emitted from pyrolysis are considered less damaging than that of incineration. On the other hand, the photochemical ozone creation potential is considered lower for incineration than that of slow and fast pyrolysis.

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LIST OF ABBREVIATIONS

REC	Restoffenenergiecentrale (an waste incinerator for green energy)
GWh	Giga watt hour
SDG	Sustainable development goals
HCL	Hydrochloric acid
CO	Carbon monoxide
NOx	Nitrogen oxides
SO2	sulfuric acid
NH3	Ammonia
HF	hydrogen fluoride
PCA’s	polycyclic aromatics
Bio-PET	bio-Polyethylene terephthalate
EU	European union
GHG	Greenhouse gas
LAP	Landelijke afvalbeheer plan (national waste management plan)
CBS	Centraal beheer van statistiek (central management of statistics in the Netherlands)
Kw	Kilowatt
Wt.%	weight percentage
VFG	Vegetables, fruit, and garden
WEEE	Waste electrical and electronic equipment
n.k.	not known
MCI	Municipal waste incinerator
GWP	Global warming potential

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CHAPTER 1: INTRODUCTION

To fight global warming and climate change, the Netherlands developed ambitious goals to reduce the CO_2 emission by 49,5% in 2030 relative to 1990 and achieve CO_2 neutral energy production in 2050 (art. 2 klimaatwet). This will have a major impact on the traditional waste to energy approaches, where more CO_2/kWh is emitted than energy produced from traditional fossil fuel and alternatives are favorable, such as wind and solar power (ZerowasteEurope, 2019). But still, municipal waste incineration (MCI) is the favorable approach compared to landfilling, as it minimize the waste density dramatically (especially in dense area's[1]) and benefits from the "green" energy production (Makrichi et al. 2018).

Due the Dutch CO_2 emissions goals, the shutdown of one MCI in the Netherlands was analyzed by Ecorys. They concluded that the shutdown of the waste combustion plant of Omrin in Friesland, the REC (Reststoffen energy centrale) will cost approximately 118-152 million euro, but will not have a major impact on the workers. Furthermore, Haffner et al. (2019) pointed out that closing the MCI in Harlingen will only move the problem towards other MCI's with less energy recovery efficiency and will not have enough capacity to process all the waste, However, other waste processing techniques were not discussed.

When it comes to incineration, the waste that is burned is classified as flammable and consist of carbon based materials (Kobus, 2019). Therefore, within this report, two different types of alternative methods are analyzed, within a case study. One of these techniques, slow pyrolysis, was already mentioned before 1980 and proposed as an alternative for incinerators. One of the main benefits of slow pyrolysis is the production of fuel/oil instead of hot water and steam and can be used as a fuel/oil or even as a chemical feedstock (Bridgwater 1980). The fuel/oil has a higher heating value (MJ/kg), but the process comes with higher production and maintenance costs. Besides this, the emission of pyrolysis is less polluting than that of incinerators and the equipment can be smaller (Gurgul et al. 2017 & Yurtsever et al. 2009). In extension of the pyrolysis technique, a second technique that can process waste into products is fast pyrolysis. In this process, more pyrolysis liquids and gases are processed by a higher heating rate towards even more valuable products (Bridgewater, 2007). On the down side of these pyrolysis products, as they are highly unstable (Meng et al. 2015) compared to fossil based materials and require additional treatment for storage.

Several enterprises constructed and developed fast pyrolysis reactors to show the commercial potential. For example, the BTG group constructed two pyrolysis reactor plants in Malaysia and the Netherlands for processing wood chips and fruit bunches from palm oil (Hamzah et al. 2019 & Yin et al. 2018). These reactors processes mostly only virgin feedstock and are constructed to obtain high quantity of bio-oil. However, literature regarding these techniques, only mentions the potential for processing waste. The same story applies for the slow pyrolysis technology, where the goal is to obtain high quantity of chars (Garcia-Nunez et al. (2017).

1) Areas that have high population/area ratio, e.g. cities or countries such as the Netherlands.

Despite the potential for high energy products derived from (slow & fast) pyrolysis and the potential for closing the loop of domestic waste, these techniques are new to the market. Furthermore, relevant research on this matter is mainly performed on lab-scale and is still in the development stage (Sharifzadeh et al. 2019). No practical examples documented for a self-sustaining pyrolysis reactor (Rollinson & Oldaejo, 2019).

Currently, the urge to reduce the REC productivity or even shut down is growing. This is a direct effect of the pressure to reduce the GHG emission for electricity production from the European Union and the Dutch government. To find a potential cleaner and more profitable technology, this report presents the quantification of the environmental impact and economical value of usable pyrolysis products. This all based on the waste stream towards the REC.

1.1 RESEARCH OBJECTIVE AND QUESTIONS

The objective of this research is to analyze and assess slow and fast pyrolysis of household waste in Friesland with respect to economic gains and environmental emissions as alternative for the current incineration of the household waste.

With respect to the economic gains objective and environmental objective of this research, the following research question is established:

To what extend can slow and fast pyrolysis of household waste be considered an alternative for incineration of municipality waste, based on environmental and financial criteria and what would that imply for household waste management in Friesland?

In order to answer the research question, the following sub-questions have been formed:

1) What is the composition of household waste currently processed by Omrin with the REC
2) What is the economic value of the products of REC and (fast & slow) pyrolysis by processing household waste?
3) What are the emission concentrations of the REC, (fast & slow) pyrolysis by processing household waste?
4) Based on the environmental and economic performance, which of the waste processing techniques should be the process in Friesland for unrecyclable and non-reusable flammable household waste?

1.2 RESEARCH STRATEGY

This research had three approaches, where on the one hand, the municipality waste flow/mass balance going to the REC was collected and constructed and on the other hand, incineration, slow pyrolysis and fast pyrolysis are in depth analyzed on their emission levels and product value. Finally the three techniques were compared to each other on their environmental impact and economic value of the products to answer the research question (illustrated overview see Figure 1).

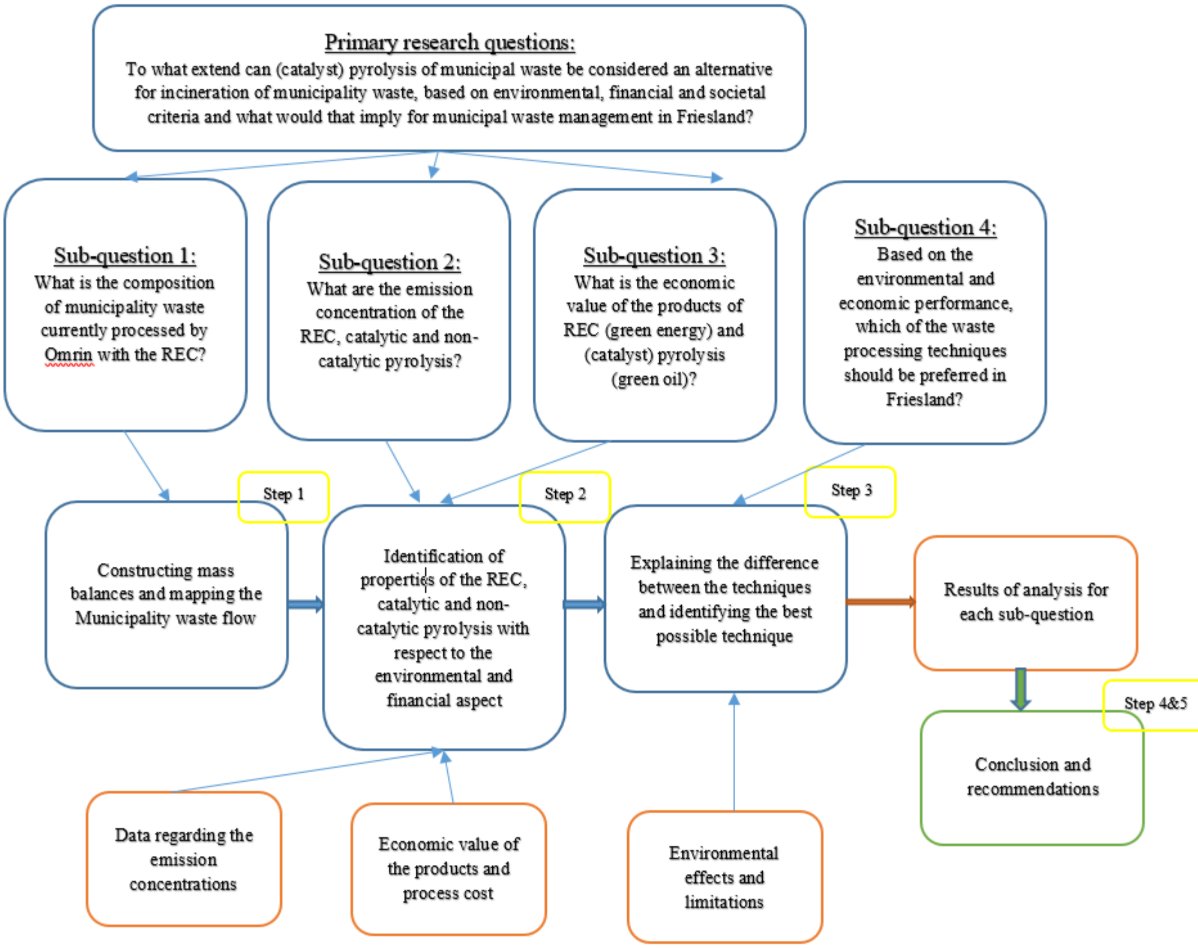

Figure 1; illustrated overview of the research setup.

For the first sub-research question, documents regarding the waste processing in Omrin were obtained and processed into a flow chart and mass balances with Excel and Word. For in depth detail and conformation regarding the results about the waste processing at Omrin, interviews with the waste & energy expert of Omrin and the REC were conducted.

For the second and third sub-research questions, large number of data were available in scientific literature, documents and the media. The data was obtained through the open libraries of the universities of Twente and Van Hall Larenstein. Subsequently, the data was stored and processed through Excel and Word. Furthermore, for in depth data, interviews were carried out with pyrolysis experts to find the missing gaps in the data.

For the final sub-research question, four scenarios were constructed based on the data of the previous approaches and analyzed on their product value and environmental effects. The four scenarios are as follow:

- No changes made on the REC
- Slow Pyrolysis for the production of electricity
- Slow pyrolysis for the production of energy, oil and fertilizer
- Fast pyrolysis for the production of electricity

With respect to the calculations and specific methods used for processing data and collecting data, this is in detail described with the corresponding chapter/sub-chapter.

1.3 READING GUIDE

In the next chapter, the waste management within Friesland is described and mapped in a flow chart. Furthermore, within this chapter, the waste that is incinerated by the REC is calculated and presented. Within the third chapter, the REC is briefly described and the product value and emissions are determined. In chapter four, similar analysis is presented as for the REC, but then for slow and fast pyrolysis. In chapter 5, the three techniques are presented in a four potential scenario for processing flammable waste and are analyzed based on the product value and environmental impact. The final chapter represents the conclusion of the research questions and recommendations.

CHAPTER 2: HOUSEHOLD WASTE FLOW WITHIN FRIESLAND

In this chapter, data to answer the sub-question "What is the composition of household waste currently processed by Omrin with the REC" is presented and described. Firstly, household waste is classified according to the EU criteria. Secondly, the average household waste per citizen within the Netherlands is presented. Thirdly, the waste flow within Friesland towards the REC is presented and lastly, the composition of the waste towards the REC is calculated.

2.1 HOUSEHOLD WASTE ACCORDING TO THE EU

Municipal waste, according to the Eurostat-unit E2 (2017), covers household waste and waste similar in nature and composition to household waste. This definition covers the waste derived from households, small businesses, office buildings and institutions and municipality services. Furthermore, this definition only focusses on solid waste only and excluding the municipal sewage network waste. Besides that, the definition is only a guideline and constructed for data collection by the EU members.

Furthermore, the legislation framework for municipality waste by the EU, what is regulated by the waste framework directive, the following definition is defined (with the exclusion of wastewater): '*waste means any substance or object which the holder discards or intends or is required to discard* (Directive 2008/98/EC 2008)'. Both definitions are very undefined and covers a range from large household waste (for example: couches and televisions) to small household waste (for example packaging and food waste).

2.2 HOUSEHOLD WASTE MANAGEMENT IN THE NETHERLANDS

Waste management in the Netherlands is written in the "landelijke afval plan" (LAP) as stated in article 10 of the "wet milieubeheer|" (environmental management law) of the Netherlands. This plan is part of the transition towards a circular economy[2] in 2050, with the target to zero waste production (Dijksma, 2016) and an adoption by the EU legislation of the EU waste directive. By law, the LAP needs to be revised every 6 years and currently LAP-3 is active. Here, 16 goals are defined, with the most interesting goals that support the objective of this thesis proposal: 50% reduction of waste incinerated or transported to the landfill and stimulating sustainable innovations in recycling, aimed on quality and environment pressure (ministerie van IenW, 2019)

Furthermore, within the LAP3, the EU legislation is translated to different waste sectors and, according to the LAP, the following waste sectors are classified as follow:

2) According to the government of the Netherlands: a economy where the materials are re-used for new products in a closed loop and raw materials are obtained in a sustainable way.

Table 1; Waste sectors in the Netherlands part of the municipality waste

Sector	Description or examples
Household rest waste (fine and rough)	Household waste after separation
separated paper	i.e. newspapers and carton packaging
Separated textile	i.e. clothing, large fabric pieces and curtains
Separated vegetables, fruit and garden waste (FVG)	Mostly organic waste
Plastic and rubber	Plastic packaging, tires and plastic bottles
metals	Ferrous and non-ferrous metals
Batteries	Lead acid, nickel-cadmium and car batteries
Small chemical and/or dangerous waste	i.e. batteries, chemicals, paint and medicines
Wood	i.e. garden wood , sawdust
Waste electrical and electronic equipment (WEEE)	i.e. electronic kitchen equipment, lamps and televisions
Rest mono streams	Everything that is technical recyclable and desirable

For each sector, described in Table 1, a plan is constructed and documented. Here, a detailed description of the waste is presented and how it should be transported & processed by the waste processor according to the waste hierarchy. Take for example the sector "Household rest waste". The sector plan described that this waste is a mixture of waste after separation of paper, glass, plastic and others and that the minimum standard for processing is burning or separation. This is decided after an assessment on the waste hierarchy in Appendix VI with determined whether or not pre-treatment on this sector is possible, but after pre-treatment some parts can be recycled and others cannot.

According to article 10.21 and 10.22 of the "wet milieubeheer", the municipalities are responsible for collecting waste and providing the facilities for the separation of compostable waste (vegetable/fruit/garden waste), unseparated household waste and large rough household waste. The first two are collected in individual household containers or a residential area container containers and the large rough household waste, for example a washing machine or a cut tree, is located on one central location.

With this approach, the Netherlands collected 8.5 billion kilogram household waste over the year 2018 (CBS 2019). A detailed overview of the separated household waste is given in Figure 2 (left graph). The presented data is based on the most common separation processes and not on the sectors presented in Table 1. Furthermore, the household rest waste part (45% of the total separated municipal waste) was analyzed and reported by Rijkswaterstaat and the distribution of this part is presented in the right graph of Figure 2. It is important to notice that the data are collected one year apart, however as the difference in household waste in 2017 and 2018 was only 2%, the difference is not significant and is still representative & comparable with the current situation.

