Evaluation of the Potential of Diaper Recycling Within AEB Amsterdam

Internship of the Master Sustainable Energy Technology

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1. Preface

For my internship within the master Sustainable Energy Technology at the University of Twente I chose to dive into the world of waste management. For four months I worked at AEB Amsterdam, the biggest waste incineration facility in the Netherlands. I was placed within the Strategy department to assist in projects that fall within the 'innovation program'. Within the innovation program six themes are addressed: Energy from biomass; biomass to materials; waste collection and separation; upgrading materials from waste; closing local cycles; and carbon dioxide capture and usage.

Within this program I worked on two main projects within the themes: closing local loops and upgrading waste materials. The first project had as focus to close local loops within the zoo, Artis, in Amsterdam. In Artis a lot of organic waste is produced in the form of manure from the animals; and swill and kitchen waste from the restaurants. Currently this waste is all transported to external companies for processing. The basis of this project was to use the organic waste to grow insects that live off of waste, the most common being the mealworm, the common housefly, and the black soldier fly. The full grown larvae of these insects could then be used as a protein source for the animals in the zoo. For this project I looked into which insects would be the best for this application, concluding that the housefly would be most suitable due to its short life cycle and its reputation as a waste processor. I made a mass balance of the entire process, looking at how many eggs would be needed over what time span and how many kilograms of larvae would be produced. A design was made of the reactor in which the larvae could grow and of the setting within Artis in which it could fulfill an educational purpose. The final design consisted of a reactor to grow the larvae as well as cages in which the flies could be reared and eggs could be produced. This design was presented to a project manager within Artis.

The second project was concerned with recovering resources from waste streams. AEB Amsterdam is making the transition from a waste incineration company to a sustainable resources and energy company. In the context of this transition they are looking at several waste streams which can be upgraded or recycled within AEB. During my internship I looked into the recycling of textile waste and diaper waste. These are both streams which account for approximately 5-8% of the residual waste from households and which contain significant value. For both streams market research was performed to determine the size of the waste stream, the composition, and the ways in which it is currently processed. Subsequently I looked at what upcoming techniques there are to recycle and re-use these streams and evaluated these.

The focus of this paper will be on the recycling of diaper waste because I spent most of my time on this and the results provide for an interesting study. Throughout my study on diaper recycling I collected information from the internet, from conferences and workshops, but also from the companies themselves that are working on these techniques. I will be presenting three different technologies which are currently in the process of up-scaling and which are seen to have the most potential. Interviews have been performed with all three companies and in some cases information has been exchanged under an NDA. As a result, some of the information remains confidential and will not be presented quantitatively in this report. The names of the companies will also not be mentioned and I will present the information in such a way that no confidentiality is infringed.

2. Abstract

This report is the product of an internship at the waste management facility, AEB Amsterdam. As part of AEB's transition towards a resource recovering company the waste stream of diapers and incontinence products was studied. Currently the waste stream is processed in the waste incinerator producing energy in the form of electricity and heat. Through this paper the results of research on the diaper market are presented, including the biggest manufacturers as well as the current disposal techniques. For AEB the potential is in the future technologies. Three upcoming technologies are presented and analyzed according to environmental aspects, the business case, the capacity, and technological advantages and disadvantages. Technology 1 is the furthest in recovering resources as all the material streams are recovered, while Technology 2 only looks to recover the plastic and uses the organic stream as an input for anaerobic digestion, and Technology 3 recovers the plastic and cellulose. The saved CO_2 emissions of Technology 2 are the highest while the risks are minimized. The main advantage of Technology 2 is also the scale of the installation. Considering that AEB would be entering an entirely new market it is more realistic to start with a smaller capacity and increase it over time instead of requiring 48.000 ton of diaper waste per year. It is essential that the business cases of the three technologies are studied in more depth and evaluated according to the situation in Amsterdam.

Contents

3. Problem definition

Natural resources are becoming scarce in today's society and as a result a worldwide shift is taking place from a linear to a circular economy. Where today's linear model is based on: 'take, make, dispose' the circular economy aims to eradicate waste in all the segments of society: industries, consumers, users and waste management, by closing resource-loops. The main idea is that materials are not destroyed in an incineration process or dumped in landfills, but rather are brought back into the economy as reusable products. For waste incineration companies, such as AEB Amsterdam, this shift significantly impacts their core business. As a result the company is in the process of making a transition from a waste incineration company to producing sustainable energy and resources.

One of AEBs main priorities is the recovery of high quality resources from waste streams via the principal of source separation as well as post separation [1]. There are already several waste streams from which resources are recovered within AEB, such as: hazardous waste (620 ton per year [1]), electric cables (103 ton/year [1]), non-ferro from dismantling [1] etc. There are, however, numerous waste streams which are not further processed at AEB or end up in the incinerator together with the residual waste. In order to facilitate the transition to a circular economy it is essential for AEB to investigate how recycling and reuse can add value to waste.

It is impossible to focus on all waste/resource streams, thus it is necessary to investigate which streams there are and which are worth building a business case for. Some examples of waste streams that need to be considered are: glas, textile, mattresses, metal, garden waste, tires, diapers etc. For this project it was chosen to look at two waste streams which make up a considerable part of the municipal waste and for which there are currently not so many recycling techniques: diapers and textile.

For the scope of this report the focus is on the recycling of diaper waste. For this waste stream several questions need to be investigated to determine whether it will be of interest for AEB to start recycling it. It is essential to determine how big the waste stream is, what it is composed of, and what the current processing techniques are. To determine the perspective of recycling it should be looked at what innovative upcoming techniques there are and these should be evaluated based on chosen factors. In the methods section it will be elaborated on how these questions will be answered.

4. Introduction diaper recycling

Diaper recycling. It may seem like a stinky business to get into but the fact is that someone has to do it. The amount of absorbent hygiene products (AHPs): baby diapers, adult incontinence products, and feminine hygiene products, in the municipal waste is significant. In the Netherlands between five and eight percent of the municipal waste is made up of absorbent hygiene products [2]. This waste ends up in waste incineration plants, with as only useful by-product being the energy in the form of heat and electricity which is extracted from the process.

The market of AHPs has exploded since the first Pampers were produced by Procter & Gamble in 1961 [3]. Currently the market is still growing as a result of the large aging population as well as the growth of the use of disposable diapers in developing nations as China, Latin-Amerika and Russia. Producers are responding to this growth by adapting their products to keep their customers happy; producing lighter, more comfortable and more absorbing diapers. As a result less fluff pulp is used and more superabsorbent polymers (SAPs). This can be translated into more plastics and less natural materials, bringing with it more negative environmental impacts.

The stages that have the most significant environmental impacts are the production of the diapers, the production of the materials and the disposal of the products after use. Producers are proud of the fact that their diapers contain less material, the question remains, however, whether the increase in the use of SAPs can be seen as an improvement in environmental perspective. It seems that improvements need to be made in the disposal of the used diaper, seeing as minor developments have been seen in this sector over the years.

From 1999 to 2007 there was a diaper recycling plant in the Netherlands run by Knowaste. On a yearly basis 35,000 tonnes of diapers from families, day care centres, hospitals and elderly homes were recycled to cellulose, plastic, and compost [4]. Sadly, the plant could not compete with the low prices of waste incineration and eventually the plant became unprofitable due to an inability to work at full capacity. The only other initiative since that time has been a facility by Orgaworld where diapers are composted together with the organic waste. Composting, however, is no longer seen as a safe option due to the SAPs, medicine rests and pathogens which are likely to remain in the compost after the process [2].

Clearly, AHP waste is something that is not easy to dispose of. According to the Ladder van Lansink, as shown in Figure 4.1, waste incineration is among the lowest waste processing technologies, however, at the moment it is the safest. Alternative recycling technologies that can compete with the incineration prices and eliminate the problems of active SAPs and medicine rests are needed to cope with this growing waste stream.

A simple solution may seem to be the shift from using disposable diapers to cloth diapers. This approach would reduce the waste generated as well as the dangers which are associated with recycling or composting. The environmental gain, however, of using cloth diapers is questionable. Cloth diapers are usually made from cotton or bamboo, leading to a high energy use during production. In addition, cloth diapers require washing, using large quantities of water and energy leading to higher greenhouse gas emissions [5]. By many consumers it is also seen as inconvenient.

Considering the number of problems that need to be solved before composting diapers will be

Figure 4.1.: Ladder van Lansink [6]

possible and safe, and the mentality switch needed by consumers as well as manufacturers, it is clear that an alternative is needed. A safe and efficient recycling technology will not only lead to a much needed waste disposal alternative, it also fits in the transition to a circular economy. The resources that are put into the production of diapers are lost during waste incineration, however, through recycling they can be returned to the production chain. This transition to a circular economy is emerging throughout the Netherlands, where diaper recycling fits in perfectly.

In the city Amsterdam there are several initiatives working towards a circular economy. The citys goal is to achieve a separation percentage of 65% in municipal waste in 2030, a significant increase from the 27% separation percentage in 2014 [7]. Nationally the goal is to achieve 75% separation [7]. Since diapers are such a significant part of the municipal waste, separating and subsequently recycling diapers would contribute significantly to this goal. Clearly there are many problems that need to be overcome to achieve diaper recycling, however, the need for recycling is undeniable.

In the rest of this paper the results of a study on the technical feasibility of diaper recycling by AEB Amsterdam will be presented and analysed. To start off the method of this project will be explained in Chapter 5. Through market research the answer to the following questions will be presented in Chapter 6.1: how big is the waste stream, what is it composed of, and what are the current processing techniques? To determine the perspective of recycling it will be looked at what innovative upcoming techniques there are as presented in Chapter 6.2 and these will be evaluated based on chosen factors in Chapter 7. The study will be closed off with some recommendations in Chapter 8 and a conclusion in Chapter 9.

5. Method

In order to determine whether it is an interesting option for AEB Amsterdam to invest in diaper recycling it is necessary to perform market research. Although the main focus of this study is on the technology needed for recycling diapers, it is necessary beforehand to determine what the existing market looks like. All the research that is performed during this study will be done via the internet and through interviews with people that are involved in the upcoming technologies.

To start off it is important to define the different factors in the market which are of importance by looking at the entire product life cycle. This can be done by considering all the steps that are involved in diaper use from the production from raw materials to the disposal: from 'cradle to grave'. By performing this analysis the key phases are identified which need to be looked into. For each of these phases it is important to determine what the current market is like and who the key players are.

Once the existing life cycle is defined and understood it is important to look at the new developments in this cycle. For the scope of this project the focus will be on the future techniques associated with waste management. Clearly there is a lack of effective technologies to recycle diapers, otherwise the waste stream that is merely disposed of rather than recycled would not be so significant. The potential for AEB Amsterdam must thus be found in upcoming technologies that are perhaps not yet functioning on a large scale. Once these future technologies are identified they need to be analyzed according to their potential for implementation by AEB Amsterdam.

The techniques must be analyzed based on several factors and must be compared to the existing waste disposal technique used by AEB. Factors that are important to look at are the environmental impact based on carbon dioxide emissions; the business case (where possible); the progress in the development of the technology, including any advantages or disadvantages of the technology; and lastly the capacity of the installation must be looked at to determine whether the market matches the capacity demand. The carbon dioxide emissions can be determined using a life cycle assessment that is limited to these emissions. By performing an LCA the whole system is considered. To evaluate the business case it is important to look at the incomes and expenditures (operational and capital). Lastly, all the advantages and disadvantages of the three technologies need to be considered and weighed against eachother to form a final conclusion and recommendations.

6. Results

In this chapter the results of the research will be presented. To start off market research was performed to get an indication of what the current diaper market looks like and to identify the qualities of the waste stream. Subsequently three future technologies are looked at that are currently under development. These three technologies lead to the recovery of different waste streams which can be reused. In the last section the market of recovered resources is discussed.

6.1. Market research

In order to get an adequate idea of the existing diaper market in depth market research was performed. To start off the product life cycle was defined to identify the key players in the life cycle of diapers. Since AEB Amsterdam is a waste management facility the focus will be on the disposal/recovery phase in the life cycle. The size of the waste stream will be identified as well as the contents. Subsequently there will be zoomed into the diaper products themselves: what are they made of and how has that changed over the years. The diaper producers are mainly responsible for these changes and greatly influence what the diaper will look like over 10 years. For this reason it is important to identify the largest diaper producers and their market share. Lastly, the existing waste processing technologies for diaper waste will be looked at.

6.1.1. Product life cycle

To start off the market research it is essential to define the different players and factors in the market that are of importance. In the circular economy it is important to think in terms of 'life cycles', where each stage of a product's life cycle is determined: from cradle to grave. The goal of this study is to ensure that this life cycle becomes a closed loop instead of a linear model. The key step is ensuring that the waste is not disposed of but rather processed in order to restore or recover the materials. This technique of assessing a product is also very useful in identifying the key points in the market that need attention. As a first step the key players are identified in the life cycle of diapers, as can be seen in Figure 6.1.

AEB Amsterdam finds itself in the position 'waste management' in the diaper chain. Currently their position is the incineration of the diapers, instead of recovering or recycling. In order to make this shift it is important to know what the rest of the chain looks like and which players are found in the various positions. Each stage in the cycle influences the others, therefore it is essential to understand the market in each of these stages. That is what will be investigated in the following sections.

6.1.2. Waste stream

Considering the average use of hygiene products in the Netherlands an estimation can be made of the waste flows of diapers. On a yearly basis on average 193,000 babies are born [2]. The average age that children become toilet trained is 3.16 while every child uses on average 4.5 diapers a day. This translates to a total of 1 billion diapers used per year. In 2013 diapers are said to weigh approximately 33.3 g [8], totalling to 33 kton diapers used per year. Taking an average content of 170 g faeces and urine after use [9] this totals 203 kton used diaper waste per year.

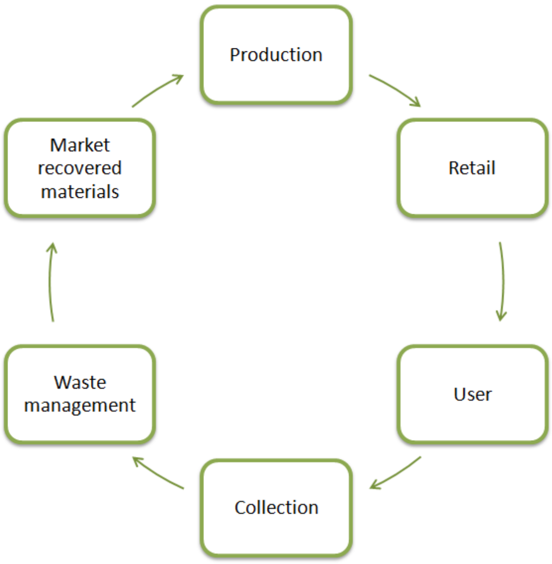

Figure 6.1.: Product cycle of diapers and incontinence products

This same estimation can be made for incontinence products. It is estimated that 750,000 people in the Netherlands suffer from urine incontinence and 100,000 from bowel incontinence [11]. The average use of incontinence products per day is 3, where each product weighs approximately 110 g in 2013 [8]. Taking an average content of 80 g faeces and urine after use this totals 190 kton used incontinence waste per year.

These two calculations are merely to give an indication of the waste streams. There are also national statistics on the amount of diaper waste found in the municipal waste. According to RWS Leefomgeving the municipal waste consists of 161 kton diaper waste [2]. This does not agree entirely with the estimation done above, however, this can be explained by the diapers that are composted and those collected in the industrial waste rather than municipal. As a general estimation the amount of diaper waste is taken to be 160-220 kton/year and 200 kton/year of incontinence waste, which corresponds to 5-8% of the residual waste stream.

For the situation in Amsterdam the waste streams specific to the city are of interest. According to a waste analysis performed by AEB Amsterdam the amount of hygiene waste found in the municipal waste of Amsterdam is 18 kton/year equating to a total of 7.1% of the residual waste stream. This is divided into 10 kton of diaper waste and 8 kton of incontinence waste per year. This data is summarized in Table 6.1. It can thus be observed that of the total AHP waste, approximately 56% is diaper waste and 44% adult incontinence waste.

Area	Diaper waste [kton/year]	Incontinence Waste [kton/year]	Total sanitary waste [kton/year]	% of residual waste stream (by weight)
Netherlands	160-220	200	360-420	5-8%
Amsterdam	10	8	18	7.1%

Table 6.1.: Data of diaper flows in the Netherlands and Amsterdam, based on a population in Amsterdam of 822,272

6.1.3. Composition diapers

Absorbent hygiene products in the form of diapers and incontinence products are made of the same materials, with slightly different compositions. Incontinence products are usually thinner and contain more cellulose pulp than disposable diapers. Disposable diapers consist of an absorbent pad between two sheets of nonwoven fabric. The components are sealed together to avoid leakage using adhesives that are applied via heat or ultrasonic vibrations [12]. To properly shape the diaper and to ensure it fits well elastics and adhesive tape are used. A visual representation of a disposable diaper is shown in Figure 6.2, where the composition of a clean disposable diaper and incontinence product is shown in Table 6.2 and a used diaper in Table 6.3.

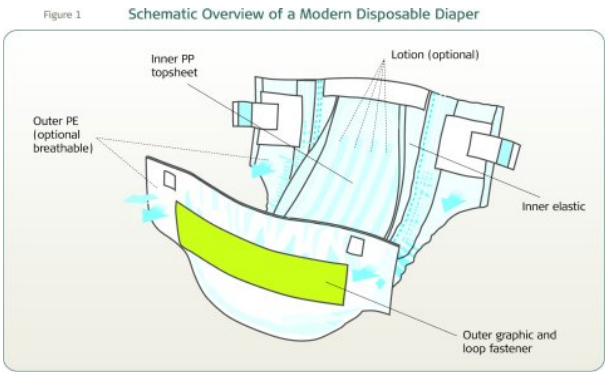

Figure 6.2.: Electric power generation sources and energy generated [10]

	Disposable diaper		Incontinence product	
Material	Weight [kg]	Weight percentage [wt%]	Weight [kg]	Weight percentage [wt%]
Cellulose pulp	0.0091	27.33	0.707	64.9
SAP	0.0126	37.84	0.0152	13.9
LDPE	0.0018	5.41	0.006	5.5
PP	0.0079	23.72	0.0124	11.4
Adhesive, tapes, elastic	0.0017	5.1	0.0047	4.3
Other	0.002	0.6	0	0
Total	0.033	100	0.109	100

Table 6.2.: Average baby diaper composition in 2013 [8]

Material	**Weight [kg]**	**Weight percentage [wt%]**
Cellulose pulp	0.014	6.86
SAP	0.010	5.01
LDPE	0.001	0.72
PP	0.006	3.14
Adhesive, tapes, elastic	0.001	0.48
Faeces	0.010	4.90
Urine	0.161	78.90
Total	0.204	100

Table 6.3.: Average composition of used baby diaper in 2013 [9]

The most essential property of a disposable diaper is that it absorbs and retains moisture, this is achieved by the absorbent pad. The absorbent pad consists of a superabsorbent polymer and cellulose fibres, a wood pulp. The cellulose fibres ensure that water is quickly dispersed throughout the polymer so that blockages cannot occur. The working of the superabsorbent polymers will be explained in more detail later on. The absorbent pad is held in place by non-woven sheets on either side, a permeable top sheet made of polypropylene and a non-permeable back sheet made from polyethylene. Nonwovens are made from plastic resins and are assembled by mechanically, chemically or thermally interlocking the plastic fibres instead of the traditional weaving of fibres [12].

Over the years the composition of the diapers has changed according to consumer's needs and desires. A large weight decrease can be observed of disposable diapers over the years, however, no significant changes are observed in the composition of incontinence products. Between 1987 and 2013 producers of baby diapers in Europe achieved a reduction in weight of nearly 50% [8]. In Figure 6.3 the change in diaper composition over the years can be viewed, illustrating the transition from a large amount of fluff pulp (cellulose) to superabsorbent polymer. Cellulose does not absorb as much moisture in weight percentage compared to SAP, making the diapers much larger. Consumers are constantly asking for smaller, lighter, better absorbing diapers and the superabsorbent polymers are what makes that possible. Now a days diapers consist of almost 70% plastics. The variation in composition of incontinence products is shown in Figure 6.4.