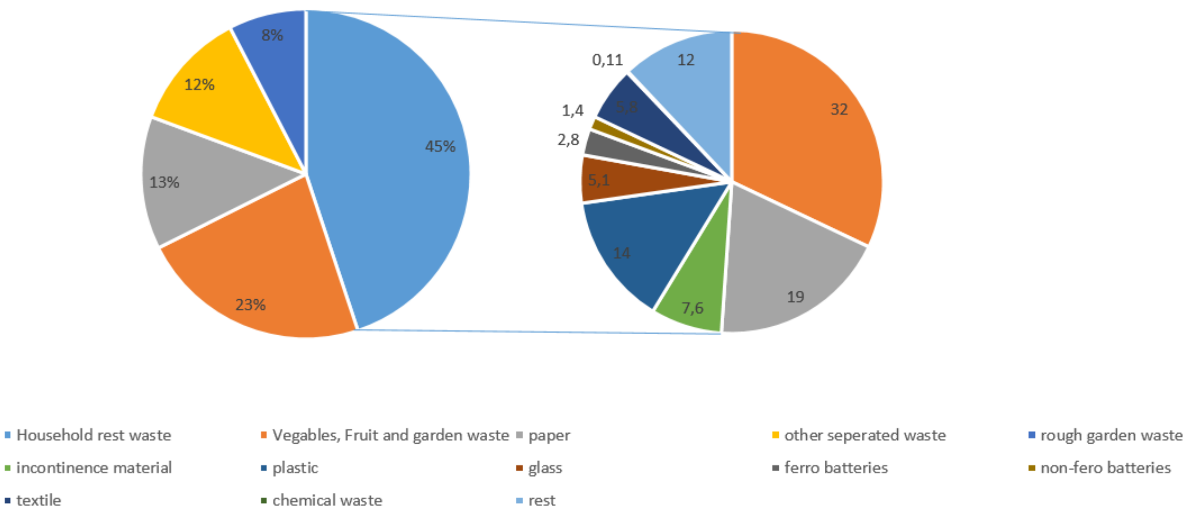

Figure 2; Left graph represents the overall collection of municipal waste (CBS, 2019). Right graph represents the household waste collection (Rijkswaterstaat, 2019)

With respect to the waste treatment management within the Netherlands, this was analyzed by the Directorate-General for Environment, European Commission on the progress of environmental implementation. The data, that was collected over the year 2017 on waste treatment, showed the following distribution of municipality waste: 1% distributed to the landfill, 26% has been recycled, 28% is used for the production of bio-gas (through anaerobe digestion) and 44% is incinerated for energy. In other words, within the Netherlands 3.74 billion kilograms of municipality waste is incinerated for the production of electricity and heat.

2.3 WASTE MANAGEMENT IN FRIESLAND AND OMRIN (CASE STUDY)

For comparing the alternative techniques for processing incinerated waste in practice, the composition of this waste has to be determined. However, as it is impossible to analyze multiple household waste streams within the research time, only the household waste stream of Friesland will be analyzed. For this, multiple year rapports of Omrin (from multiple sub-organizations, 2018), data obtained from the CBS and the management of Omrin regarding household waste composition within the Netherlands are obtained.

2.3.1 DESCRIPTION OF OMRIN

Within this province of Friesland, Omrin (also referred to as "afvalsturing Friesland NV") is the responsible company for collecting and processing the household waste of 14 municipalities. This company is the owner of waste separations machinery, located in Heerenveen and one waste to energy incinerator, which is located in Harlingen. One of the main goals of Omrin is to increase the separation efficiency of the waste after collection, with will be called further on "secondary separation". This strategy forces Omrin to invest in new secondary separation technologies and decreases the separation stress for households (primary separation).

Currently, households in Friesland where Omrin is operation, have individual, near their houses, separation bins for compostable waste unseparated household waste and large rough household waste. Furthermore, for larger household waste (for example, car batteries, tires and household construction waste) ten dumping sites are available, located in different cities within Friesland. After primary and secondary separation, the remaining waste is transported to the incinerator in Harlingen, where the waste is processed to steam and eventually electricity. The separated part is re-used by bringing it back to the market.

2.3.2 WASTE FLOW PROCESSED BY OMRIN

Combining the data as discussed in section, 2.3, the flow chart presented in Figure 3 has been constructed. According to the year report of Omrin, 414 kg/person household waste was collected, through dumping sites (25 wt.%) and near house waste collecting (75 wt.%) in 2018. During this year, Friesland had 647.268 inhabitants that produced 267.969 ton household waste (647.268 inhabitants *0.414 ton waste). The illustrated sectors in figure 2 (left graph) is representative for the primary separation, with exclusion of the waste distribution. In Friesland, the following waste distributions was calculated by using the data presented in appendix I: 30,0 wt.% separated vegetable, fruit and garden (VFG) sector, 14,3 wt.% separated paper sector and 47,1% unseparated household rest waste. The last two mentioned sectors are comparable with the average household waste distribution of the Netherlands, however the VFG is 7% higher. An explanation for this is the missing rough garden waste sector in the year rapport of Omrin. Because, combining the wt.% of the rough garden waste and the VFG sectors, gives a total of 31wt% of the total household waste and is comparable with the wt.% VFG presented by Omrin. Furthermore, the "other separated waste" sector presented in figure 3 is described by Omrin as follow: 1,7wt.% thrift shop material (e.g. re-usable toys, desks..), 4,6wt.% glass, 1,2% textile and 1,2% WEEE. In total, this is 8,7wt.% and is 3,3% lower than the average of the Netherlands. This is probably the effect of zero primary waste separation of plastic management in Friesland. As such, the rest of the provinces within Netherlands started separating plastic since 2008 (Dijkgraaf & Gradus, 2016), the average wt.% of separated waste increases in the

Netherlands. Friesland rather separates the plastic secondary and therefore can differ from the average wt.% in comparison with the other provinces.

Besides the separated waste, Omrin collected a total of 47,1wt.% household unseparated waste. This is transported towards a plastic separation installation (KSI, part of Omrin) in Heerenveen for secondary separation. Here, the unsorted waste is sorted as follow: 1,4 wt.% metals, 3,9 wt.% plastic, 0,7 wt.% paper, 9,2 wt.% bio-organic waste and 2,9 wt.% minerals, according to Omrin. In total, 18,1% rest waste is sorted after this process and the total separated household waste in Friesland increases to 71 wt.%.

After primary and secondary separation, 39,1 wt.% is anaerobic digested for the production of 7.6 million m^3 green gas and bio-granulate. According to the management of Omrin, the solid residue derived from this process is transported towards the REC. However, the management did not presented quantified or qualified data regarding this and is not recorded in any available documentation. None the less, scientific experiments, that conducted a research involving the anaerobic digestion of municipality organic waste, methane (green gas), bio-granulate and other emission were obtained. Approximately 15% residue after anaerobic digestion consisted of organic solid residue, depending on the type of anaerobic digestion (Sun et al, 2019 & Ardolino et al, 2018). As these experiments are comparable with the situation at Omrin, approximately 15% of the 39,1 wt.% (6 wt. % of the total household waste) is transported to the REC.

It can be assumed that, from the total household waste obtained and processed by Omrin, 32.6 wt.% is re-used/sold, 39,1 wt.% is fermented and 29 wt. % is incinerated. According to Omrin, 615.983 MWh is generated over the year 2018 and with that 9.5 ton NO_x, 0.4 ton SO_2 and 231.000 ton CO_2 (Haffner et al, 2019). However, this is not only produced from the 29% household waste and will be discussed in the next subchapter.

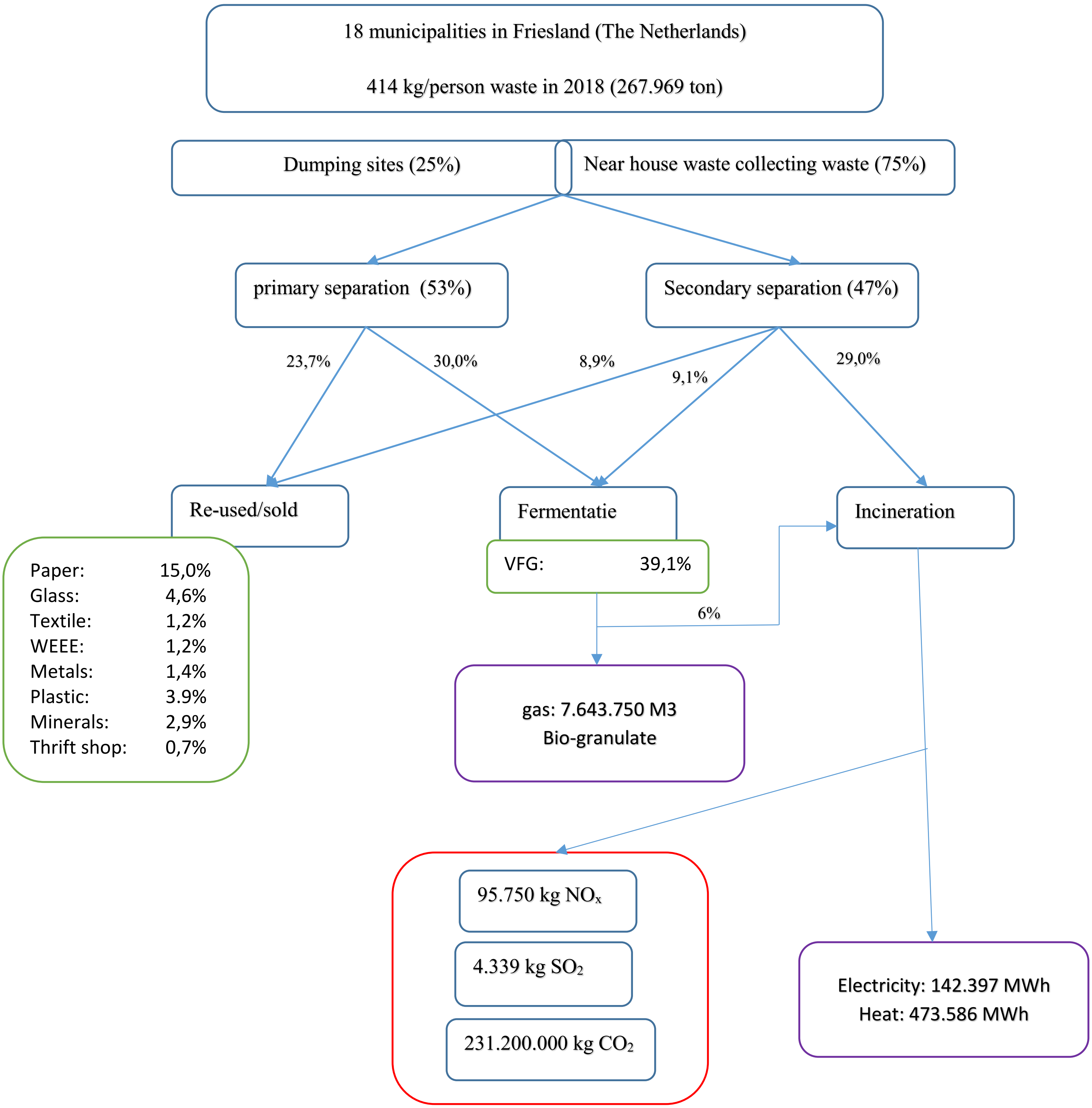

Figure 3; illustrated overview of the household waste flow within Friesland

2.4 WASTE STREAM TOWARDS THE REC

According to the management of waste and energy department of Omrin, the REC processes approximately 250.000 ton waste each year. This waste is derived from business (40%) and household waste (60%) and are classified as follow:

- Household rest waste
- Large household rest waste, derived from dumping sites
- Business waste, comparable with household rest waste
- Residue from fermentation of VFG
- Residue of plastic recycling

Zero in depth data regarding the distribution or heat of combustion of these components were available nor officially documented. Therefore, to determine the distribution of the household waste towards the REC, the year rapport of Omrin is combined with literature data regarding the waste stream within the Netherlands and the result is presented in Figure 4 (Appendix II). This research focusses mainly on the household waste and therefore the business waste is excluded in the calculations.

Firstly, the available data regarding household waste collected by Omrin (as illustrated in Figure 3) are classified and combined as the sectors presented in Table 1. Several waste types did not match any sector description, therefore it is possible that some additional sectors in the following statements will be used. Furthermore, FVG and wood are not mentioned separately in the data of Omrin and are combined to form one sector.

With this approach, 71,0 wt.% of the total waste stream can be classified. The VGF/wood and paper sector are good for 54,1 wt.% of the total household waste (respectively 39,1 and 15,0 wt.%). The smaller parts are as follow: 1,7 wt.% thrift shop, 4,6 wt.% glass, 1,2 wt.% textile, 1,2 wt.% WEEE, 1,4 wt.% metals and final 2,9 wt.% minerals. According to Omrin and the year rapports of Omrin, this fraction is re-sold and/or re-used and will not be incinerated. Furthermore, as mentioned in the previous chapter, the VGF/wood part is anaerobic digested for the production of bio-gas. During this process, approximately 15,6% is organic residue (Ardolino et al, 2018) and is incinerated for energy, as such the classification "Residue from fermentation of VFG".

The remaining 29 wt.% unclassified waste is derived from household rest waste, separated secondary[3] in Heerenveen. To determine this fraction, the secondary fraction (47,1 wt.% household rest waste) is combined with the waste distribution reported by Rijkswaterstaat (2019). Here, the household rest waste is analyzed within the Netherlands, by taking samples over a period of three years and sorting the waste manually. The results are summed up to the primary separation portions to give a full overview

3) Separated by the KSI

of the assumed household waste distribution at Omrin (Figure 4: Omrin + household rest waste). The same method has been used to determine the average waste distribution within the Netherlands (CBS 2019 & Rijkswaterstaat 2019) for comparison. The waste distributions are similar to each other with minor differences. Notable is the addition of plastic, metal cans and carbon packaging (PCC) sector (4,2 wt.%) in the data of the Netherlands. This can explain the higher fractions of the paper and plastic sectors within Friesland, as the PCC sector are separated secondary at Omrin and this is not the case in all provinces (Rijkswaterstaat 2019).

Finally, the total classified household waste distribution at Omrin is subtracted from the total assumed household waste distribution to give the incinerated fraction (Figure 4: Waste stream processed by the REC). In addition to this stream, the fermentation residue is added to give an total of 37 wt.% household waste stream towards the REC. The total distribution is as follow: 19,6% FGV + wood, 22,4% paper, 6,5% glass, 7,4% textile, 1,4% metals, 6,1% unclassified rest waste, 7,4% plastic, 9,7% in-contamination waste, 16,6% fermentation waste and 2,7% inorganic rest material.