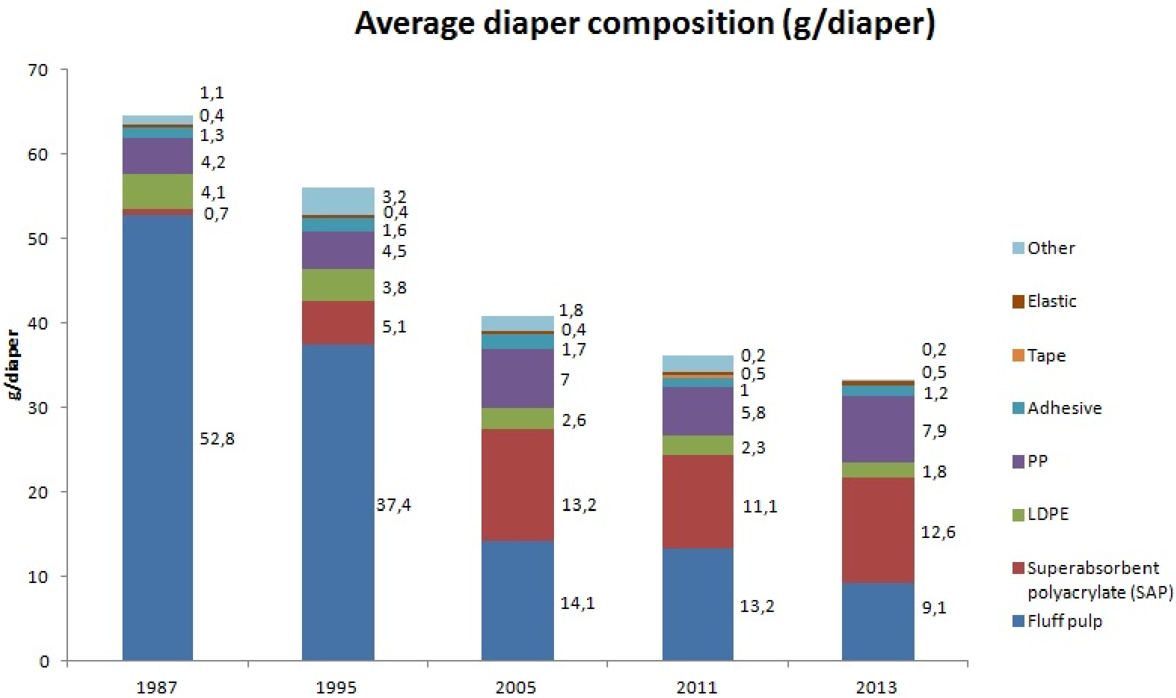

Figure 6.3.: Average diaper compostion from 1987 to 2013 [8]

What is a SAP?

Superabsorbent polymers (SAP) that are found in diapers and incontinence products are chemically referred to as polyacrylates. A polymer is a large compound based on its molecular weight, and consists of small repeating units called monomers. By varying the reaction conditions the length of the chain and the properties of the polymer can be altered. The most commonly used SAPs in diapers are made using acrylic acid and sodium acrylate as the monomers; thus giving

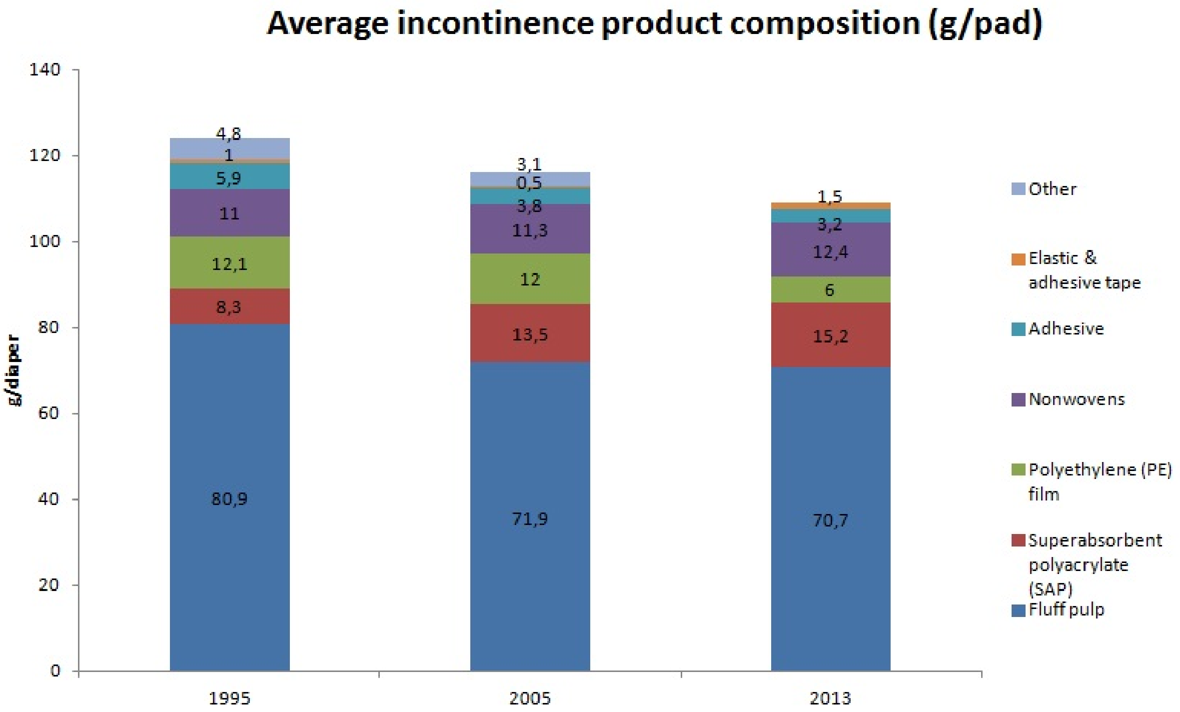

Figure 6.4.: Average incontince product compostion in 1995, 2005 and 2013 [8]

the name sodium polyacrylate. The schematic of the chemical structure of sodium polyacrylate is shown in Figure 6.5, where this structure is repeatedly connected to form a chain. Through chemically bonding one point in the chain to another, cross linkages are formed to produce a type of tangled chain, as seen in Figure 6.6.

One of the most important characteristics of the polymers used in diapers is the ability to absorb liquids. The ability to swell and absorb liquid is, however, also dependent on the ionization of the acid groups on the polymer chain. When the polymer comes into contact with water the sodium atoms will dissolve into the water as sodium ions (Na+). The polymer chain that is left behind becomes negatively charged. Due to the cross-linked structure of the polymer chain the sodium ions are somewhat trapped and are partly attracted to the negatively charged 'cage'.

The water that is thus found inside the negatively charged 'cage' has a high concentration of dissolved sodium ions, while on the outside the concentration is low. This difference in concentration leads to osmosis, the phenomena that when two solutions with different concentrations are separated by a membrane the solvent will tend to diffuse across the membrane to equalize the concentrations [13]. The water, or solvent, thus moves from the outside to inside of the polymer 'cage'. The polymer thus soaks up the water molecules until it can no longer expand. How far the polymer can expand and swell is dependent on the structure of the polymer network and the number of cross-linkages. This means that with an increased cross-link density the swelling capacity of the polymer decreases, and vice versa.

In diapers the superabsorbent polymers do not come into contact with water but with urine and feces. The difference in the chemical composition of water and urine influences the absorbency of the polymer. Sodium polyacrylate can absorb up to 800 times its weight in distilled water, however, it can only absorb about 30 times its weight in urine [13]. Although urine consists mostly of water and urea it also contains a high concentration of the following ions: chloride, sodium and potassium [14]. As a result, the process of osmosis, the driving force behind

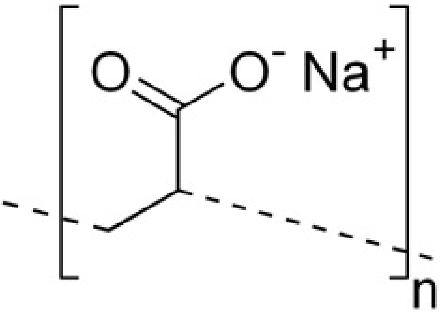

Figure 6.5.: Schematic of the chemical structure of sodium polyacrylate [15]

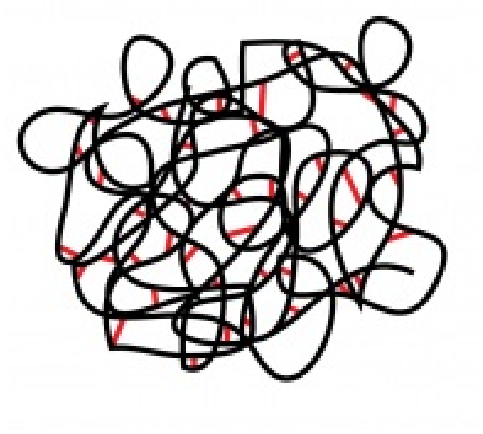

Figure 6.6.: Artists conception of a cross-linked polymer. The black line represents the polymer chain, and the red bars the points where the cross linkages are made [13]

absorption, is slowed down and decreased because there is also a concentration of sodium ions in the surrounding liquid. As explained above, by decreasing the number of cross links the absorbency can again be increased. This is done in superabsorbents used for diapers and results in the polymer appearing as a gel-like substance [13].

6.1.4. Diaper manufacturers

There are several companies that manufacture diapers from small eco-friendly initiatives to multinationals. The two largest disposable diaper producers worldwide are Procter & Gamble (Pampers) and Kimberly-Clark (Huggies) with a global market share of 35,3% and 22,9% respectively [16]. The global market share for disposable diapers is shown in Figure 6.7. The market size was valued at $44.3 billion, which is a 7% increase from 2012 [16]. This increase in market size is a result of the increase in disposable diaper use in emerging economies.

These leading companies also produce adult incontinence products, which is an industry that is thought to grow significantly over the years due to the aging global population. The market is currently dominated by the Swedish hygiene product producer Svenska Cellulosa (SCA), Kimberly-Clark and Japans Unicharm as can be seen in Figure 6.8. Procter & Gamble is, however, looking to increase its share in this market as well.