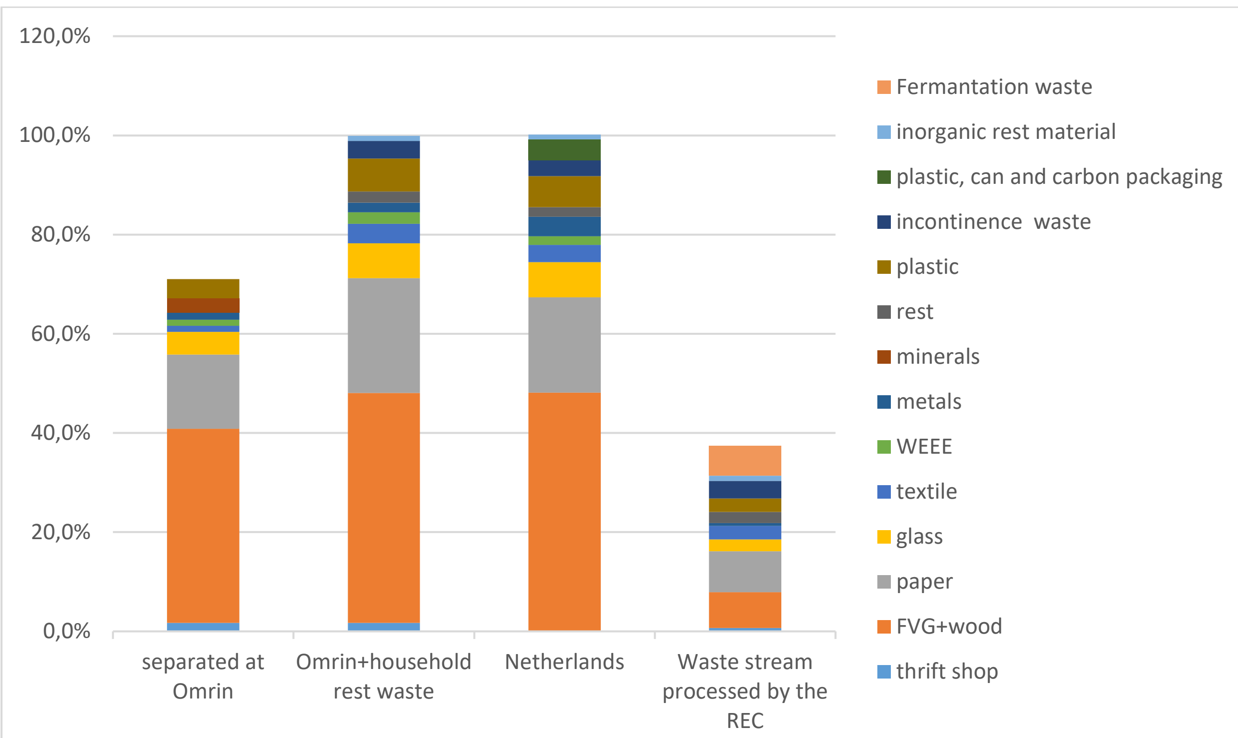

Figure 4; Estimated waste distribution incinerated in the REC

An total of 150.000 ton household waste (250.000 ton waste * 60%) is incinerated with the REC according to Omrin. However, with the calculated household waste fraction towards the REC, it is assumed that this is only 98.544 ton (267.969 ton waste * 37 wt.%). Recent data show that the REC processed 217.457 ton waste over the year 2018 (Afvalverwerking in Nederland, 2020). Approximately, 61 wt.% was derived from household rest waste and accounts for 132.647 ton. However, this is still 34.000 ton higher than was previously calculated. This can be explained by the fact that Omrin collects household waste outside Friesland, as stated in the year rapports. This way, an additional of 123.000 ton household rest waste was collected and with that, an addition of 45.232 ton waste to be incinerated. Now, the calculated total waste (143.777 ton) is still 8% different than was counted by Omrin. More data regarding the actual waste distribution is required for a more precise calculation. However, for the next chapter, the total processed household rest waste according to "Afvalverwerking in Nederland (2020)" will be used (132.647 ton) in combination with the waste distribution presented in Figure 4.

2.5 CONCLUDING REMARKS

Within this chapter, the sub-question "What is the composition of household waste currently processed by Omrin with the REC?" is answered by calculating the waste stream towards the REC. The total amount of household rest waste is calculated over the year 2018 and accounts for 132.647 ton. Furthermore, the total household waste is transported to the REC with the distribution as presented in Figure 5.

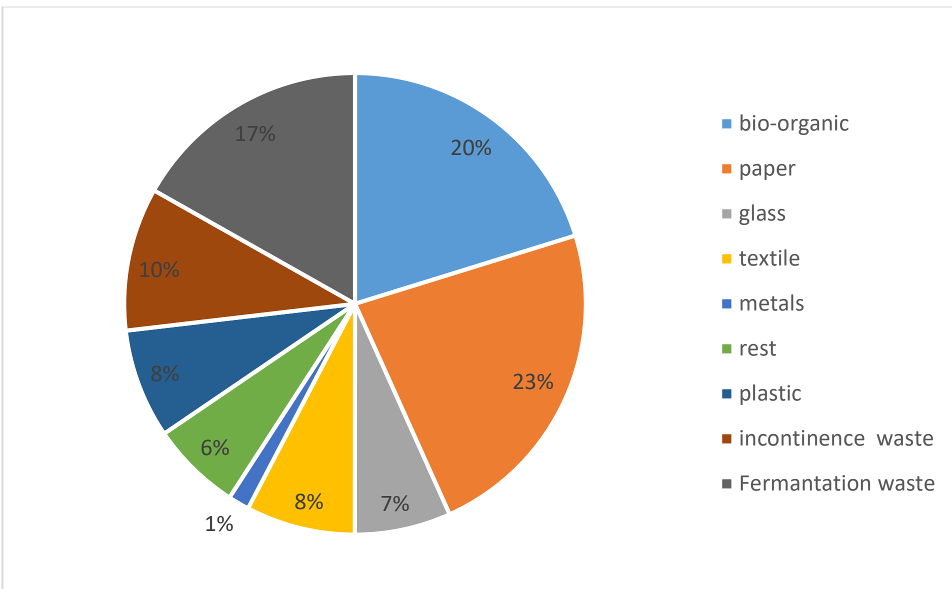

Figure 5; Waste distribution incinerated by the REC

This distribution of the household waste within Friesland, that is estimated to be processed by incineration, consist of 81,9-91,3 % organic material (108.000-120.000 ton household waste). This is the total incinerated fraction and can be used for (catalytic) pyrolysis (Czajczyńska et al. 2017).

CHAPTER 3: REC, CATALYTIC AND NON-CATALYTIC EMISSION AND PRODUCT VALUE ANALYSIS

In this chapter, the product value (excluding process costs) and the emission concentrations of the REC in Harlingen (The Netherlands) is analyzed. This answers the REC part of the sub-questions: "What is the economic value of the products of REC and (fast & slow) pyrolysis by processing household waste?" and "What are the emission concentrations of the REC, (fast & slow) pyrolysis by processing household waste?".

To support the findings, this chapter starts with an overview of the incinerated waste distribution at Omrin that is determined in chapter 2. Subsequently, the incineration process of the REC is holistically described and followed by the product value and emission analysis. In the final sub-chapter, the results are merged together to give a clear overview of the results.

3.1 INCINARATED HOUSEHOLD WASTE

As determined in Chapter 2, 132.647 ton household waste is incinerated at the REC. An overview of the total incinerated waste is presented in Figure 6. Glass (7,7 wt.%) and metals (1,7 wt.%) are considered non-flammable and accounted for 12.469 ton waste. Furthermore, the actual composition of rest waste (7,2 wt.%) and thrift shop material (2,2 wt.%) is not determined, therefore this is classified as potential flammable waste and accounts for 11.540 kg waste. Taking this into account, the total flammable waste incinerated by the REC is approximately: 108.000-120.000 ton waste. Here, paper (26,2 wt.%), bio-organic (23,0 wt.%) and fermentation waste (19,1 wt.%) are the main components that is incinerated by the REC.

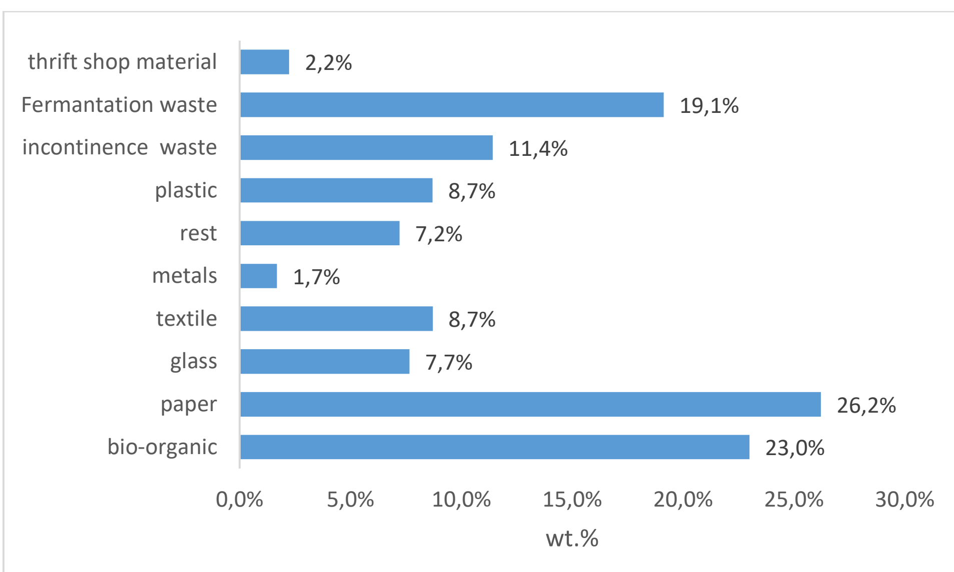

Figure 6; Waste distribution incinerated by the REC in 2018

3.2 REC HARLINGEN (THE NETHERLANDS)

The REC in Harlingen has an R1[4] status, which is the highest status for valuable application according to guidelines of the EU directive 2015/1127. The application for this incinerator is the production of steam and electricity from unsorted flammable waste. However, to analyze the composition of flammable waste stream, it is required to understand the waste management through the available data. The waste flow towards the REC is controlled by Omrin. This company separates the collected waste on an efficient rate of 79 wt.% (Kobus, 2019) and reports this yearly extensively in their year rapports of Omrin. This all to answer the sub-question: "What is the composition of household waste currently processed by Omrin with the REC".

The REC consist of four stages: The waste hall, oven, boiler and gas treatment (Pirovano et al, 2017). In the first stage, the waste is collected and stored before it enters the oven. With an maximum of 35 ton/hour (Rijkswaterstaat, 2017), the waste is combusted in the oven. Subsequently, the produced heat and gases warms up water to produce steam, with is transported to a steam to power generator for the production of electricity. The remaining heat is used for the evaporation of water to produce salt by a third party. Finally, the gases from the boiler are pre-treated to decrease the Greenhouse gas (GHG) emissions before it is released into the atmosphere. An overview is presented below (Figure 7):

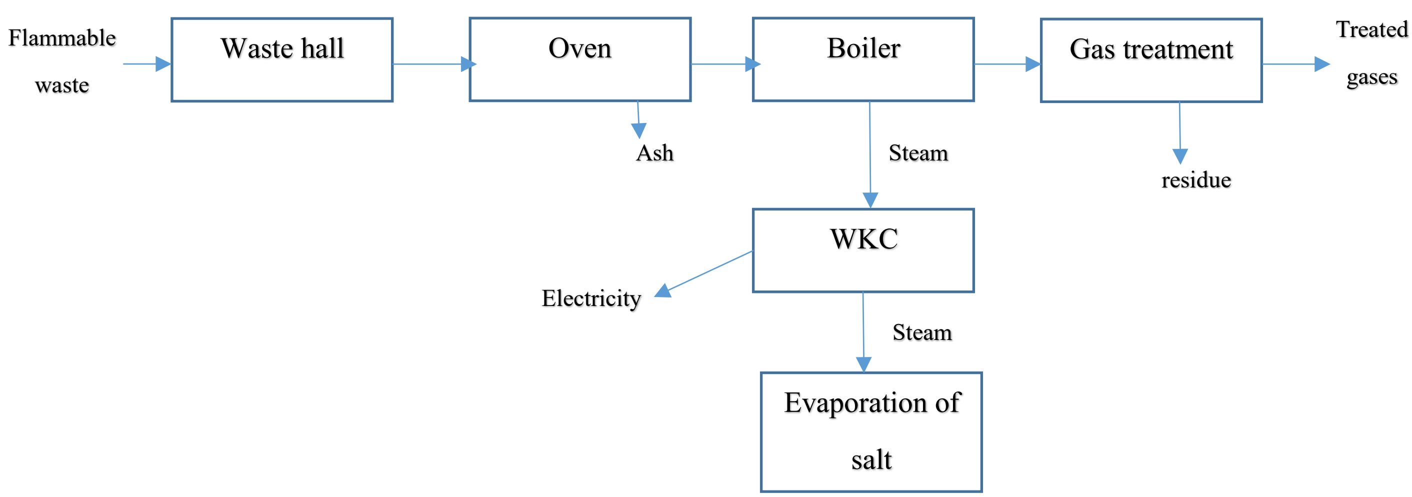

Figure 7; Schematic overview of the REC (Pirovano et al, 2017)

Before the gases are released into the environment, most of the gases are removed in several stages (Pirovano et al, 2017), as presented in Figure 8. In the first chamber, an electrostatic precipitator (ESP) captures 90 wt.% solid ash particles. These solids are discarded and subsequently the gases are sprayed with active coal and bicarbonate. SO_2, HCl, HF, Heavy metals, Dioxins, Furans and C_xH_y fractions react

4) Energy efficiency indicator of incinerators, ranging from R-1 (high efficiency) to D-10 (low efficiency) according to the EU) 2015/1127 directive

with the spray and larger particles are formed. These particles are captured by a fiber filter and removed from the remaining gases. The final chamber contains an catalyst that reacts with the NO_x in the gases to form N_2 and water. Finally, the remaining gases are removed through a 44m high chimney into the atmosphere (Pirovano et al, 2017).