The market of diaper manufacturers in the Netherlands closely resembles the global situation. Table 6.4 shows the market shares of different diaper manufacturers in the Netherlands, in 2007 as no other up to date information could be found. As can be seen Procter & Gamble has the highest market share at 45% while supermarket/drugstore brands have a share of 30%. This data does not provide an entirely accurate image because some of the large manufacturers such as SCA also produce supermarket brands, thus giving them a larger market share as a company instead of their specific brand such as Libero. Considering the different diaper brands that are produced by each manufacturer, a summary of these brands, retailers, and manufacturers can be found in Appendix A. The biggest manufacturers in the Netherlands are: Procter & Gamble, Svenska Cellulosa (SCA), Ontex and Abena. Although Kimberly-Clark is found in this table,

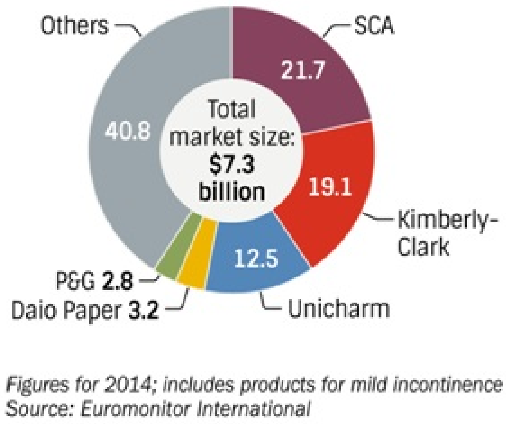

Figure 6.7.: Global market share of disposable baby diaper producers [16]

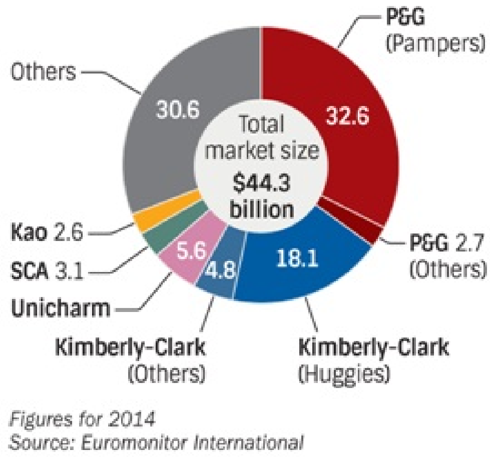

Figure 6.8.: Global market share of incontinence products producers [16]

as of 2012 they no longer sell diapers on the Dutch market [17].

Brand	**Manufacturing companies**	**Market share 2007**	**Market share 2008**
Pampers	Procter & Gamble	45%	43%
Libero	Svenska Cellulosa Aktiebolaget (SCA)	13%	11%
PullUp	Kimberly-Clark (Huggies)	2%	
Baby Love	Absorbin	2%	4%
Other B-brands		3%	2%
Supermarketbrands	Ontex, Abena, SCA	30%	33%
Diaper liners		7%	5%
Total		100%	100%

Table 6.4.: Market share of diaper manufacturers in the Netherlands in 2007 and extrapolated for 2008 [18]

The market of incontinence products in the Netherlands is dominated by the same set of companies as the market of baby diapers. There is only data concerning this market available from 2001, showing the market share of manufacturers of incontinence material in the public pharmacies in Figure 6.9. It can be seen that SCA is market leader with a share of 69% of the market with Kimberly-Clark being the second largest with a significantly smaller market share of 15.5%. Since 2001 Procter & Gamble has also started producing incontinence products, however, data on this share is not available.

6.1.5. Existing waste processing technologies

Currently there are only two main disposal techniques used in the Netherlands for hygiene products: incineration and digestion/composting. When hygiene products are collected together with the municipal waste there is only one route they follow in the Netherlands and that is to a waste incineration plant. Hygiene products are alternatively collected separately, or together with organic waste. In this case they will either be processed by Orgaworld or they

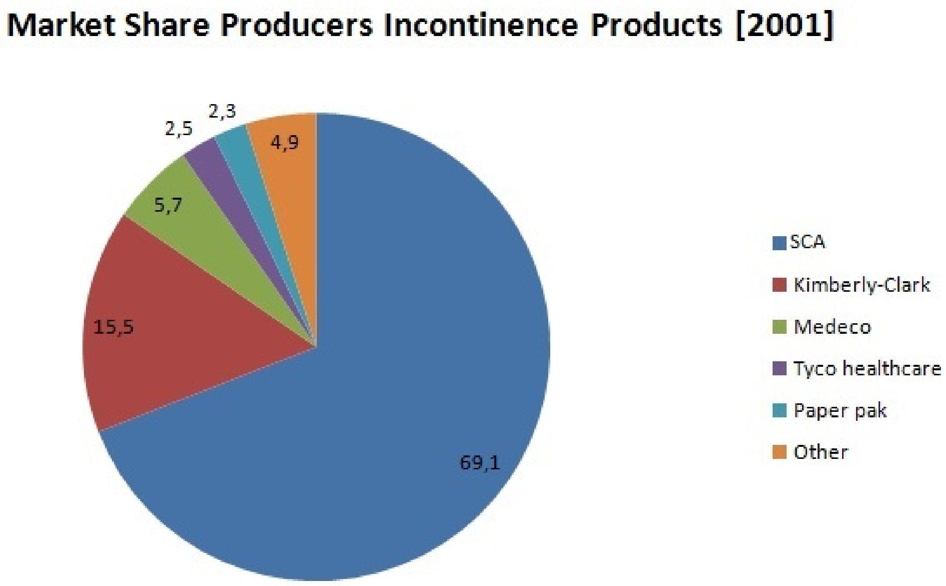

Figure 6.9.: Market share of producers of incontinence products in the public farmacy [19]

will still follow the route to the waste incineration plant.

Waste incineration is a common practice in the Netherlands, with twelve different waste incineration plants [20]. Through combustion of the waste, energy is generated in the form of electricity and heat. The efficiency of the various plants differs, with the High Efficiency Incinerator plant of AEB Amsterdam being the most efficient in the world at 30.56% (in 2014) [1]. Although this disposal method is only one level higher than landfilling on the Ladder van Lansink, it leads to a relatively clean production of energy. When it comes to AHP disposal an advantage of incineration is that all the pathogens, medicine, and SAPs are deactivated due to the high temperatures [21].

Alternatively to incineration there is a plant in Lelystad of the company Orgaworld where hygiene products are processed together with organic waste. The organic waste together with the AHPs is delivered in plastic bags which are opened to extrude the organic substances, using a bag opener [22]. This mixture of organic waste and plastic is first processed via anaerobic digestion and subsequently composted. During anaerobic digestion, without the presence of oxygen, the organic material is broken down by microorganisms, producing biogas. The biogas consists primarily of methane (55%) and carbon dioxide [21] and can be used as a fuel to produce electricity.

The digestate that remains after anaerobic digestion is upgraded by removing the plastic components through sieving, where after it can be composted via an aerobic process. Oxygen and moisture facilitate bacteria and other microorganisms in breaking down the organic material. Organic bonds are broken apart during this process to the components: carbon dioxide and water with as by-product heat. The plastic that is separated from the compost is either recycled or used as a secondary fuel.

The advantage of this process is mostly the ease for households, leading to a higher separation rate. Organic waste can be delivered in plastic bags and diapers have found a new destination, the organic waste bin. However, there is currently much discussion about the possible disadvantages/dangers to this technology. The quality of the compost is influenced by the presence of plastic/SAPs, medicine rests and pathogens. According to research done by CE Delft sieving leads to the removal of approximately 98% of the plastics whereas the SAPs remain in the compost [21]. SAPs are not biodegradable and they are not removed during the sieving process [21]. Although there remains discussion about the harmfulness of SAPs the European Commission wants to introduce an European regulation against composting diapers.

In Germany and Belgium regulations forbid the composting/digesting of hygiene products together with the organic waste. This is due to the hygienic risks of pathogens and medicine rests present, an increased zinc concentration due to the use of baby lotion, the unclear effects of superabsorbents and the plastic that is still present in the compost [23]. Due to these regulations it is also forbidden for the Dutch compost which is produced using diapers to be exported to Germany or Belgium. This compost does not receive an approved label by the national institute for trade in compost (De Stichting Regeling Handels Potgronden: RHP), making it challenging to market. In the Netherlands the compost is still used by farmers, up until now. There are rumours, however, from reliable sources, that Orgaworld will be stopping their process within the next two years.

Abroad there are some other initiatives when it comes to AHP disposal, however, incineration and land-filling are still the main disposal techniques. Companies performing similar processing techniques as Orgaworld, in the form of composting and digesting, also exist abroad. Envirocomp, a New Zealand based company, uses the same technique as Orgaworld to process their diapers via anaerobic digestion and composting. Toronto has a Green Bin program where organic waste is expanded to include: meat, fish, diapers, animal feces, etc. Hydropulpers are used to separate the waste into a light fraction (plastic, wood, textile), a heavy fraction (bones, stones, batteries, metal) and a homogeneous fluid organic fraction. Via an extra separation step the organic stream is transferred to an anaerobic digester and subsequently composted.

The only real recycling initiative is by a producer of diaper products, Fater S.p.A, that has researched the possibility of creating a closed loop cycle by developing a recycling technique for their diapers after use. Fater S.p.A is part owner of Procter & Gamble (for 50%) and produces among others the brand Pampers. According to press releases the company has opened an installation with a capacity of 10.000 ton/year in March 2015 for the recycling of diapers. Their technology consists of a cylindrical rotating autoclave where the diapers are torn apart and sterilized via pressurization and heating using steam. Two different steam flows are applied, one that comes into contact with the diapers leading to pressurization and one that is injected into blades in the autoclave that transfer heat via conduction. In a second autoclave the materials are separated via sieving into a cellulose stream and a plastic stream [24]. Currently the process is such that there is no market for these two streams, however, in the future the cellulose fibres can be used in producing cardboard and the plastic for urban furniture.

6.2. Future technologies

In this section results on the technologies that are currently in development regarding the recycling of diapers will be presented. As mentioned earlier, due to confidentiality of some of the information the three companies will be referred to as Technology 1, 2 and 3. The technique that is used for recycling the diapers will be presented in as much depth as allowable according to confidentiality agreements. All the information has been obtained through interviews with the companies or via public sources on the internet.

6.2.1. Technology 1

The first technology that will be discussed is based on 100% recycling of the materials in the disposable diapers. The technology has been proven to work on lab scale with a capacity of a couple hundred kg/hour, where the next step is up-scaling to a pilot plant and eventually to a production plant. The process is unique in the sense that the disposable diapers are separated into the constituents: plastic, fibres, and polymers (superabsorbents). The effective separation of the fibres and the polymers is something that has not been demonstrated in other processes. The process is illustrated in Figure 6.10.

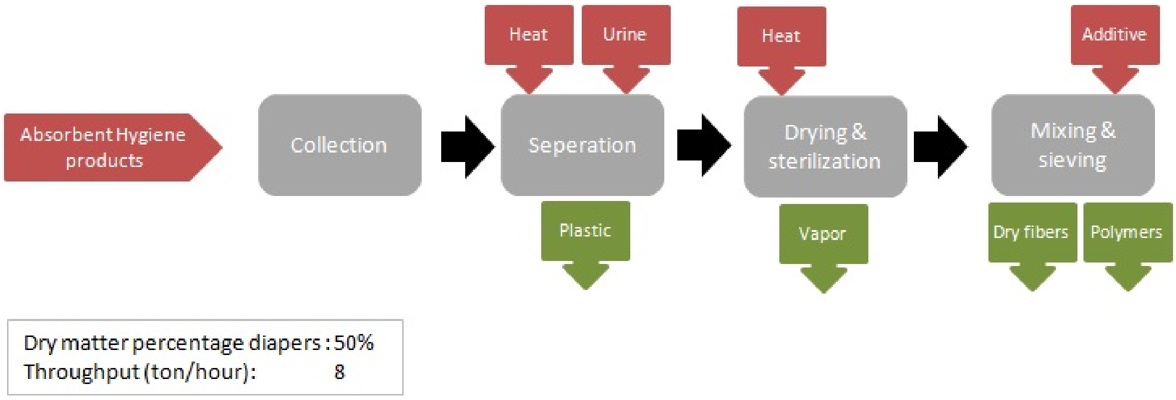

Figure 6.10.: Process overview of diaper recycling as recieved by Technology 1 [Source: interview technology 1]

In order to decrease the energy use in the process, no large amounts of water are added to the material prior to processing where after the product has to be dried, requiring large amounts of energy. The material is first sterilized in an autoclave at a high temperature and pressure using steam at a high temperature. After tearing apart the disposable diapers the materials are separated into a plastic stream and a fibre and polymer stream. Drying during this process and during the disinfecting of the fibre/polymer stream is done using low temperature waste heat. The vapour that comes out of these steps is cleaned to be ejected from the process. By using a specific additive the polymers and fibres can be separated through sieving.

The plan for the eventual production plant is to use modules instead of one large installation. According to the company, six or seven machines with a capacity of 1.5 ton per hour would lead to a total throughput of about 8 ton/hour. The plans for the full scale plant are a throughput of 48.000 ton per year, requiring a terrain of approximately 1.5-2 hectares. One of the bottlenecks during the lab scale process was removing and immobilizing the pathogens and medicine rests. This remains a bottleneck and norms need to be defined of the required breakdown of these substances. The RIVM is performing a study on this and will provide results as soon as these are available.

In addition to safety aspects associated with the recovered materials, separate collection of the absorbent hygiene products has also been considered. Interviews have been held with healthcare facilities and municipalities about the willingness to separate hygiene products from municipal waste. The parties were positive and willing to facilitate separate collection.

The company has plans to set up a demo scale plant in the south of the Netherlands, however, no partnerships have been formed with large companies/factories to achieve this. In order to achieve the up-scaling a positive business case is required. The business case is based on income from gate fees which are lower than incineration: 45-50 EUR/ton, as well as income from the reuse of recovered materials. Currently the plastic stream is guaranteed to be a source of income, while the fibres and the polymers still require a norm indication of the allowed pathogens and medicine rests. In the future it is expected that these two streams will also find a suitable market. The highest costs in the plans are the land and the energy use. It would be beneficial if the installation would be placed next to a large factory that produces waste heat and where a large capacity of diaper waste is available.

6.2.2. Technology 2

Technology 2 is based on a recycling process developed by a university. The technology is based on the use of an autoclave at a high pressure (20 bar) and temperature (220-240 °C). At this temperature the material is sterilized and the pathogens and medicine rests are deactivated. The plastic components of the diaper melt and agglomerate into a ball, while the cellulose and the human rests form a slurry. The superabsorbents are deactivated during the process and do not return as microplastics.

With regard to the presence of superabsorbents and bacteria/medicine rests tests have been done and results show that all has been sufficiently broken down. From the process the two outgoing streams are the agglomerated plastics and the organic waste slurry, as shown in Figure 6.11. The plastic stream is further cleaned to be used in products made from hard plastics such as fences, benches, and rainwater infiltration crates.

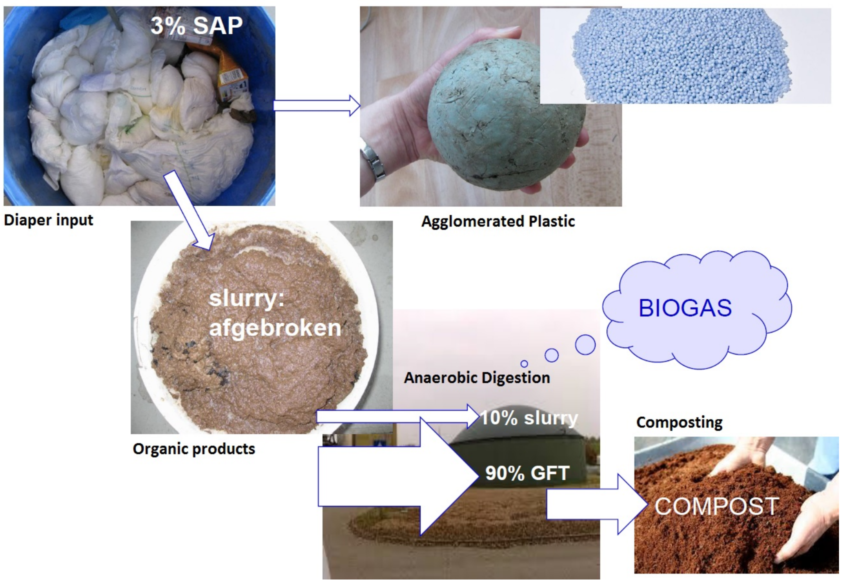

Figure 6.11.: Process overview of diaper recycling as recieved by Technology 2 [Source: Interview Technology 2]

The organic waste stream contains cellulose pulp and the urine and feces from the diapers. This stream is an ideal input for anaerobic digestion to produce biogas, with the input for digestion being 90% household organic waste and 10% this organic stream from diapers. The organic waste stream undergoes a pretreatment step prior to anaerobic digestion in the form of thermal pressure hydrolysis. In this process the organic stream is treated at a high temperature (130-180 °C) and pressure (19-21 bar) [25] in order to increase the biogas production. During this process the cell membranes of the organic substrate are destroyed, leading to solubilization of organic compounds [25]. In essence the process breaks up the cells making the organic matter more available for bacteria during anaerobic digestion. As a result, the material conversion rate is improved and the biogas production has been found to increase.

The digestate that is leftover after anaerobic digestion is then further processed via aerobic digestion to compost. The company claims that this application for the organic stream is safer and more energy efficient because the associated risks in using the cellulose in new products are avoided, as well as the extra steps required for cleaning. The amount of cellulose in diapers is also so minimal and expected to decrease even further, that it is not worth recycling.

The lab scale tests of the overall process have been completed and the next steps will be scaling the process up. In February 2016 a larger scale pilot installation, with a capacity of a couple hundred ton per year, will go into operation at a waste management facility in the Netherlands. One of the important things that will be looked at during this pilot is the optimization of the process to decrease the cycle time and increase the capacity. In November 2016 this pilot installation will be scaled up to a full scale production installation with an expected capacity of 10.000 ton per year.

The main advantage of the process is the size of the required installation, estimated at l=25m, w=25m, h=10m [Source: Interview Technology 2]. According to the company, the process fits like a module in the existing infrastructure of many waste management plants. The process itself can run on waste heat from the waste incineration and the available pressure of 40 bar. The small size of this installation ensures that the costs of the process are much lower than when a new installation needs to be built. Along with the income from the biogas produced and the plastic sold for reuse the business case for this process seems to be positive.

6.2.3. Technology 3

The last technology that will be discussed is Technology 3, which is based on a previously existing diaper recycling technique. Currently the technology is being tested at two separate pilot installations, and building plans for a full scale facility with a capacity of 36.000 ton/year have been made. The process recycles the diapers to two streams: the plastics and the cellulose, while the feces and urine are removed in the form of waste water. The technology of the final full scale process cannot be discussed due to confidentiality, however, the pilot plant technology (open to the public) closely resembles it and will be discussed below.

As first step the absorbent hygiene product is shredded to expose the contents of the hygiene product. The shredded product is then added to a rotating cylindrical autoclave, where it is sterilized and dried. The inputs in the autoclave are a salt, aluminium sulphate, and heat via a heat exchanger, in the form of steam. The salt is added to dehydrate and/or crosslink the SAP, where an equivalent of approximately 3% to 5% of the weight of the material is added in salt. In order to disinfect the material and speed up the dehydration process heat is added to the autoclave. This is done by a heat exchanger (jacketed vessel) and/or by adding steam to the system. The salt (in solution) and steam added are less than 100 L per ton of material added to ensure that a slurry is not formed.

The heat that is added to the system also causes the water which is removed from the material to evaporate. This resulted water vapour together with the injected steam cause pressurization in the autoclave. The pressure in the autoclave is kept around 2.1 bar with a temperature around 121 °C. After processing in the autoclave the water vapour is removed and the system is depressurized. Subsequently a dry screen is used to remove most of the SAP and fibres while the plastic remains. The plastics still contain some fibres and SAP which are removed in a washer/pulper, where the particle size of the plastic is also reduced. Via a sidehill screen the waste, SAP and fibre are separated from wastewater which is treated via dissolved air filtration. The separated stream is pressed to remove water and can subsequently be recycled or used for energy production. A graphic representation of this process has been made and is shown in Figure 6.12.