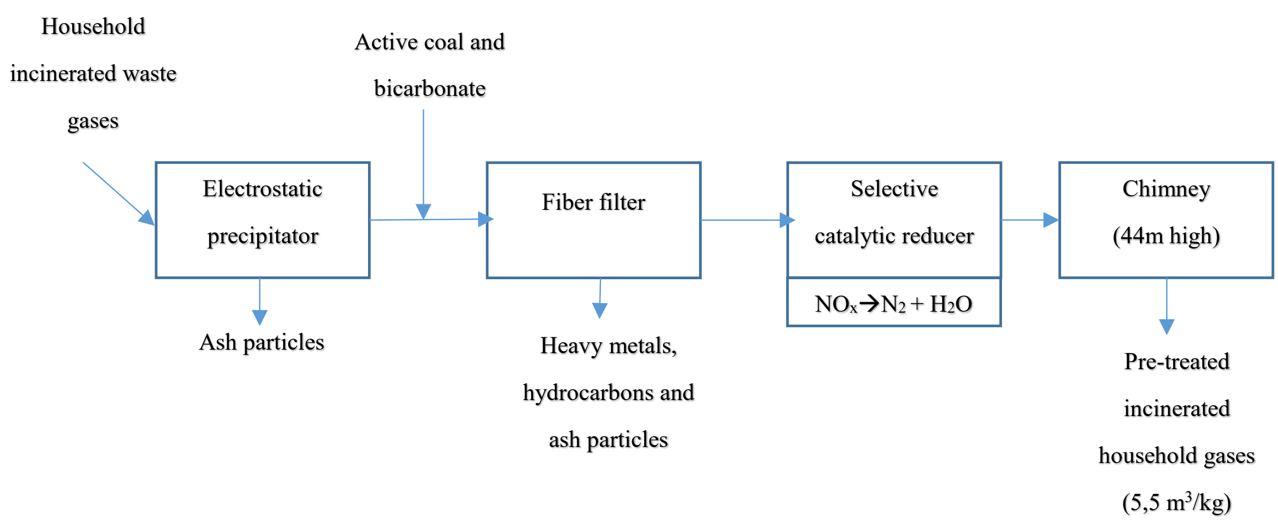

Figure 8; Schematic overview of the gas removal chain, as part of the REC (Pirovano et al, 2017)

The REC produces two products, one is electricity and the other is heat. The electricity is directly added to the grid and the heat is used for the production of salt by Frisia zout B.V. (from now on called: Frisia) and electricity through heat to electricity turbines. It is unknown how the contract between Frisia and Omrin is arranged and how much Omrin earns this way. However, Haffner et al. (2019) calculated this and stated that the heat had an value of 8.1 million euro's when it had to be produced with commercial gas.

According to article 5 of the Dutch activity rules, regarding environmental management, large energy plants (capacity higher than 50 MW thermal energy) are obligated to monitor every six months the following emission concentrations: SO_2, NO_x and CO. The concentration limits are fixed in the incineration permit, in coherence with the EU industrial emission directive and published by the company (Bosh & Jonker, 2019). In addition, the permit of the REC describes more emission limits to the following gases: Hydrogen chloride (HCL), Ammoniac (NH_3), Hydrogen fluoride (HF), Hydrocarbons (C_xH_y) and oxygen (O_2). These emission levels are measured by an autonomous company, official executed according to NEN-EN 14181 and published on the website of Omrin. The carbon dioxide concentrations are not measured this way. However, as this is the substance that is an indicator for the effect on global warming, this data is subtracted from scientific literature.

3.3 PRODUCT VALUE

The earnings before interest, taxes, depreciation and amortization (EBITDA) and efficiency of the REC has been calculated and are presented in Table 2. The EBITDA of recycling of waste and the production of electricity was in 2018 47.680.000 euro (NV Friesland miljeu, 2019). From this, 15.756.000 euro was derived from the REC, 4.898.000 from sustainable development subsidies and the remaining from selling recycled raw materials (Haffner et al, 2019).

In total, 43.151 households were provided with the produced energy, that accounted for 142.397 MWh. This is 3300 kWh per household which is in the range of the 3000kWh-3600kWh of an average household within the Netherlands (as claimed by energy suppliers of the Netherlands). When it is considered that Frisia gets the heat for free, the earnings per kWh is determined to be 0.11 euro[5] and 0.05 euro[6] when the gas price is payed. With respect to the EBITDA derived from the REC, 0.07 euro[7] profit is made per kilo waste

Table 2; REC EBITDA & REC efficiency

REC EBITDA	
EBITDA	€ 15.756.000,00
electricity produced	142.397 MWh
EBITDA/kg waste	€ 0,07
EBITDA/kWh	€ 0,05-0,11

REC efficiency	
GCV input	14,83 MJ/kg
Energy input	3,22E+06 (GJ)
Energy produced	2,22E+06 (GJ)
REC efficiency	68,9%

With the waste distribution as stated in chapter 2.5, the average GCV is approximately 14.83 MJ/kg. As such. 217.457.00 kilo waste is incinerated, the yearly energy input is $3,2*10^6$ GJ. With an input of $3,2*10^6$ GJ, the efficiency of the REC is approximately 68%.

One addition note to the calculation for the REC efficiency: The total energy input has been calculated according to the average gross calorific value (GCV) of household waste that is incinerated by the REC. The GCV is ideally in the situation within the research strategy, as such this indicates how much heat/electricity can be obtained from the feedstock (an overview of values are presented in appendix IV). Furthermore, within the GCV, the water content and water vapors are included in the calculation and is therefore representative within this study for comparing the different techniques. For calculating the energy efficiency, excluding operational fuel input, the following equation has been used:

5) 142.397.000 kWh divided by 15.756.000 EBITDA
6) 142.397.000 kWh divided by [15.756.000-8.138.095]
7) 15.756.000 euro divided by 217.457.000 kilo waste.

$$Energy\ efficiency\ = \frac{heat\ and\ energy\ and\ output}{(waste\ GCV\ input)}$$

3.4 ACTUAL EMISSIONS

The end of the pipe gases of the REC had an total volume of approximately 1.955,4 million m^3 gas over the year 2018 (explanation in appendix VI, point 1) and is 9,0 m^3 gas/kg waste.

The gas distribution is presented in Table 3, as such is monitored by Omrin and independent companies. In the column "average emissions", the periodic emissions are presented of 2018 and as can be observed, NO_x (58,29 mg/m3) is the main component, followed by CO (9,6 mg/m3), HCL (7,64 mg/m3) and SO_2 (5,04 mg/m3). Furthermore, small traces of hydrocarbons (0,5 mg/m3), Hg (0,44 mg/m3), NH3 (0,33 mg/m3) and HF (0,11 mg/m3) were found.

Table 3; Actual emission levels emitted by the REC (Excluding CO_2)

	Average emission (mg/m3)	**Total emission (kg) according to Omrin**	**Total emission/kg household waste (mg/kg)**
HCl	7,64	12.009	68,7
NO_x	58,29	91.606	524,2
CO	9,6	15.091	86,3
SO_2	5,04	7.923	45,3
C_xH_y	0,5	790	4,4
Hg	0,44	697	3,9
NH_3	0,33	518	2,98
HF	0,11	171	1,0
CO_2		196.000 ton	903.125

The second column "total emission according to Omrin" are based on the yearly emission per compound published in the year rapport with respect to yearly emission levels in 2018. The same trend as in the first column can be observed. This accounts for the third column as well, where the emission is determined based on the emission per kg household waste.

Carbon dioxide emission levels are not measured by Omrin. This is calculated and presented by Haffner et al. (2019) and accounted for 903.125 ton waste in 2016. The total emission concentrations did not differ significantly over the years (2012-2019). Therefore it is assumed that the 2016 CO_2 is

8) 1.955,4*106 m3 gas / 217.457*103 Kg waste

representative for 2018, as such, no other data is available. In total, the CO_2 emission over the year 2018 was approximately 196,4*10^6 kg (903.125kg * 217.500 ton waste).

The data, with respect to CO_2, is obtained from an official government website that is keeping track of the emission levels in the Netherlands (emissiregistratie.nl). Although this is not scientific literature, the data is collected through individual experts on the field of emission measurements and therefore can still be considered valid

3.5 REC EMISSION REDUCTION TECHNOLOGY

The end of the pipe emission concentrations are re-calculated with the efficiency of the gases treatment technology of the REC, the results are presented in Table 4. In the first stage of the gases treatment technology of the REC (ESP), most of the heavy metals and fly ash are removed (Hong et al. 2000). The remaining fractions are collected in the fiber filter after injected with active carbon (Li et al. 2017)). With respect to mercury (heavy metal), 88% is removed from the gases (22% ESP & 60% active coal injection). With this, it assumed that the mercury emission level from household waste is approximately 13 mg/kg. Furthermore, the active coal is efficient in the removal of hydrocarbons, as was analyzed by Cuduhy & Helsel (2010). Here, data was published derived from several waste incinerator plants in Europe on gas treatment with activated charcoal. The data with active coal injection show an efficiency of 70-98%, depending on the hydrocarbons. However, the precise distribution of the hydrocarbons are not measured and documented by Omrin, and therefore, the efficacy is averaged to 84%. With this, the assumed hydrocarbons emission before treatment is 79 mg/kg. However, this can differ significantly per carbohydrate.

The efficiency of bicarbonate injection is analyzed for the removal of HCl and SO_2 extensively and reported in scientific literature. Both gases are removed efficient and the emission before gas treatment is assumed to be respectively: 5725-6870 mg/kg and 281-302 mg/kg. With respect to HF, it is mentioned in the literature that bicarbonate removes acids from the gases. However, no actual data regarding the efficiency has been found.

In the final stage, NO_x is reduced through an selective catalyst that produces N_2 and water. Zandaryaa et al. (2001) analyzed the performance of this technology with different environmental conditions. This is representative for an incinerator as the conditions differ over time in the incinerator due difference in material input. They found an efficiency between 46,7 and 76,7%, with has a wide range and is depending on the gas composition and operating conditions. However, the conditions of the REC are unclear on this matter and the wide range is the most acceptable data that is available. With this, the gas NO_2 gas emission before treatment is approximately 965-2249 mg/kg.

Table 4; Individual incinerated household waste gas reduction efficiency (calculation in appendix VI, point 2)

	Incinerated gases after (mg/kg)	**Removal stage**	**Removal efficiency (%)**	**Incinerated gases before (g/kg)**	**Reference**
HCl	68,7	Bicarbonate	98,8-99	5,73-6,87	Kong et al. (2011) & Antonioni et al. (2011)
NO_x	524,2	catalyst	46,7-76,7	0,965-2,25	Zandaryaa et al. (2001)
CO	86,3	Not reduced	--	0,086	--
SO_2	45,3	Bicarbonate	83,9-85	0,281-0,302	Kong et al. (2011) & Antonioni et al. (2011)
C_xH_y	4,4	Active coal	70-98	0,014-0,22	Cuduhy & Helsel (2000)
Hg	3,9	ESP & Active coal	22 & 60	0,09,9	Takahashi et al. (2010) & Li et al. (2017)
NH_3	2,98	Not reduced	--	0,030	--
HF	1,0	Bicarbonate	Only mentioned	N.k.	Wienchol et al. (2020)
CO_2	903.125	Not reduced	--	903.113-1.200,00	Johnke et al. (2006)

With respect to CO_2, CO and NH_3 gases, no gas treatment has been installed in the REC. However, for incinerators overall, an average of 0,7 to 1,7 kg CO_2 per kg waste is emitted into the atmosphere (zerowasteEurope, 2019). This is in the range of what the REC is emitting (0,9kg/kg). That this is on the low side of the average emission level is not a cause of CO_2 removal, but moreover due the waste input (Larsen & Astrup, 2011). It was found that the CO_2/GJ increases when plastic is better sorted and not incinerated. As Omrin separates plastic with an efficient rate of approximately 58% (from 7 wt.% to 3,9 wt.%), this can explain the relative low CO_2 emission.

3.6 CONCLUDING REMARKS

A clear overview of the results from this chapter are merged together and presented in Table 5. In the upper box, the product value is given with the product that is produced. In the bottom box, the emission concentrations are presented. These are the emission concentrations before gas treatment has taken place. This all to be able to compare this with slow and fast pyrolysis.

Table 5; overview of the REC product value and emissions

Product value based on business waste and household waste incineration	
Electricity produced	142.397 MWh
EBITDA	€ 15.756.000,00
energy input	2,22E+06 MJ
energy produced	3,22E+06 MJ
EBITDA/kg waste	€ 0.07
Emission concentrations based on the incineration of household waste	
HCl (g/kg)	5,73-6,87
NOx (g/kg)	0,965-2,25
CO (g/kg)	0,086
SO_2 (g/kg)	0,281-0,302
C_xH_y (g/kg)	0,014-0,22
Hg (g/kg)	0,09,9
NH_3 (g/kg)	0,03
HF (g/kg)	>0,001
CO_2 (g/kg)	903113-1.200,00

CHAPTER 4: PYROLYSIS EMISSION AND PRODUCTS

In this chapter, slow and fast pyrolysis are analyzed on their products value and their emission concentrations. This all to answer both pyrolysis parts of the sub-questions: “What is the economic value of the products of REC and (fast & slow) pyrolysis by processing household waste?” and “What are the emission concentrations of the REC, (fast & slow) pyrolysis by processing household waste?”.

To support the findings, this chapter starts with an overview of the potential pyrolysis feedstock, as such determined in chapter 2. Subsequently, both pyrolysis processes are holistically described and followed by the product value and emission analysis. In the final sub-chapter, the results are merged together to give a clear overview of the results.

4.1 POTENTIAL HOUSEHOLD WASTE FOR PYROLYSIS

Such as determined in Chapter 2, 132.647 ton household waste is incinerated at the REC. An overview of the total incinerated waste is presented in Figure 6 (chapter 3.1). In total, 108.000-120.000 ton is flammable waste and a potential feedstock for pyrolysis. From the total household waste, the flammable components are as follow: 26,2 wt.% paper, 23,0 wt.% bio-organic. 19,1 wt.% fermentation waste, 8,7 wt.% Textile, 8,7 wt.% plastics and 11,4 wt.% incontinence waste material (e.g. diapers), as can be observed in Figure 9.

Due the absence of oxygen (for example due the addition of nitrogen), these materials are not continuously burned during pyrolysis, moreover additional heat is required to initiate the decomposition. In extend, the required heat can be divided into two parameters that have significant influence on the pyrolysis conditions, one that states the initial and final temperature and the other one is the residence time of the feedstock. With emphasis to the first mentioned, data[9], corresponding to the household waste composition is obtained from scientific literature and presented in Figure 9.

As can be observed in Figure 9, there are significant differences in the decomposition profiles under nitrogen conditions. For example, textile decomposition is initiated at 150 °C and is completely decomposed at 450 °C, whereas PS/PET/PE plastics has a smaller decomposition band, which is between 350°C and 450°C. With respect to fermentation waste, only 30% was decomposed at pyrolysis temperature of 550°C (Wang et al. 2012) and is an indicator that this will result in high un-pyrolysed residues. This is probably due high inorganic material content that remained after fermentation. Furthermore, data for incontinence material was not available and this material will be discussed later in this chapter. However, as can be observed, the decomposition of all flammable materials are found between 150 and 550°C. This means that these materials are possible feedstock for pyrolysis and a minimum temperature of 500-550°C is required.