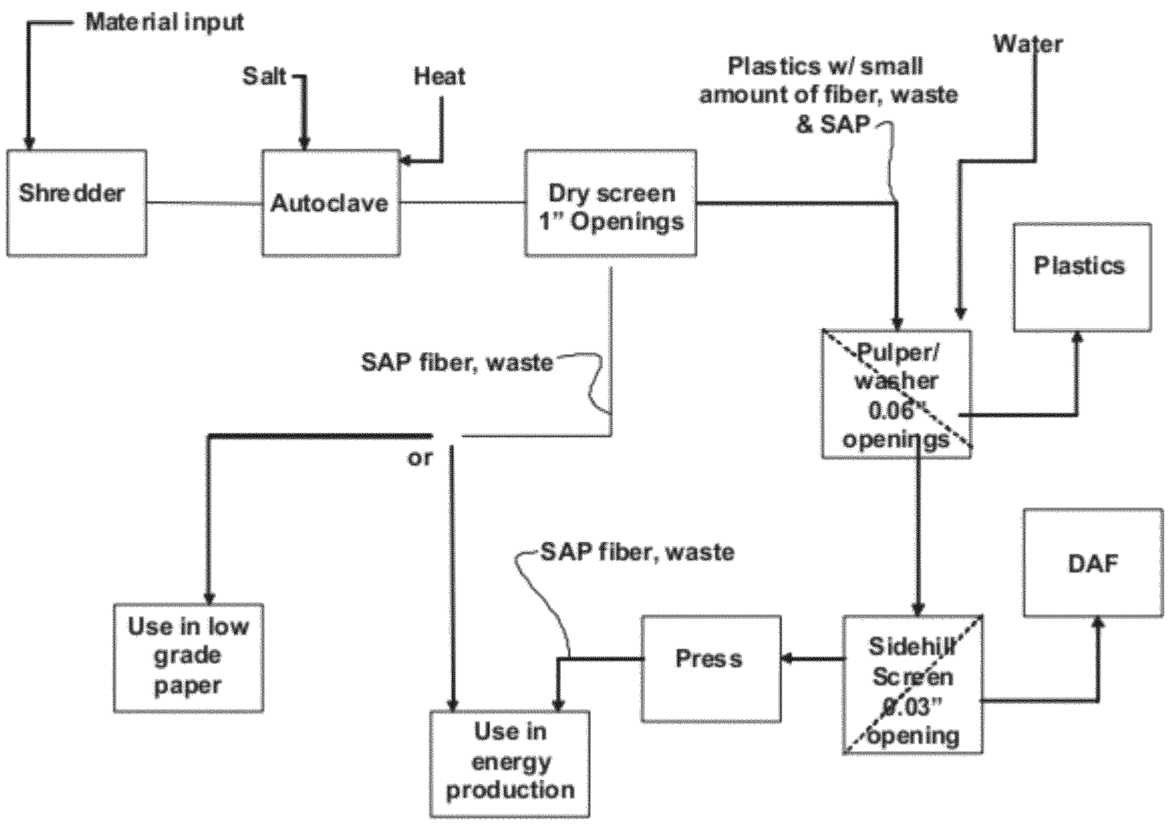

Figure 6.12.: Process diagram of pilot plant of Technology 3 [Source: Patent Technology3]

6.3. Market of recovered resources

When studying the previous technologies it can be concluded that there are three possible material streams which can be recycled: plastic, cellulose fibres, and superabsorbent polymers. Since the product has been in contact with human excretion regulations are strict concerning what products can be produced using these recovered materials. First the risks associated with recycling will be discussed and subsequently the possible applications of the three streams as claimed by the companies will be presented.

The risks that are associated with recycling diapers are caused by the fact that the product has been in contact with human excretion. In human excretions various types of pathogens can be found. A pathogen is an infectious agent as for example a bacterium, a virus, or a parasite that can cause disease in its host. There is no information available whether these pathogens remain in the materials or to what extent, in the three processes. It is claimed, however, that the treatment of the product with a high temperature results in the breaking down of pathogens. Another risk that is found in the urine of mostly elderly patients is medicine rests. Although there is some literature on medicine rests in wastewater where it has been proven that certain medicines remain in the sewage sludge [26], there is no information available concerning diapers. These are two important risks that need further study, which is at time of writing being executed by the RIVM.

In all three processes plastic is recovered as a resource to recycle. The plastic that is extracted from the recycling process is a combination of all the plastic components: the non-woven inner sheet formed from a liquid permeable material and the liquid impermeable back sheet, both formed from either polyethylene or polypropylene. Granulated plastic is already a resource stream that is currently being recycled. Due to the fact that it is a mixture of polypropylene and polyethylene the quality is lower than if it was a single plastic type. The granulated plastic mixture is, however, suitable for use in hard plastic products such as: roof tiles, benches, fences, poles, filtration crates, furniture, waste containers etc. Currently, there is no high quality application.

The recycling of superabsorbent polymers is a relatively new concept and has not been applied in any large scale plants. In some cases they are deactivated during the recycling process and cannot be retrieved in the products, however, there are techniques developed that claim to retrieve the SAP in a usable form. The proposed application of these SAPs is in the agriculture industry as a moisture retention polymer. The SAP can be placed in the soil together with seeds, where the SAP acts as a time-release source of water by slowly releasing the water over a long period of time. In arid climates this is particularly useful. SAPs are also used for collecting and removing toxic waste, hazardous chemicals and heavy metals from water and soil.

The cellulose fibres that are used in diapers are of a very high grade due to their length. When these fibres are extracted from the recycling process in a clean and sterilized form they can be re-used in a range of products. Ideally the fibres would be re-used in products such as tissues, toilet paper, or paper, however, due to consumer perception this would not be socially accepted. According to one company, products where the fibres can be used is in paper, cardboard, cement sheeting, bricks, insulation or even asphalt. Research done by TNO has concluded that the fibres cannot be used in packaging in the food industry due to risks of bacteria and mold [27]. To make use of the absorbency of the fibres and the left over SAP they can also be used in products like premium grade cat litter or soft animal bedding. The benefits of recycling these fibres is that virgin materials do not need to be used. An additional innovative technique for using the cellulose fibres is discussed in the next section.

Ideally the materials that are recovered from the recycling process would be used in producing new disposable diapers and thus closing the cycle. This is something which according to the diaper manufactures is not an option. Although the recovered materials would be suitable for the use in new diapers, diaper manufacturers do not want to take any risks. The diaper production business is a million dollar industry and diaper producers do not want to risk potential contamination of the materials. The potential of harm to babies as a result of using recovered materials is something that manufacturers do not want to risk.

6.3.1. Waste to Aromatics

The current focus of many diaper recycling developments has been the use of the recovered cellulose fibres in producing cardboard or sanitary products. Although this is technically feasible there is a negative consumer perception associated with this application. An alternative use of these cellulose fibres is the chemical conversion of the sugars within these fibres into chemicals. In partnership with TNO, Vito, Green Chemistry Campus, Attero and Orgaworld, AEB Amsterdam is looking into the production of aromatics from organic waste streams.

Aromatics are hydrocarbons that consist of a ring structure of carbon atoms. The most common known aromatic is benzene, the simplest aromatic hydrocarbon. Benzene has the chemical formula C_6H_6 where the carbons are attached in a ring form as shown in Figure 6.13, where a number of chemicals are shown that contain a benzene ring. Aromatics are important building blocks in a range of products in the chemical industry such as: soaps, aspirin, rubber, paints, perfumes etc. Currently aromatics are produced from fossil fuels, however, a shift to a biobased economy would require alternative, biological, sources. Not only would the use of biomass lead to an improved position price competitively and an improved delivery certainty, it would also lead to improved sustainability in the chemical industry. This shift is supported by a global market volume of aromatics of more than 100 Mt/year and a growing market of 3-5% per year.

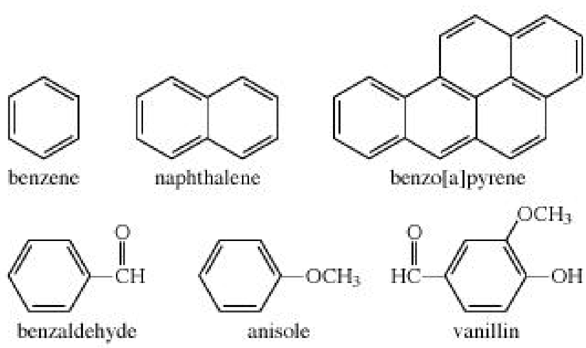

Figure 6.13.: Chemicals that contain a benzene ring [28]

The technology is based on the process of converting sugars (carbohydrates) in organic waste to furans, which are precursors to aromatics. The process step from furans to aromatics is well developed and the step from sugars to furans is also well developed for homogenous sugar streams. The goal of the Waste 2 Aromatics project is to study the production of furans from heterogeneous organic waste streams. This process consists of the breakdown of biomass to a sugar and lignin component using a biorefinery. The sugar is subsequently dehydrated to form humins and furans. The furans can further be processed to form aromatics via hydrogenation and decarbonylation or oxidation and decarboxylation [29]. This process is outside the scope of the Waste 2 Aromatics project, where the different process steps are illustrated in Figure 6.14.

In the scope of the Waste 2 Aromatics project several organic waste streams were tested on lab scale including disposable diaper filling: cellulose fibres with feces fibres. This material contains mainly c6 sugars (79%) and c5 sugars (6%) and has a high dry matter content [29]. The results of these lab scale tests provided positive results, with a high yield of furans. A business case was worked out which also came out positive for diaper filling. This does not take into consideration any pre-treatment steps which will certainly be necessary prior to the production of furans.

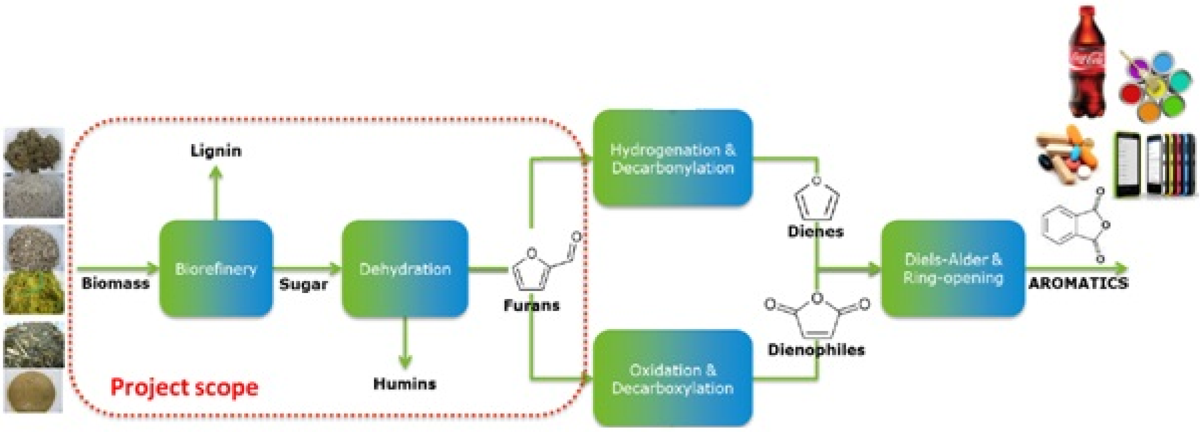

Figure 6.14.: Process steps from biomass to aromatics, including the bounderies of different initiatives [29]

7. Analysis

The three future technologies, as presented in the Results section, will be evaluated according to different factors: the environmental impact based on carbon dioxide emissions; the business case (where possible); the progress in the development of the technology, including any advantages or disadvantages of the technology; and lastly the capacity of the installation must be looked at to determine whether the market matches the capacity demand. Again, not all this information can be provided due to confidentiality of the information.