9) Thermal gravimetric analysis

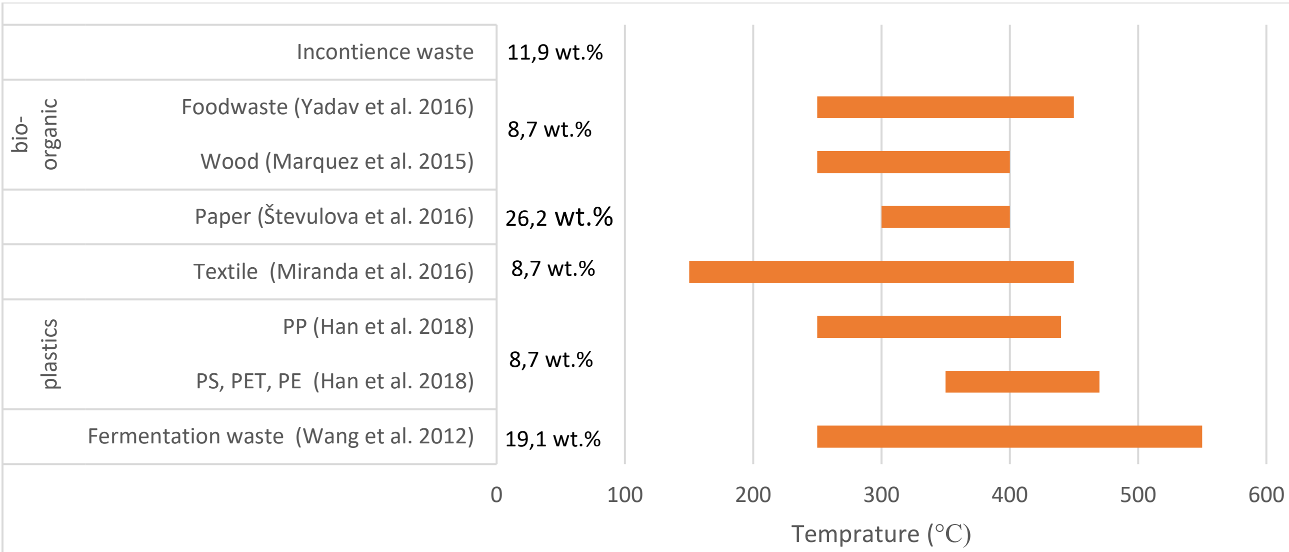

Figure 9: Potential decomposition of waste material during pyrolysis

4.2 OVERVIEW OF SLOW & FAST PYROLYSIS

In contrary to incineration, pyrolysis occurs with the absence of oxygen. When this is controlled through the addition of an inert gas, for example nitrogen, significant different products are obtained. Where combustion releases mostly gases, with pyrolysis more liquids and solids are obtained (Bridgwater, 1980).

Furthermore, the pyrolysis conditions, with respect to residence time and operating temperature, have significant effect on the pyrolysis products, as can be observed in Figure 10. The left graph shows the influence of temperature on wood and the derived pyrolysis products. With low temperatures, high yields of solids (char) are observed, in contrary to the gas fraction. When the temperature increases to 450°C, the liquid and gas fractions increases, while the solid fraction decreases. With even higher temperatures than 450°C, the solid phases remains relatively the same, the liquid phases decreases significantly and the gas fraction increases. This is an indicator that with high temperatures, more light/small hydrocarbons are formed. It is important to notice that the graph represents only the pyrolysis of wood. Other substances, such as plastics and food waste, will show a different product distribution profile. This is depends on the decomposition rate of the material and temperature.

Pyrolysis is in literature classified as slow, intermediate and fast pyrolysis (Bridgewater, 2012 & Bhaskar et al. 2019), with the following descriptions;

- Slow pyrolysis is operated with temperatures higher than 300C, have long residence time and heating rates below 60°C/min.
- Intermediate pyrolysis is operated with temperatures higher than 500°C, intermediate residence times and heating rates between 60-200°C/min

- Fast pyrolysis is operated with temperatures higher than 500°C, low residence times and heating rates higher than 1000°C/min or instant.

The effect of these conditions are presented in Figure 10, right graph. As can be observed, the liquid yield increases significantly when higher heating rates and lower residence time are used (fast pyrolysis). The consequence of this, is that the gas and solid yield are decreased whereas this is approximately evenly distributed with slow pyrolysis. Therefore, the type of pyrolysis have great influence on the desired product. For instance, if a company is interested in the solids products, slow pyrolysis is the most logic choice.

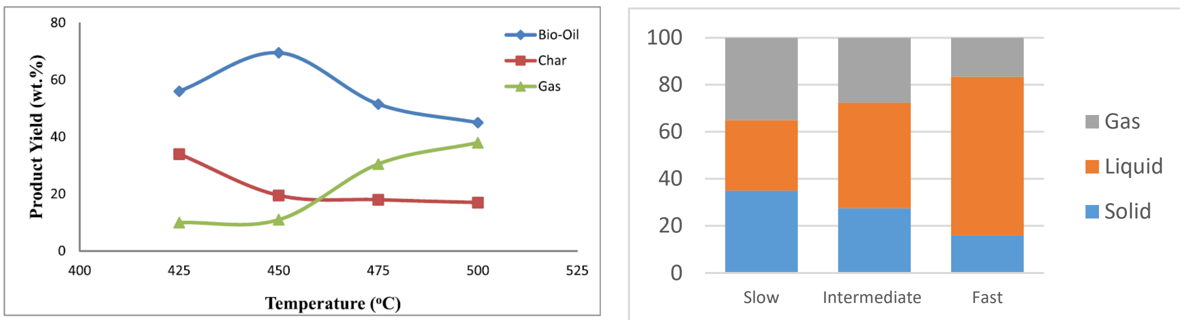

Figure 10; Left: Effect of temperature on pyrolysis products (Chukwuneke et al. 2019). Right: Effect of Pyrolysis heating rate (Bridgewater, 2012)

It is impossible within the research time to analyze all pyrolysis conditions and combinations (temperature, heating rate, inert gas flow, catalyst type/size/ratio). To limit this, the research will focus on fast and slow pyrolysis, with one single operating temperature range, based on the most abundant available data in literature and decomposition under nitrogen conditions temperature. As such, the household waste is completely decomposed between 150 and 550°C, the desired operating temperature is higher than 550°C. However, most pyrolysis described in scientific literature are based on temperature of 500°C and this is required to make assumption regarding the emission concentrations and product value. Therefore, the chosen temperature range is set between 500-550°C.

4.2.1 TYPICAL PYROLYSIS REACTOR

There are many different types of pyrolysis reactors (Garcia-Nunez et al. (2017). However, the principle of every reactor is in all cases comparable and a typical cyclone pyrolysis reactor is presented in Figure 11. Firstly, the feedstock is transported to a reactor chamber with the absence of oxygen, due the addition of an inert gas. Subsequently, the feedstock is heated to the desired temperature and with the desired heating rate (slow, intermediate or fast). Furthermore, after the reaction, the solids are removed (in Figure 11 through a cyclone), the liquids are collected and the gases are discarded through an outlet.

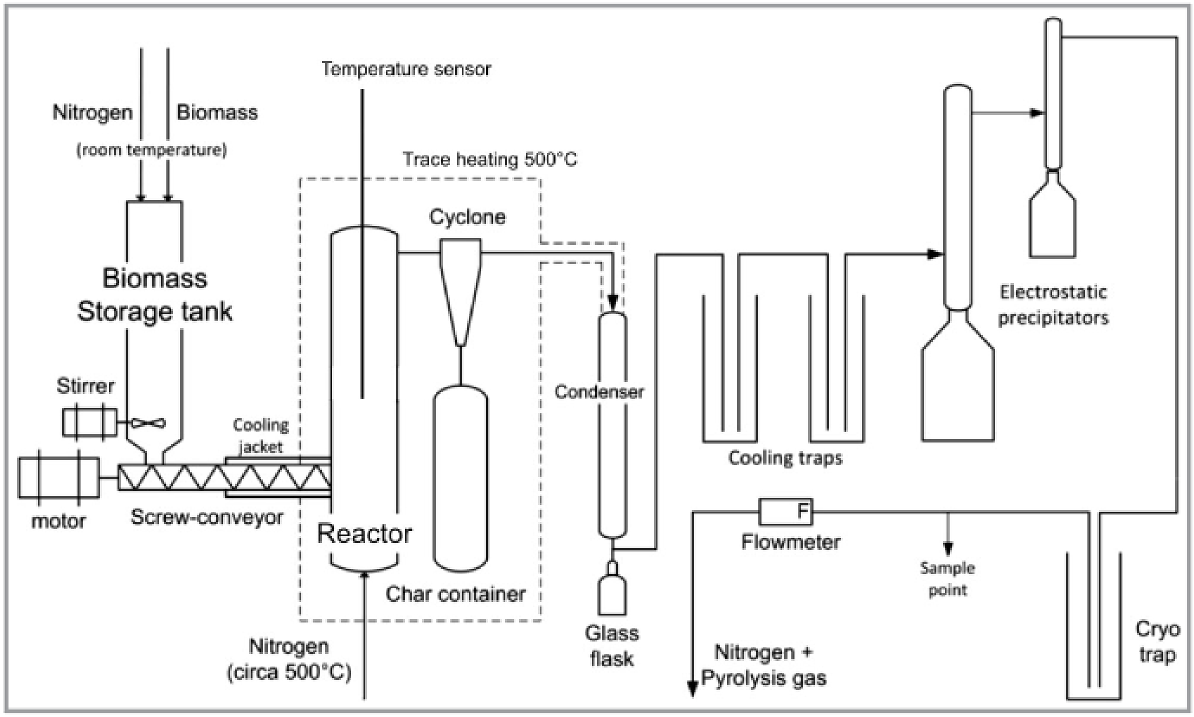

Figure 11; Cyclone pyrolysis reactor (Weber et al. 2015)

4.3 PRODUCT VALUE

For analyzing the current market for pyrolysis products, it is assumed that the three pyrolysis fractions (solid, liquid and gas) are collected and stored separately. Czajczyńska et al. (2017) described the possible function of the pyrolysis products and will be used as guidance for the analysis. Their descriptions are as follow: Gases for energy production; Liquids for the production of energy, synthetic gas, heat and chemical feedstock; Solids for the production of energy and bio-char.

The application description of pyrolysis products by Czajczyńska et al. (2017), only mentions the difference in yields and contractions, with respect to fast and slow pyrolysis. This is confirmed within many other fast pyrolysis publications. However, the product value for fast pyrolysis is only determined for the production of electricity, as such the required scientific data for a complete survey on all the different waste types is not available .

For the calculations and determinations of the product value of slow and fast pyrolysis, several guidelines are required to be mentioned for a better understanding. Firstly, when it comes to calculating the product value as an energy source, the current market prices of natural gas, coal and heating oil are obtained. As such, these trade products are most comparable with the pyrolysis products as an energy source and a global or national market for pyrolysis products are not available. Furthermore, most commonly market prices are stated in USD/gallon or USD/BBU and are first re-calculated to Euro/GJ. This is required to give a more accurate prediction of the product value, as such heating oil, coal and natural gas have a different gross caloric value (the total amount of heat released, from now on called GCV). Natural gas represents the pyrolysis gas and is currently 1,39 euro/GJ. Coal represent the solid phase and has an average value of 1,72 euro/GJ. Finally, the heating oil represents the liquid phase and is currently 1,37 euro/GJ

Secondly, for the gases GCV, these were mostly presented in MJ/m^3. This is re-calculated to MJ/kg with the following formula, where the individual numbers are the GCV of the gases:

$$GCV = (CO2\% * 14{,}1) + (H2\% * 141{,}1) + (CH4\% * 55{,}5) + (CxHy\% * 22{,}198) + (CO\% * 12.0)$$

4.3.1 SLOW PYROLYSIS

For making assumptions regarding the emission concentrations derived from the slow pyrolysis of the waste sectors, corresponding scientific data is obtained. For this, the data is collected from pyrolysis experiments with the following pyrolysis conditions: Slow pyrolysis (10-20 °C/min), final temperature of 500-550°C and a nitrogen flow between 0.5-1 L/min. The results are shown in Table 6.

When plastic, biomass, textile, paper and fermentation waste are pyrolysed, it is found that the type of feedstock has significant effect on the liquid, solid and gas formation (Table 6). For example, the highest liquid yield can be obtained with textile waste (47wt.%), whereas the lowest yield with the pyrolysis of fermentation residue (31,8 wt.%). Furthermore, paper waste resulted in the high gas yields (41,8 wt.%), where this is between 28,2wt.% and 33,7 wt.% for the other materials. Lastly, fermentation residue (33,5wt.%) is the main producer of pyrolysis solids, whereas textile is the lowest produces for this (18,5 wt.%).

The “Pyrolysis of waste flow towards the REC” column within Table 6, shows the predicted product distribution when the household waste is pyrolysed. This is based by combining the pyrolysed products of the individual components with that of the potential household waste (Figure 9). This is calculated to have to following ratios: 34,8 wt.% liquids, 32,5 wt.% gases and 29,7 wt.% solids. Within these calculations, the inorganic materials are added to the solid phases (Czajczyńska et al. 2017). This accounted for glass, metals, rest and thrift shop material of the waste stream towards the REC. Furthermore, no pyrolysis data was available for the incontinence waste material. This is due the fact that this is a very complicated waste type, which consist of many different materials (for example plastics and paper). Therefore, this waste type is divided into different waste sectors, as presented in appendix III (Odegard et al, 2018). Their assumption was based on different source of data within the Netherlands, what makes it ideally for the case study. An example for this procedure is as follow: Incontinence waste consist of the plastic polyethylene (1,7 wt.%) and was added to the plastic waste sector.

As Table 6 is showing, the calculated GCV is also depended on the feedstock. Here, the biomass, textile and paper have relative low GCV, compared to plastic and fermentation waste, as a result of high water content in the liquid fraction. This is the other way around when it comes to the solid fraction. In total, it is found that plastic (28,4) produces the highest average GCV and fermentation waste (17,4) the lowest. Biomass, textile and paper have a GCV between 20,4-22,4.

Furthermore, Table 6 states the GCV per feedstock and fractions. It has been found that the liquid phase had a GCV of 16,8 MJ/kg, gas fraction 23,2 MJ/kg, the solid fraction 24,7 MJ/kg and an average value of 20,3 MJ/kg. When this is yearly produced with the household waste from 2018, the yearly energy value and the predicted value of these fractions are as follow: $7{,}7 \cdot 10^5$ GJ from liquids (1,06 million euro), $10{,}0 \cdot 10^5$ GJ (1,39 million euro) from the gases and $7{,}8 \cdot 10^5$ GJ (1,35 million euro) from the solids. Per kg waste, the EBIDTA with this approach is approximately 0,28 euro.

Table 6; GVC of the pyrolysis products

	Plastic	**Biomass**	**textile**	**paper**	**fermentation waste**	**Pyrolysis of waste flow towards the REC**
Liquid (wt.%)	40,9	44,7	47,0	32,0	31,8	34.8
Gas (wt.%)	28,2	33,1	33,5	41,8	33,7	32.5
Solid (wt.%)	25,9	22,2	19,5	26,2	33,5	29,7
liquid (MJ/kg)	36,6	11	11	11	31,64	16,8
gas (MJ/kg)	37,2	25.1	32.6	27	12.6	23,2
solid (MJ/kg)	11,5	32,3	31,4	25,6	9,27	24,7
Total (MJ/kg)	28,4	20,4	22,2	21,5	17,4	20,3
	Adrados et al. (2012)	Phan et al. (2007) *water content is high and reduces GCV			Choi et al. (2019)	Chapter 3.5

As was mentioned above, the liquid fraction can be used as a chemical feedstock, as such pyrolysis oil has similarities with crude oil (Krutof & Hawboldt, 2016). These chemicals are obtained through refining petroleum and is a process that will be processed by a third party. Therefore, within this approach, the market value is determined, through an interview with a manager of a pyrolysis plant (medium scale).

It was found that pyrolysis oil is comparable with naphtha. Therefore, the current market of naphtha is used to calculate to predict the possible pyrolysis oil value. As Naphtha is the distillate of crude oil with a boiling point up to 200°C (Ross 2019), this fraction within the pyrolysis oil has to be determined. Within the literature, that is previous used to determine the GCV, not all publications contained in depth detail regarding the liquid composition. Lopez et al. (2010) conducted a paper rich waste sample with slow pyrolysis and is ideal for assuming the naphtha concentration within the liquids. For this, the liquid compounds (appendix V) are sorted on their boiling point: 70-200°C and higher than 200°C. With this approach, 73,3% of the liquids can be classified as Naphtha and the remaining is considered to have a boiling point higher than 200°C.

The current market price for naphtha was over the last five years 0,48 dollar/kg (0,43 euro/kg), however over the last six months it dropped significantly to 0.28 euro/kg. This is an direct result of the covid-19 crisis as such many countries and or cities initiated lockdowns and other measures. This resulted in an significant decrease in crude oil uses and is currently lower than the current supply. As the liquid phase after household waste pyrolysis is approximately 34,8 wt.% (Table 6), this fraction is assumed to be $46{,}2*10^6$ kg after the pyrolysis of household waste (34,8% * household waste in 2018 in kg). According to the paper rich waste experiment, 28% of the liquids is an aqueous fraction and is not part of the Naphtha. Considering this, the total Naphtha fraction is calculated to be approximately $24{,}4*10^6$ kg ($46{,}2*10^6$*72%*73,3%). This has a value of $6{,}8*10^6$ euro.

Besides the production of energy, the solid fraction can be used as high carbon content fertilizer for the agricultural sector, when this is supplied without contaminations, such as heavy metals. A total of $31{,}6*10^6$ kg of bio-char is produced from pyrolysis household waste with the data provided from Table 6 (Household waste in 2018 in kg * 23,9% solid fraction). The current market value of fertilizers is between 0.229 euro/kg and 0.377 euro/kg (Brummerlaar, 2020). With this, the bio-char from the case study has an annual value between $7{,}2*10^6$ and $11{,}9*10^6$ euro.

4.3.2 FAST PYROLYSIS

Compared to slow pyrolysis, fast pyrolysis produces more liquids and less solids. This is also observed within scientific data, with respect to the pyrolysis of waste, as such presented in Table 7. The liquid yield almost doubled and the solid fraction was reduced significantly from 27,9 wt.% to 6,8 wt.%.

The operation temperature of fast pyrolysis has significant effect on the liquid, solid and gas fractions, as was observed by the data published by Crombie & Mašek (2014). A few examples are given in Table 7. With operation temperatures between 500-550°C it is notable that the solids are reduced and the liquids increased compared to slow pyrolysis. This is also stated in the description of Bridgewater (2007), regarding the pyrolysis types (Figure 10, chapter 4.2). With high operation temperatures, the liquid faction decreased dramatically and resulted in high gas yield. To hold on the pyrolysis conditions, as stated in above, the results from Velghe et al. (2013) will be used for the product value calculations.

Table 7; examples of fast pyrolysis product distribution

Reference	Operating temperature (°C)	feed	Solids (wt.%)	Liquids (wt.%)	Gas (wt.%)
Table 4	slow pyrolysis	household waste	27,9	34,8	32,5
Velghe et al. (2013)	510	MSW (mostly household waste)	6,8	67	26,2
Xue et al. (2013	525	plastic/wood	20	43	37
wei et al. 2006	500	pinewood	15	45	40
Waheed et al. 2013	750	forestry residue	14,14	20	60

The GCV of fast pyrolysis of household waste, are presented in Table 8. As can be observed, the liquid fraction consists of two separated products: Wax and oil. Here, GCV of the liquid fraction (37,0 MJ/kg) could be determined, however, the wax could not. Furthermore, the gas GCV was determined to be 34,07 MJ/kg and the char at 20,3 MJ/kg. When this is yearly produced from the flammable household waste, as stated in chapter 4.1, the following predicted value and energy production has been determined: $18,1*10^5$ GJ (2,48 million euro) from the liquid, $11,7*10^5$ GJ (1,6 million euro) from the gases and $1,9*10^5$ GJ (0,32 million euro) from the solids. With this approach, per kg waste, the EBIDDTA is approximately 0,041 euro.

Table 8; GCV from fast pyrolysis of household waste

	gas	Oil	Wax	char	total
Fraction (wt.%)	26%	44%	24%	7%	100%
GCV (MJ/kg)	34,07	37	Not known	20,3	26,4

4.4 EMISSIONS

Within this section, the emission concentrations of slow and fast pyrolysis are calculated and presented. However, to support the findings with the underlying calculations and brief overview of the method, the following guidelines are required for a better understanding.

Firstly, from the scientific literature, the gas, solid, liquid and the gas distribution are collected for slow pyrolysis. However, the gases were stated in wt.% based on their feedstock input and were first re-calculate to g/kg feedstock with the following formula (important note: published data in mol%. was first re-calculated to wt.%, before the formula was used):

$$gas\ emission_x \text{ (g/kg waste)} = gas_x \text{ (wt.\%)} * \text{total gas (\%)} * 10$$

With the emission gases per waste sector, the total emission of the total GHG in coherence with the waste distribution towards the REC is calculated. This is done with the following formula:

$$GHG \text{ (g/kg)} = \sum(feedstock\ wt.\%_{HW} * GHG \text{ (g/kg)}_x) + (feedstock\ wt.\%_{HW} * GHG \text{ (g/kg)}_x)$$

Secondly, for making assumption regarding the emission of fast pyrolysis, with a comparable analysis approach for slow pyrolysis, insufficient data is available to cover all the waste sectors. Therefore, the assumption is based on fast pyrolysis of waste data that is available in combination with the overall difference in product distribution between slow and fast pyrolysis.

Finally, the best available data, with respect to the fast pyrolysis of municipality waste is the experiment conducted by Velghe et al (2013), however the gas analysis was not extensively, fully analyzed and was missing significant components that are formed during fast pyrolysis, such as hydrogen and methane (Waheed et al. 2013 & Wei et al. 2006). Therefore, this data is combined with other data (Fast pyrolysis of solid waste: Velghe et al. 2013) to assume the emission concentrations. This is done by applying the following formula for each compound, where 26,2 wt.%. is derived from Velghe et al. (2013) and the gas% from Table 5 (column: Waste flow towards the REC):

$$Gas \text{ (mg/kg waste)} = 26{,}2\ wt.\% * gas\% * 1000 \text{ (g/kg to mg/kg)}$$

4.4.1 SLOW PYROLYSIS

When it comes to emissions of pyrolysis, H_2, CO, CO_2, methane and light hydrocarbons (C_xH_y) are the main components that are mentioned in literature. As can be observed in Table 9, fermentation residue is the lowest producer for H_2 and methane gas. However, it is the main CO_2 polluter, what is two times higher than the other feedstock's. When it comes to the emission of small hydrocarbons, these are mainly produced by the pyrolysis of plastic.

After all, with the pyrolysis of household waste, is assumed that the following emissions are produced, as can be found in Table 9: 12,54 g/kg CO_2 (highest emission), 7,61 g/kg CO, 2,24 g/kg H_2, 3,56 g/kg methane and 2,34 g/kg small hydrocarbons.

Besides the regular emission gases, it has been found that chlorine and fluorine are present in the solid and liquid phase of the pyrolysis products. These are present in the solid phases as salts and in the liquid phases bound to hydrocarbons. Lopez et al. (2010), documented the pyrolysis of several waste composition at pyrolysis temperature 500 °C (20°C/min) and found that 1.0 wt.% of their "glass" rich waste sample, consisted of chlorine. From this fraction, they reported that only 0.16 wt.% was found in the solid fraction and 0.016 wt.% in the liquids. Their "paper" rich fraction is more comparable with the waste distribution of the case study, however no data regarding the liquid chlorine concentration was reported. The remaining, 0.82 wt.% chlorines must be present in the gas fraction. Du et al. (2010) analyzed the fate of chloride in detail. They pyrolyzed agricultural waste at different temperatures and at 500°C, the same trend were observed. The dominant chloride formation at this temperature is KCL and K_2Cl and limited traces of HCL were measured.

For Fluorine, the same trends as for chorine were observed by Du et al. (2010). Approximately 60% can be found in the gas phase, 35% in the solids and 5% in the liquids. Above 500°C, fluorides are present as SiF_4.

Table 9; Pyrolysis emissions based on the waste stream incinerated by the REC

	Plastic	**Biomass**	**Textile**	**Paper**	**Fermentation residue**	**Waste flow towards the REC**
Liquid (wt.%)	40,9	44,7	47,0	32,0	31,8	34.8
Gas (wt.%)	28,2	33,1	33,5	41,8	33,7	32.5
Solid (wt.%)	25,9	22,2	19,5	26,2	33,5	29,7
H2 (g/kg)	2,32	2,32	1,81	5,60	0,03	2,24
CO (g/kg)	2,34	10,10	11,63	15,30	3,21	7,61
CO_2 (g/kg)	4.230	14,80	11,93	13,543	28,04	12,54
Methane (g/kg)	3,22	4,87	6,43	6,40	0,53	3,56
CxHy (g/kg)	15,60	1,02	1,71	0,96	1,88	2,34
Reference	Adrados et al. (2012)	Phan et al. (2007)			Choi et al. (2019)	Chapter 4.1

4.4.2 FAST PYROLYSIS

To determine the emission levels of fast pyrolysis, the data from fast pyrolysis of biomass is compared with that of slow pyrolysis. As such, the biomass is the largest fraction and is assumed to have the highest effect on the emission concentration. For this, the gas composition is determined to 100% for the results of slow pyrolysis and fast pyrolysis data obtained from Wei et al. (2006) and Waheed et al. (2013). The results are presented in Table 10. At 500C°, it can be observed that with fast pyrolysis, hydrogen (7 to 15%), CO (31 to 40%) and C_xH_y (3 to 6%) increased significantly and that CO_2 (45 to 34%) and methane (15 to 5%) decreased. Similar results are observed at 750°C.

With the pyrolysis of household waste conducted by Velghe et al. (2011), 26,2 wt.% gas was produced. When the gas distribution of Wei et al (2006) is applied, the following GHG emission are formed: 3,93 g/kg H_2, 10,48 g/kg CO, 8,91 g/kg CO_2, 1,31 g/kg methane and 1,57 g/kg small hydrocarbons.

Table 10; Assumed emission from the fast pyrolysis of household waste

	Slow pyrolysis	Fast pyrolysis (500)	Fast pyrolysis (750)	increase factor at 500C	assumed emission (g/kg)
H2	7%	15%	26%	2,14	3,93
CO	31%	40%	46%	1,31	10,48
CO_2	45%	34%	11%	0,76	8,91
Methane	15%	5%	11%	0,34	1,31
CxHy	3%	6%	5%	1,94	1,57
Total	100%	100%	100%		
Reference	Phan et al. (2007)	Wei et (2006)	Waheed et al. (2013)		Velghe et al. (2011)

4.5 CONCLUDING REMARKS

A clear overview of the results from this chapter are merged together and presented in one single table. The table is presented below:

Table 11; Overview of the product value and emission from pyrolysis of household waste

	Slow Pyrolysis			**Fast Pyrolysis**		
	liquid	solid	gas	liquid	solid	gas
wt.%	34,8	29,7	32,5			
Energy (MJ/kg)	16,80	23,20	24,70	37,00	20,30	34,07

Yearly Energy value prediction (€)	1.062.459	1.346.873	1.390.239	2.487.867	324.209	1.633.291
liquid as Naphtha	€ 6.821.454					
solid as fertilizer	€ 7.200.000-11.900.000					
Emissions						
H2 (g/kg)	2,24			3,93		
CO (g/kg)	7,61			10,48		
CO_2 (g/kg)	12,54			8,91		
Methane (g/kg)	3,56			1,31		
CxHy (g/kg)	2,34			1,57		

CHAPTER 5: FOUR SCENARIOS, THEIR ENVIORMENTAL EFFECTS AND PRODUCT VALUE

Within this chapter, the results from chapter 3 & 4 are merged together and from this, four scenarios for the process of household waste are presented. Subsequently, these four scenarios are discussed and compared to each other, based on the emission and product value. Which answers the sub-question: "Based on the environmental and economic performance, which of the waste processing techniques should be preferred in Friesland for the process of unrecyclable and non-reusable flammable household waste?"

5.1 ANALSYSIS CRITERA

For comparing the REC with slow and fast pyrolysis, two factors have been determined during the research. One is the product value, independent of process cost, and the other one are the emission concentrations.

First of all, the techniques will be compared on their product value (value/kg household waste). However, this only indicates the value without any process cost and therefore the products will be subsequently compared to their heating value and product demand. To determine the best available technology regarding these factors, the order is as follow: Product demand→ heating value→Product value/kg household waste. This way, product security is set above profit.

Secondly, for assessing the technologies based on their emissions concentration without gas treatment, the total global warming potential (GWP) is calculated. This value indicates the potential effect on the global warming and is calculated based on the individual GWP per gas compared to GWP factor of CO_2 over a period of 100 years. These factors are obtained from the Intergovernmental Panel on Climate Change and the latest values will be used from their fifth assessment report (Myhre et al, 2013). For example, methane has a GWP factor of 28 compared to CO_2. To calculate this, the following equation is used:

$$Total\ GWP = \sum (gas_x\% * GWP_x) + (gas_y\% * GWP_y) \ldots..$$

Furthermore, the yearly environmental analysis of the REC is described and compared to the potential surrounding environmental effects of pyrolysis. This is based on the environmental potential impacts described by Čuček et al. (2015), as such described in appendix VII and in coherence with the obtained data. This means that not every impact is analyzed, as such not every substance were found in the literature. To quantify the data, the emission is analyzed based on the presence of the potential substance and classified as high, medium and low. High means, many substance are present and in significant numbers. Medium means, several substance are present and in significant numbers and low means, several substances are present, but in low concentrations.

5.2 RESTRICTIONS

First of all, this research focused mainly on the three techniques and the current technologies within Omrin. Other preferable techniques for this municipality waste part will not be analyzed. Besides that, the technology preliminary for incinerations, such as waste separation, have a strong influence on the products derived from (catalytic) pyrolysis. Only the currently installed preliminary separating techniques were taking into account during this research.

Furthermore, the research focusses only on the different effects on environmental & financial status of the products and did not focus on the dismantle and construction costs due the limited amount of time for the research. Furthermore, these costs are strongly dependent on subsidies and economy welfare of the nation and are impossible to predict. To investigate this, an advanced research will be required.

With respect to the analyses pyrolysis, only data regarding the slow pyrolysis and slow catalytic pyrolysis are obtained, with a maximum pyrolysis temperature of 550°C. When it comes to these two techniques, the parameters (temperature, heating rate, inert gas flow, catalyst type/size/ratio) have great influence on the product distribution. However, due the limited time of the research, it is not possible to analyze all these parameters.

The analysis of the product value of both pyrolysis techniques is mainly focused on the market of the gases, solids and liquid fractions. However, similar to incineration, heat is produced and can be considered as a potential feedstock for electricity.