For reference Table 7.1 is provided with the most important results from the previous section.

Technology	Seperated streams	Market streams	Planned capacity [ton/year]
Technology 1	Cellulose SAP Plastic	Cardboard/packaging Agriculture Furniture/poles	48.000
Technology 2	Plastic Organic	Filtration crates Digestion and composting	10.000
Technology 3	Cellulose Plastic	Cat litter/packaging Furniture/poles	36.000

Table 7.1.: Most important results of the three future technologies

7.1. Business case

A very important factor that must be considered when looking at the three technologies is the business case. All the data that has been acquired concerning the business case is confidential and has not been presented in the Results section. The key to a successful business case is in the balance between the incomes and the expenditures. The incomes and expenditures will be discussed here in a purely qualitative form to provide some insights into the business cases.

The main expenditures will be the same for the three initiatives: the capital expenditure (CAPEX) which includes the cost of developing the site and equipment and the operational expenditure (OPEX). The operational expenditure includes labour, chemicals, energy, water/sewer, general maintenance, rent & rates, insurance, disposal, licences/patents, and other overheads. The CAPEX is dependant on the capacity of the installation and will be the lowest for Technology 2 and the highest for Technology 3 and 1 (highest). The OPEX is, however, largely dependent on the process, where energy costs are among the highest. The technologies that re-use energy from their process or use waste heat from the waste incineration installation will have lower energy costs.

The main income is dependant on the gate fees as well as the income generated by selling the recovered materials. The gate fee is the amount paid by a company/government to bring their waste to an installation for processing, and is measured in Euro/ton. No information can be provided on the proposed gate fees, except that the higher the capacity of the installation the higher the income will be from gate fees which are determined per ton of incoming waste. In order to compete it is desirable for the gate fee to be lower than the standard gate fee for incineration which is approximately 80 euro/ton in the Netherlands [2]. In the Netherlands there is also a tax which must be paid for landfilling or burning waste of 13 euro/ton [30]. Thus, in order to compete with incineration the gate fee for recycling should be below 90 euro/ton.

The income from selling the recovered materials is dependant on the streams that are recovered: what is recovered and how much of it. All three technologies look to recover the plastic, which is a mix of polypropylene and polyethylene after recycling. This mixture is said to have a market value of 190-350 euro/ton [21]. In the three cases this will provide the same income depending on the losses in the process. In the case of Technology 1 and 3 the cellulose fibres are recovered, where the market value is said to be around 50 euro/ton [21]. There is no data available for the market value of recovered SAP. Technology 2 has a different income than the other two, as the organic stream is sent to a digester to produce biogas. It is assumed that this is an income stream as the biogas can be used to produce electricity, however, because it contains human excretions which are considered a waste product according to the Dutch law it may cost money instead. There is no data available on these costs/income.

Clearly the business case depends on a number of different factors. The more efficient the process, thus ensuring less losses in the recoverable streams, the higher the income. The two technologies that look to recover more than just the plastic stream will, however, require extra cleaning steps to ensure that the cellulose fibres are also suitable for the market, leading to higher costs. Whether the organic waste stream of Technology 2 will lead to an income instead of an expenditure is the factor that makes or breaks that business case.

7.2. Market capacity

All three technologies have planned for a different capacity of their full scale installation: 1) 48.000 ton/year, 2) 10.000 ton/year and 3) 36.000 ton/year. This accounts for respectively 12, 3, and 9 percent of the total amount of diaper waste produced in the Netherlands. According to economies of scale, generally the cost per unit of output will decrease with increasing scale, due to the fact that the fixed costs are spread out over more units of output. Although this may be true, it is also so that if the installation does not run at full capacity because the input is not available extra costs are being made for nothing.

It is thus important to make an estimation of the market size available in the Amsterdam region. According to analysis from when the Knowaste plant was in operation in the Netherlands it was found that approximately 10 kg of diaper waste is collected per citizen [2]. Considering the population of the city of Amsterdam this would account to 8.2 kton of waste per year, while in the Metropolitan region of Amsterdam 23 kton/year. This would only allow the installation of Technology 2 to work at full capacity. However, since there are no other existing installations in the Netherlands the scope may be taken to be larger. The municipalities where diapers are already collected separately can be also included, although they will have to travel large distances. For Technology 1 a total of 4.800.000 citizens are needed, Technology 2 1.000.000 citizens, and for Technology 3 3.600.000 citizens.

For a company that is new to this market and has no previous experience it is advisable to not aim for too high capacity. The high inputs are probably needed to make for a successful business case for Technology 1 and 3, thus if this capacity is not met it is likely that no profit will be made. Since there is currently no separate collection in Metropolitan region of Amsterdam there is a high risk associated with assuming that the high input capacities will be reached. Ideally the collection system would be in place prior to determining the capacity of the installation, however, this is not realistic. In order to avoid high costs it is advisable to start small and increase the capacity over time.

7.3. Environmental aspects

When looking at the environmental aspects of the three future technologies it is important to compare them to the current waste disposal technique: incineration. It has been chosen not to look at the existing technique of composting by Orgaworld because this process is likely to not exist on the long term. There are several themes which are important to consider within environmental aspects such as: climate; acidification; fertilization; human toxicity; and final waste. It is chosen to focus on the climate and look at the amount of emitted carbon dioxide. Carbon dioxide is a greenhouse gas which is scientifically proven to have a negative influence on our climate. When considering the carbon dioxide emissions it is very important to define the system boundaries. This is done first for the waste incineration process at AEB Amsterdam and subsequently for the future technologies.

7.3.1. System boundaries

It is essential in every study of environmental aspects, as is done in life cycle assessments, to define the system boundaries of the process to be studied. For all the routes the starting point is the collection of the diapers by the private or public collectors. The end point of the various processes is in all cases the production of a final product, be it energy or a material resource. For both these end products the avoided production emissions are taken into consideration, and are thus considered negative emissions. The system boundaries of the four different processes can be seen below in Figure 7.1 to 7.4.