5.3 SCENARIO'S

With the results from chapter two, three and four, four scenarios are constructed for processing unsorted, flammable household waste (on page 42), based on product value and emission concentrations. On top of this flow chart, the composition of the household waste is presented, as such was determined in

Chapter 2. In total, 132.648 ton household waste, including fermentation residue, is currently incinerated yearly by the REC, with a yearly GCV input of $1{,}967*10^6$ MJ. The main components within the household waste stream are bio-organic material (23%), paper (26,2%) and fermentation waste (19,1%). Plastics and textile are pre-separated, however these are still present in the incinerated stream and accounted for respectively: 8,3% and 8,7%. Glass (7,7%) & metals (1,7%) are considered inorganic material, are not burned or pyrolysed and left out the equations to determine the pyrolysis products. Furthermore, thrift shop material (2,2%) & rest waste (7,2%) are considered potential feedstock for incineration and pyrolysis, however, as the composition are not determined, these feedstock's are treated as inorganic material.

All four scenarios are based on the feedstock as described above, presented in Figure 12 and are classified as follow:

Scenario I: Current situation in Friesland and the REC. Here, household waste is burned in and continues oven to reduce the waste volume. Subsequently, the heat produced steam what is transferred to a steam to energy system for the production of electricity.

Scenario II: Slow pyrolysis at 500°C of household waste for the production of solids, liquids and gases that can be used as an electricity source. Within this approach, it is considered that the products are sold as heating oil (liquids), natural gas (gas) and coal (solids). One additional note, the current market price was determined per MJ products to increase the product value accuracy.

Scenario III: Slow pyrolysis at 500°C of household waste for the production of solids and liquids that can be used as an alternative "green" feedstock and gas as an energy source. Within this approach, it is considered that the products are sold as Naphtha (liquids), natural gas (gas) and Fertilizer (solids).

Scenario IV: Fast pyrolysis at 500°C of household waste for the production of solids, liquids and gases that can be used as an electricity source. This approach is similar to that of scenario II.

$1{,}967*10^6$ MJ

Total household waste incinerated by the REC: 132.648 ton									
bio-organic	paper	glass	textile	metals	rest	plastic	incontinence waste	Fermentation waste	thrift shop material
23,0%	26,2%	7,7%	8,7%	1,7%	7,2%	8,7%	11,4%	19,1%	2,2%

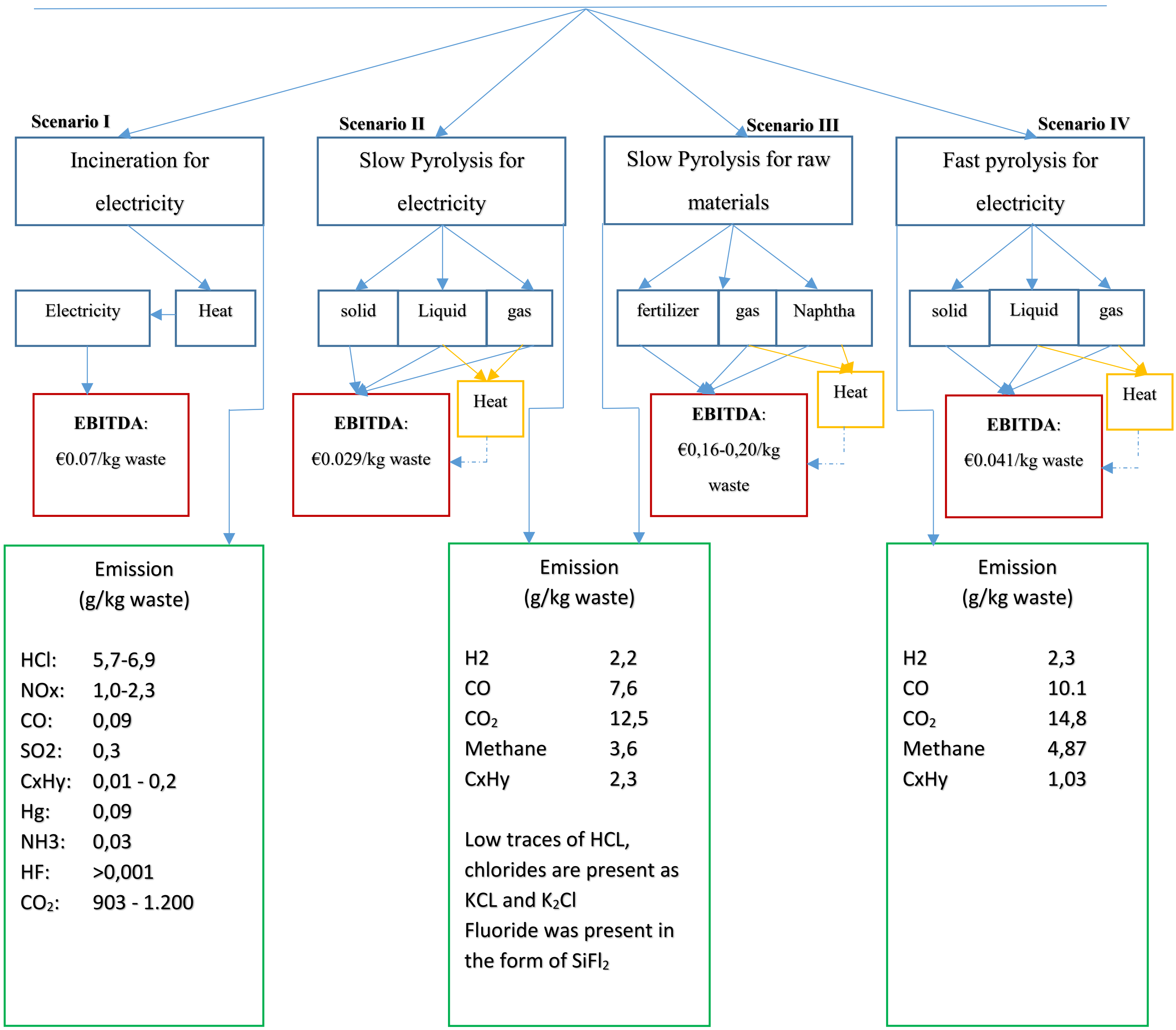

Figure 12; Four scenario's to process unsorted flammable household waste

5.4 COMPARISION OF THE PRODUCTS

The products of scenario II & IV are classified as potential replacements for fossil based heating oil, coal, and natural gas. Therefore, the security and future demand of these products are determined on the depletion prediction, as such stated by Hubbert hypothesis (Richtie 2017). Here it is stated that the reserves of heating oil is the lowest and approximately depleted in 50 years. This is followed by natural gas, where approximately 52 years are left. On the other hand, it is assumed that the reserves of coal are depleted in 114 years. This resulted in the fact that these materials are classified as "high", as such can be observed in Table 12.

Currently, covid-19 has a significant effect on the use of fossil based oil and natural gas worldwide, as such the unemployment rate increases and lockdown rules are implied. This is not different within the Netherlands. With respect to the oil consumption, this decreased significantly in the first 6 months of 2020, from approximately 100 million barrels/day in 2019 to 92 million barrels/day in 2020 (OGJ editors). However, it is expected that this will increase the similar levels in 2021, as such the pandemic measures are expected to decrease. The same trend can be observed for natural gas, where an decrease of 2,9% in the first 6 months was observed and 5% over 2020 is expected (IEA, 2020). The most targeted sector is the power generation sector, however it is expected to increase again in 2021.

Furthermore, the liquids and gases of scenario III are respectively a potential replacement for fossil based Naphtha and natural gas. These are classified, with respect to security and future demand as high, with the same explanation as stated in the first paragraph. Furthermore, within this scenario, the solids can be used as a fertilizer (bio-char). This is used in agriculture to increase the nutrient intake by plants and crops (Prastiwi et al. 2018). This way, less nutrients are needed to reach the optimum nutrient uptake by the plants for optimal grow and decreases the most abundant fertilizers use, as such they are becoming more scarcer. For example, phosphorus fertilizer is thought to be depleted between 35-300 years (Daneshgar et al. 2018). Therefore, the market for bio-char is forecasted to increase significantly in the coming years, as such is confirmed by bio-char market research literature. Despite this, there are a number of fertilizers that are abundant on the market and therefore, this is classified as "medium" with respect to the scarcity and future demand. However, the liquids and gas represents 2/3 of the total products, and therefore scenario III is classified as high.

The transition towards electrical heating, transport and other industrial processes has a major impact on the electricity demand in the Netherlands. It is expected that electricity production will increase by approximately 20% (ministry of economic affairs, 2016). Besides that, it is expected and stated in the sustainable goals, that the electricity production from "green" sources will increase to 55% and is currently 18% (CBS, 2020). At first sight, electricity from incineration plants or pyrolysis is considered an important step for the production of “green” electricity. However, other techniques, such as solar power and offshore & onshore wind farms are considered to emit less pollution over their lifespan and on this criteria more preferable. Current development in the subsidies for green electricity technologies within the Netherlands show the same trend, by an attempt to remove the subsidy for biomass to electricity plants. In the end, with all the statements made, electricity production from incineration is classified as “medium” with respect to the scarcity and future demand.

The heat from scenario I is indirect used to produce electricity at a WKO system at an efficacy rate of 68,9%. As the GCV from scenario II and scenario IV are respectively 37% and 77% higher than the input of scenario I, more heat can be produced. This means that, in theory and similar production efficiency, more electricity can be produced than scenario I. Besides the pyrolysis products, the heat that is formed during pyrolysis is not considered in the product value calculations. However, as such heat is used in scenario I, this can increase the product value significantly of scenario II and IV.

The EBIDTA of scenario III is assumed to be significant higher compared to the other scenarios (0,16-0,23 euro/kg). This is mainly due the high market value of naphtha and bio-char as fertilizer. When the household waste is used to produce electricity, the EBIDTA is significant lower and for incineration the highest (0,07 euro/kg waste). Scenarios II and IV are considered to have the lowest EBIDTA, and is mainly due the fact that, within this research, it is considered that the products are sold as an energy source. As the market price for heating oil and coal is relative low, the EBIDTA of slow and fast pyrolysis are respectively 0,029 euro/kg waste and 0,041 euro/kg waste. The possibility for creating electricity with the pyrolysis products on site by Omrin has not been taking into account.

Table 12; Comparison of four scenario’s processing household waste on product value

	scenario I	**scenario II**	**scenario III**	**scenario IV**
Scarcity and product demand	medium	high	high	high
Gross caloric value (GCV)	14,83	20,3	20,3	26,3
EBIDTA (euro/kg waste)	0,07	0,029	0,16-0,23	0,041

5.5 COMPARISION OF THE EMISSIONS

With respect to the GWP, three compounds that are found in incineration or pyrolysis that have effect on global warming: NO_x, methane and CO_2. As such, during incineration, high quantities of CO_2 (903 g/kg) is produced and is significant higher than the pyrolysis of household waste (Slow pyrolysis: 12,5 g/kg & fast pyrolysis: 14,8 g/kg). This has an significant effect of the total GWP of incineration and in addition, NO_x emission contribute to this. Due the absence of oxygen, pyrolysis tents to form amino acids, instead of

NO_x (Ren et al, 212). Therefore, this polluter is not present in the gases of slow and fast pyrolysis, instead methane is formed as a GWP polluter. But still, as can be observed in Table 13, the total GWP factor of slow and fast pyrolysis is significant lower than incineration, from 11,6-15,0 GWP incineration to 0,5-1,1 GWP pyrolysis.

When it comes to the ozone depletion, the components are fluoride and chlorides. During this research, for all technologies, traces of these calcifications are found, however not in the form that it will harm the ozone layer.

For incineration the acidification on surround nature are classified as high, as such many acidification substances are present after combustion. However, many of these compounds, such as HCL, SO_2, HF and NO_x are removed from the gases before it is released to the atmosphere. This is so efficient that the environmental reports states that the concentrations found in the surrounding area is far below the European limits of industrial emissions and the permit limits (Dijk et al, 2020). Less acidification potential substances are found during pyrolysis and is stated as medium, with HCL as the main polluter.

The photochemical ozone creation potential is high for pyrolysis, as such high concentrations of methane, CO and small organic compounds (stated as volatile organic compounds). This is significant higher than that of incineration, however these compounds (plus NO_2 and excluding methane) are present as well and therefore this is classified as medium.

Table 13; Comparison of four scenario's processing household waste on environmental effects

	Incineration (scenario I)	**Slow Pyrolysis (scenario II & III)**	**Fast pyrolysis (scenario IV)**
Ozone depletion potential	Low	Low	Low
Global warming potential (GWP)	11,6-15,0	1,1	0,5
Acidification potential	high	Medium	Medium
Photochemical ozone creation potential	medium	high	high

5.6 CONCLUDING REMARKS

It is found that the future potential of the pyrolysis are high, as such they are potential replacements for fossil oil products. For the REC, this was stated to be medium, as such other technologies for electricity production are more preferable, with respect to less polluting emission levels (for example solar panels). Furthermore, it is found that the GCV increases with pyrolysis and for fast pyrolysis it increased by 77%. Finally, the EBIDTA is for slow pyrolysis for the production of chemical feedstock and fertilizer (scenario

III) the highest and for the production of an energy source the lowest. The REC was in the middle, however significant lower than that of scenario III.

Based on the emission concentration, without any form of gas treatment, the best available technology is fast pyrolysis. This technology has the lowest GWP effect, low ozone depletion potential and medium acidification substances. However, as such stated, the photochemical ozone creation potential is high and is required to have some sort of gas-treatment.

CHAPTER 6: CONCLUSIONS

Within this chapter, the conclusion and recommendations are presented. Here, the conclusion is based on the data presented in chapter 2, 3, 4 and 5 to answer the research questions. Furthermore, the recommendations are based on the conclusion and on waste monitoring within Friesland.

6.1 CONCLUSION

The aim of this research was to analyze and asses the feasibility of slow and fast pyrolysis as a potential replacement for incinerators, based on in depth analysis of the emission concentrations and product value (excluding the process costs). This all in coherence with the waste flow in Friesland and the incinerator (REC) located in Harlingen. Furthermore, the research was divided in four separated analysis, whereas firstly the current incinerated household waste was determined. Subsequently, based on the household waste, the emissions and product value were determined, individually for the REC, slow and fast pyrolysis. Finally, the results were compared based on the product and environmental impact, this all to answer to research question: *To what extend can (catalyst) pyrolysis of household waste be considered an alternative for incineration of household waste, based on environmental, financial criteria and what would that imply for household waste management in Friesland?*

The research began in chapter 2 where the household waste flow that was currently incinerated by the REC was determined. It was found that 71 wt.% waste, which is collected by Omrin, is separated at source or post-separated. The remaining 29 wt.% is transported towards the REC and accounted for 132.647 ton waste. The composition of the flammable part is assumed, based on literature data and is classified as follow: 23 wt.% bio-organic (e.g. organic garden waste and food waste), 26,2 wt.% paper waste, 8,7 wt.% textile, 8,7 wt.% plastics, 11,4 wt.% incontinence waste and 19,1 wt.% fermentation residue. Besides this, the waste consisted of 9,4 wt.% inorganic material (7,7 wt.% glass and 1,7 wt.% metals) and 9,4 wt.% potential flammable waste (2,2 wt.% thrift shop material and 7,2 wt.% unclassified rest waste).

In coherence with the flammable waste part that is currently incinerated by the REC, the product value of the REC, slow and fast pyrolysis are calculated and predicted in chapter 3 & 4. For the REC, published data showed that 142.397 MWh electricity was produced in 2018 and with that, the EBIDTA was 0,07 euro/kg waste. With respect to slow and fast pyrolysis, it was predicted that the EBIDTA is respectively 0.032 euro/kg waste and 0.041 euro/kg when the products are sold as an energy source. Besides that, it was found that pyrolysis products as a chemical feedstock and fertilizer has significant higher value. This was predicted for slow pyrolysis and here it was found that the EBIDTA is approximately 0,16-0,20 euro/kg waste.

With respect to the emissions, the same method has been applied as such stated for the product value. The presented concentrations in Table 14 are found and with respect to the REC, before gas-treatment, it has been found that high amounts of CO_2 (903-1200 g/kg) are produced. Furthermore, this way, SO_2 (0,3 g/kg), HCL (5,7-6,9 g/kg) and NO_x (1-2,3 g/kg) polluters are emitted. With pyrolysis, the CO_2 emission is calculated to be 12,54 g/kg for slow pyrolysis and 8,91 g/kg for fast pyrolysis. Furthermore, for slow and fast pyrolysis, significant concentrations of H_2, small hydrocarbons, CO and methane are found.

Table 14; Overview of the emission concentration of all three techniques

Gas	REC
HCl (g/kg)	5,7-6,9
Nox (g/kg)	1,0-2,3
CO (g/kg)	0,1
SO_2 (g/kg)	0,3
C_xH_y (g/kg)	0,01-0,2
Hg (g/kg)	0,1
NH_3 (g/kg)	0,03
HF (g/kg)	N.k.
CO_2 (g/kg)	903-1.200

Gas	Slow pyrolysis	Fast pyrolysis
H2 (g/kg)	2,2	3,9
CO (g/kg)	7,6	10,5
CO_2 (g/kg)	12,5	8,91
Methane (g/kg)	3,6	1,3
CxHy (g/kg)	2,3	1,6

In chapter 5, four scenarios for processing the flammable waste part are presented. These scenarios are in coherence with the product value & emission concentrations and are analyzed based on three product value criteria and four environmental impact criteria. It is found that the predicted future demand of the products of pyrolysis are higher than that of the electricity of REC. This is mainly due the depletion of fossil derived feedstock and alternative technologies are available for the production of electricity. Besides that, the GCV of pyrolysis are found higher than that of the input of the REC. This means that more heat can be produced and with that more electricity. With respect to the EBIDTA, it has been found that the products of slow pyrolysis for chemical feedstock and fertilizer have the highest value.

Zero ozone depletion gas compounds were found for every technology that was analyzed in this research. However, it is found that the GWP of the REC is significant higher than that of both pyrolysis technologies. This is found that this is mainly due the high CO_2 emission of the REC, compared to that of pyrolysis, even with the fact that methane is formed with pyrolysis. The third criteria is Acidification potential. It is found that this is higher for the REC than that of pyrolysis, however every technique has the compounds that are considered to influence this. The last criteria is the photochemical ozone creation potential. This is found to be high for pyrolysis and low for the REC.

To answer the main research question, it is found that pyrolysis is an interesting technology to replace incinerators, as such was determined by answering the sub-questions with respect to the emission concentrations and product value. In general, with pyrolysis, significant lower pollutants are emitted due the absence of oxygen and production of potential liquids, solids and gases. Furthermore, when the products are used as a chemical feedstock and fertilizer, instead of an energy source, the EBIDTA is also promising and is significant higher than that was calculated for the REC. Finally, household waste management in Friesland can be considered efficient when it comes to re-use and recycling (72% in 2018). The remaining part that is currently incinerated (29% in 2018), can be replaced by pyrolysis and with that, increase the recycling efficiency even more in Friesland. As such, with pyrolysis, the waste is recycled to create potentially new products.

6.2 RECOMMANDATIONS

First of all, the research show promising results for pyrolysis as a flammable waste technology. However, the research was limited to the analysis of product value, excluding process cost and the potential emissions and their effects. Therefore, it is recommended that waste processors that processes waste with incinerators, initiate a more extensive research to investigate the possibility of pyrolysis. Furthermore, it is recommended that these companies will do this on fast pyrolysis, as such the liquids are the most promising product for future demand and product profits.

Secondly, during the research, it was found that limited data was available on the waste composition that is incinerated. Moreover, Omrin transported this waste to the REC without monitoring, as such was stated by Omrin. However, it is well known that incineration will be reduced in the future and other techniques has to be found to process this. Therefore, it is recommended to monitor more extensively this waste flow, with can be done with extracting sample periodically and determine the composition. This way, better and faster analysis can be made for new technologies.

As such this research is based on literature data derived from different sources, it is recommended to perform actual medium scale experiments for the scenarios routes presented in section 5.3. This to confirm the calculated emissions and products derived from the waste distribution presented in section 2.4. Furthermore, these experiments should focus on the purity of the products and predict a more accurate market value. This will give a better practical understanding of the potential of processing household waste through pyrolysis

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APPENDIX I; WASTE DISTRIBUTION AT OMRIN DERIVED FROM NEAR HOUSE COLLECTION AND DUMPING SITES (TRANSLATED FROM DUTCH TO ENGLISH)

Components	*Primary separation*	*Secondary separation*	*Flammable residue*	*Total (kg/person)*	*% separation*
VFG waste	124				
Paper	59				
glass	19				
Thrift shop	7				
Textile	5				
WEEE	5				
metals		6			
Plastic		16			
Paper		3			
Organic waste		38			
minerals		12			
Rest flammable waste			120		
Total	219	75	120	414	71%

APPENDIX II; EXACT NUMBERS REGARDING THE WASTE FLOW TOWARDS THE REC

	separated at Omrin	Omrin + household rest waste	Netherlands	Waste stream processed by the REC
thrift shop	1,7%	1,7%	0,0%	0,0%
FVG + wood	39,1%	45,0%	47,0%	5,9%
paper	15,0%	23%	19,2%	8,2%
glass	4,6%	7%	7,1%	2,4%
textile	1,2%	4%	3,5%	2,7%
WEEE	1,2%	1%	1,8%	0,0%
metals	1,4%	2%	2,8%	0,5%
minerals	2,9%		0,0%	
rest		7%	4,9%	7,0%
plastic	3,9%	7%	6,2%	2,7%
In-contamination waste		4%	3,2%	3,6%
plastic, can and carbon packaging			4,2%	
Fermentation waste				12%
total	71,0%	101%	100%	44,8%

APPENDIX III, COMPOSITION OF INCONTINENCE MATERIAL

Material	LHV (MJ/kg)	Diapers (wt%)	Diapers (LHV)	Incontinence material (wt%)	Incontinence material (LHV)
SAP	25.0	9.7%	2.4	3.9%	1.0
Fluff/pulp	16.8	7.1%	1.2	17.9%	3.0
Nonwoven (PP)	41.6	6.2%	2.6	3.0%	1.3
Elastics and adhesive tape	27.2	3.8%	1.0	0.3%	0.1
PE film (PE)	41.2	1.5%	0.6	1.7%	0.7
Adhesive	41.0	0.9%	0.4	0.8%	0.3
Other	0.0	0.3%	0.0	0.0%	0.0
Liquid biowaste	-2.6[1]	67.5%	-1.8	67.5%	-1.8
Plastic bags (PE)	41.2	3.0%	1.2	5.0%	2.1
LHV			7.7 MJ/kg		6.6 MJ/kg

(Odegard et al, 2018)

APPENDIX IV; CV VALUE OF WASTE

	Without pre-treatment CV(MJ/kg)	CV (MJ/kg) waste distribution	References:
bio-organic	16,58	3,81	Olisa et al, (2018)
paper	14,085	3,69	Olisa et al, (2018)
textile	17,475	1,52	Olisa et al, (2018)
plastic	33,712	2,93	Olisa et al, (2018)
Fermentation waste	9,115	1,74	Choi et al, (2019)
Incontinence material	6.6	0.75	Odegard et al, (2018)
thrift shop material	16,58	0,37	Olisa et al, (2018)
	total	14,83	

APPENDIX V: LIQUID COMPOUNDS OF SLOW PYROLYSIS OF A PAPER RICH WASTE SAMPLE

		%	**Boiling point**
aromatics	toluene	11,5	110
	ethyl benzene	17,8	135
	xylenes	3,4	139
	styrene	27,2	145
	methylethyl benzene	1,6	110
	methyl styrene	6,1	166
alkenes	decene	1	172
	indene	2	182,2
	undecene	1	193,5
	methyl indene	1,7	199
	tetradecene	1	261
	Anthracene	1,4	363
alkanes	phenyl ethanone	1,7	202
acids	benozic acid	1,3	250
polyaromatics	naphatlene	4,5	218
	Propanediyl-benzene	1,5	n.k.
	Phenyl-naphthalene	3	334
	7-200 (%)	73,3	
	higher than 200 (%)	14,4	
	Total (%)	87,7	

APPENDIX VI: ADDITION EXPLANATION REC EMISSION

1) With respect to the NEN-EN 14181 emission analysis, the data is presented in weight per cubic meter. However, for comparing this data with the data that will be obtained for pyrolysis, the data has to be presented in substance per kg household waste. For this, the total cubic meter gas emitted in 2018 is calculated. According to Pirovano et al. (2017), 215.184 - 227.490 m^3 gas was measured to emit every hour between 2012 and 2015. A more recent measurement, conducted in 2019, recorded an total emission between 200.000-230.000 m^3 gas/hour over a period of 24 hours (Dam et al. 2019). No changes has been made in the permit of the REC over the last year (Bosh & Jonker, 2019) and with that, no changes in the REC setup were allowed. Finally, the emission year rapport of the REC stated that 223.221 m^3 gas was emitted without any calculations nor the analysis method. However, as this value falls in the range of other measurements, this value is adequate and used for further calculations. In total, 1.955,4 million m^3 was emitted in 2018.

2) An important note for the calculations: The emission analysis are limited to the end of the pipe monitoring. To assume the actual emission levels derived from incineration, literature data regarding the gases (as mentioned in Table 6) in coherence with the gas reduction technologies of the REC were blend together. Subsequently, the incinerated household emission before gas treatment is calculated with the following formula:

$$emission\ before\ [\text{mg/kg}] = \left(\frac{Emission\ after\ [\text{mg/kg}]}{(100 - efficicency\ [\%])}\right) * 100$$

APPENDIX VII: BAT CRITEREA

- *Ozone depletion potential* is the potential for the reduction in the protective stratospheric ozone layer. The ozone-depleting substances are freons, chlorofluorocarbons, carbon tetrachloride, and methyl chloroform. It is expressed as CFC-11 equivalents.
- *Global warming potential* represents the potential change in climate attributable to increased concentrations of CO_2, CH_4, and other GHG emissions that trap heat. It leads to increased droughts, floods, losses of polar ice caps, sea-level rising, soil moisture losses, forest losses, changes in wind and ocean patterns, and changes in agricultural production. It is expressed in CO_2 equivalents usually for time horizon 100 y.
- *Acidification potential* is based on the potential of acidifying pollutants (SO_2, NO_x, HCl, NH_3, HF) to form H^+ ions. It leads to damage to plants, animals, and structures. It is expressed in SO_2 equivalents.
- *Eutrophication potential* leads to an increase in aquatic plant growth attributable of nutrients left by over-fertilization of water and soil, such as nitrogen and phosphorus. Nutrient enrichment may cause fish death, declining water quality, decreased biodiversity, and foul odors and tastes. It is expressed in PO_4^{3-} equivalents.
- *Photochemical ozone creation potential* is also known as ground-level smog, photochemical smog, or summer smog. It is formed within the troposphere from a variety of chemicals including NO_x, CO, CH_4, and other volatile organic compounds (VOCs) in the presence of high temperatures and sunlight. It has negative impacts on human health and the environment and is expressed as C_2H_4 equivalents.
- *Ecotoxicity (freshwater, marine, terrestrial) potential* focuses on the emissions of toxic substances into the air, water, and soil. It includes the fates, exposures, and effects of toxic substances and is expressed as 2,4-dichlorophenoxyacetic acid equivalents.
- *Human toxicity potential* deals with the effects of toxic substances on human health. It enables relative comparisons between a larger number of chemicals that may contribute to cancer or other negative human effects for the infinite time horizon. It is expressed as 1,4-dichlorobenzene equivalents.
- *Abiotic depletion potential* is concerned with the protection of human welfare, human health, and ecosystems, and represents the depletion of non-renewable resources (abiotic, non-living (fossil fuels, metals, minerals)). It is based on concentration reserves and the rate of de-accumulation and is expressed in kg antimony equivalents.

APPENDIX VIII: WASTE HIERACHY

The EU waste framework directive has the task to construct frameworks for handling waste (in general) in a community and defining key concepts for waste, recovery and disposal with respect to environment protection and human health (Directive 2008/98/EC 2008). Regarding waste management, this directive set up a waste hierarchy as follow:

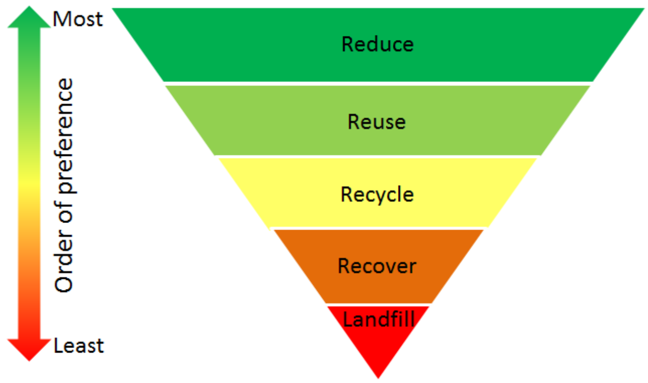

Figure 13; Hierarchy of waste management preference (Bourguignon 2018)

First of all, the most preferred situation for waste management is the reduction of the total waste. For example, food packaging has the benefit to extend the lifetime of a product, however the packaging is intended to become waste and therefore preferable not to be used. Another example is to reduce the use of plastic straws and plastic stirrers, what is meant to be waste after single use, by banning them nationally as was done in England. Secondly, reusing material and products as they are is likewise preferable. This way, the lifetime of a product is extended and reducing the production of new similar products. Take for example a used couch that is unwanted by the first owners. Cleaning this product and bringing it into the market for a reasonable price will give the product a second life. This is done in the car industry for a long time, but for household products this can and must be improved. This was also noted by Kunamani et al. (2019), where they researched the problems and possibly for reusing the products and found that reusing will lower the CO_2 burden on the environment, lower the toxicity effects of a product is safer for users and producers. However, the consumer is so used to the habitat of buying new products, more awareness is needed for the benefits of reusing of products and must come from governments by policy's and the industry. As reuse is more preferable than recycling, in the end a product will always end into this layer. Here, the product is brought back to starting material, such as wood, metals and even oil for the production of new products. This type of waste management is very popular under the population and is used in many different areas. Ranging from recycling tired for the building of houses to the recycling in waste deposits of paper for the production of new packaging material. When reusing or recycling of a product is not possible, incineration, digestion or a different technique for processing waste into energy or fuel is desired. The least desired waste management tool is the waste disposal on landfill. This is undesired due the fact that it will fill up land that can be used for other more desired activities, such as agriculture and of course the negative effect on the environment as it leaks pollutants.