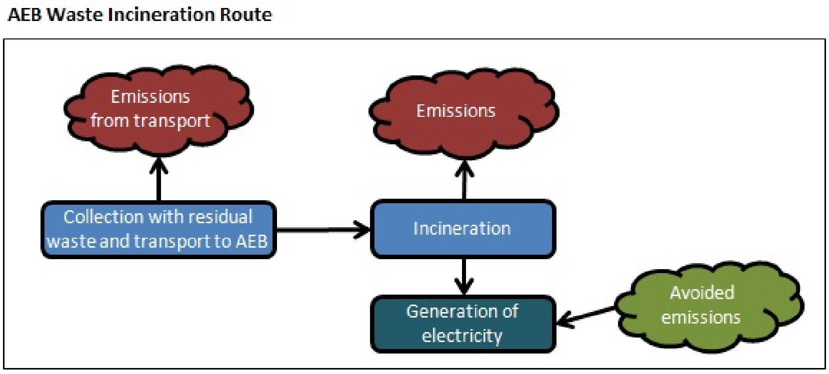

Figure 7.1.: System boundaries waste incineration route at AEB

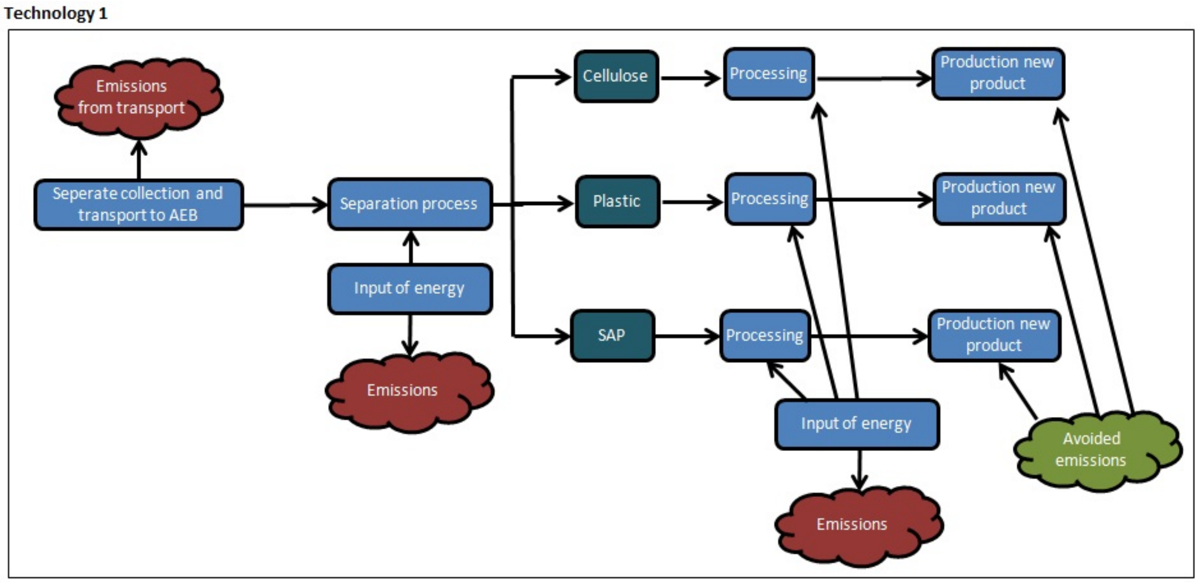

Figure 7.2.: System boundaries recycling Technology 1

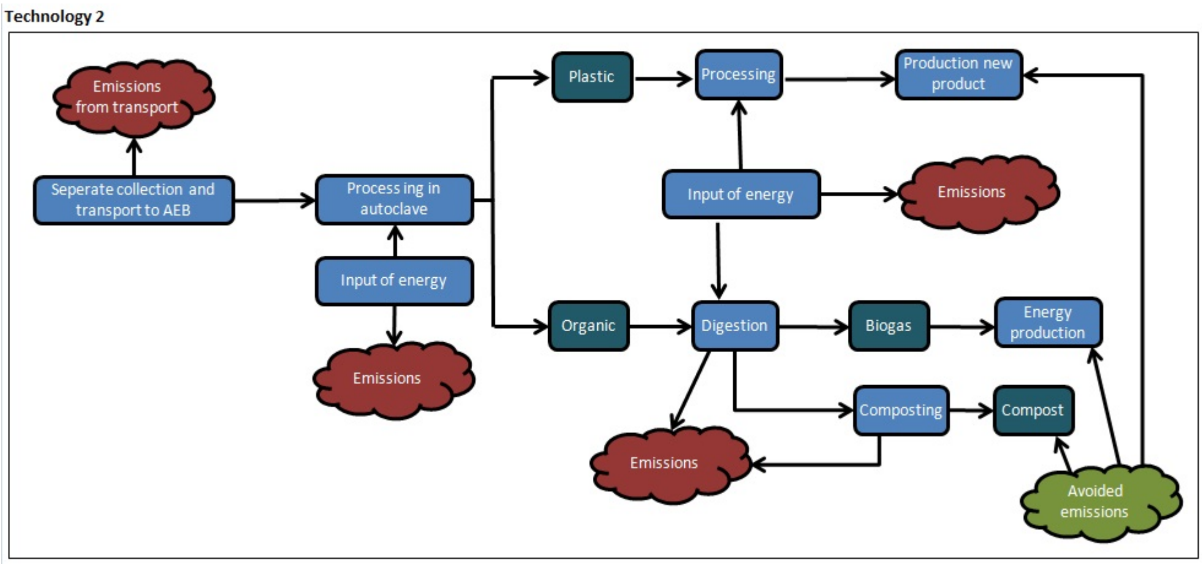

Figure 7.3.: System boundaries recycling Technology 2

7.3.2. Emissions waste incineration

Initially the route of sending the diapers to the waste incineration plant, AEB Amsterdam, is looked at. In this process the diapers are collected together with the municipal waste and brought to the waste incineration plant. Here the waste is incinerated to produce energy in the form of electricity and heat, with as rest products: fly ash, scoria, and the flue-gas residue. For the cleaning of the flue-gas calcium-carbonate, ammoniac, and active coal are used. The process and the emissions were schematically represented in Figure 7.1.

The emissions in the form of carbon dioxide were determined. These emissions are in the form of direct emissions from the combustion of SAP and plastic; indirect emissions in the form of used salts; saved emissions due to the production of energy; and emissions from transportation. To determine the direct emissions it is necessary to look at the composition of the diapers and to use the combustion equations to calculate the amount of carbon dioxide produced. Only the

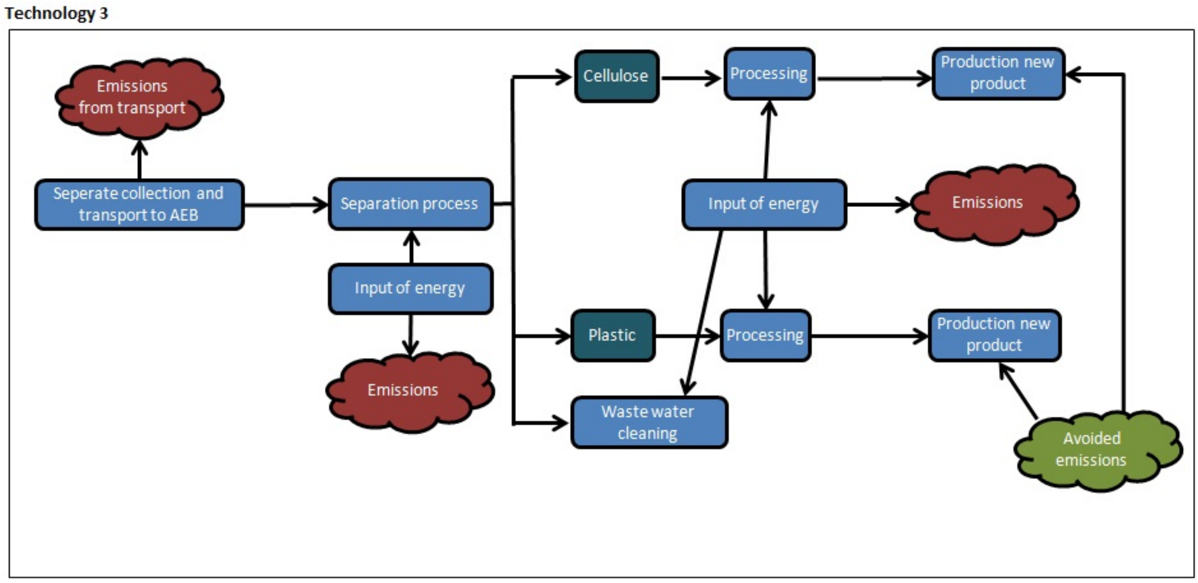

Figure 7.4.: System boundaries recycling Technology 3

superabsorbents, the polyethylene and the polypropylene are considered, as the emission of the combustion of human waste is negligible. Cellulose has a net carbon dioxide emission of zero because it is produced using tree fibres. The chemical equations of the combustion processes are shown below.

SAP:
$3\,O_2 + C_2H_3COOH \longrightarrow 3\,CO_2 + 2\,H_2O$

Polyethylene:
$\frac{9}{2}O_2 + (C_3H_6)n \longrightarrow 3\,CO_2 + 3\,H_2O$

Polypropylene:
$3\,O_2 + (C_2H_4)n \longrightarrow 2\,CO_2 + 2\,H_2O$

Using the stoichiometry of these reactions the amount of carbon dioxide produced due to the combustion of each of these materials can be determined. Per kg of SAP combusted 0.814 kg of CO2 is produced. Per kg of polypropylene as well as polyethylene 3.14 kg of CO_2 is emitted. These values are converted to the amount of CO2 in grams emitted per kg of diaper waste.

The saved emissions due to the production of energy require the determination of the amount of energy that is produced by the waste incineration plant by burning the diaper waste. This is done for two cases, for incineration in the AEC and the HRC at AEB Amsterdam with a net energetic efficiency of 16.8% and 30.56% respectively determined in 2014 [1]. To determine the amount of energy produced the Lower Heating Value (LHV) of the various materials needs to be determined. The lower heating value is defined as the amount of energy released when a compound undergoes complete combustion under standard conditions where water in the flue gas is not condensed. To determine the LHV the Higher Heating Value (HHV) is first determined, where water is condensed. The formulae used for these calculations, known as the Formula of Milne, are shown below where *ar* stands for as received and *dry* is without any moisture. C, H, O etc are in wt-% of the dry material.

$$HHV_{dry} = 0.341 \cdot C + 1.322 \cdot H - 0.12 \cdot O - 0.12 \cdot N + 0.0686 \cdot S - 0.0153 \cdot \text{ash}$$
$$LHV_{dry} = HHV_{dry} - 2.442 \cdot 8.936(H/100)$$
$$LHV_{ar} = LHV_{dry} \cdot (1 - (w/100)) - 2.442 \cdot (w/100)$$

The results of these calculations can be found in Table B.1 in Appendix B. The LHV as received of 4.34 MJ/kg is found and can be used to determine the energy produced for both installations, based on their energetic efficiency. To translate this to saved emissions an average amount of emissions for electricity production in the Netherlands is used of 164.2 g CO2/MJ [21].

Transport emissions must also be considered, from the households to AEB Amsterdam. Emissions are taken to be 0.07 kg CO_2 per tonkm [21]. Considering the Metropolitan region of Amsterdam an average distance that needs to be traveled is taken to be 35 km. This leads to an emission of 2.45 g CO_2/kg diaper waste. The results of all the calculations of the carbon dioxide emissions are displayed in Table 7.2 in g CO_2 per kg diaper waste.

	Efficiency [%]	Direct emissions [g/kg]	Indirect emissions [g/kg]	Saved CO_2 Energy production [g/kg]	Transport emissions [g/kg]	Net CO_2 emissions [g/kg]
HRC	30.56	245.56	1.07	217.81	2.45	31
AEC	16.8	245.56	1.07	119.74	2.45	129

Table 7.2.: Carbon dioxide emissions from diaper waste incineration at AEB Amsterdam

7.3.3. Emissions compared

For the future technologies it is essential to determine the emissions that have been defined in the system boundaries. These results cannot be discussed quantitatively but will be addressed briefly in a qualitative fashion.

In all three cases the emissions from transport can be determined using the average distance that needs to be covered to bring the waste to AEB and the standard emission value of 0.07 kg CO_2 per tonkm. For the energy inputs in the processes it can be assumed that the electricity is used from the standard Dutch electricity net with carbon dioxide emissions on average of 164.2 g CO2/MJ [21]. The reuse of the specific material streams leads to a saving in emissions because it has been avoided that raw materials need to be used. The emissions of the primary production of the streams are shown in Table 7.3. There was no data found for superabsorbent polymers.

Material stream	CO_2	Saved emissions [% of primary production]
Cellulose	770	50
Polyethylene	1680	25
Polypropylene	1660	25

Table 7.3.: Carbon dioxide emissions from primary production of the material streams [21]

As can be seen in Table 7.3 the saved emissions are not chosen to be 100% of the emissions from primary production of the material streams. In the case of cellulose fibres that is because the recycled fibres do not follow the same life cycle as recycled fibres from paper or cardboard for example. The fibres from these products can be re-used up to seven times before the fibres become too short. However, when the diaper fibres are used in products such as cat litter, afterwards the cat litter will not be recycled and will instead end up in the incineration plant. In addition the cellulose fibres in the diaper contain two types of pulp (CTMP and CP) [21] as well as perhaps some left over superabsorbent polymers.

Similarly the saved emissions for the re-use of the plastics is not taken to be 100%. The percentage is determined by looking at the price of the primary plastics as well as the price of the retrieved plastic. Looking at the price for different types of plastic the cost for primary plastic is taken at 1.150-1.250 EUR while that of retrieved plastic is around 190-350 EUR. This corresponds to a decrease in value of approximately 25%.

In the case of Technology 2 it is also necessary to look at the emissions which occur due to the anaerobic digestion and composting of the digestate. An anaerobic digestor as well as a composter require energy to keep the process going, both leading to emissions. However, in both cases the production of energy from biogas and the production of compost leads to saved emissions because no primary sources needed to be used. Using the amount of biogas produced, the electricity production can be calculated and thus the saved emissions from not using primary energy.

The results of the emissions from incineration as well as from Technology 2 and 3 are shown in Figure 7.5 (values are left out). For Technology 1 there was not enough information available on the process and on the recycling of the superabsorbent polymers to make an estimation. As can be seen in Figure 7.5 there are best and worst cases considered. For the incineration process the best case is the HRC and for the worst case the AEC. For Technology 2 the worst case is not recycling the plastic but instead incinerating it, while in the best case it is recycled. It can be seen that there are some significant differences, especially Technology 2 seems to have a clear advantage. This is due to the avoided emissions that are considered from the biogas production. It is expected that in a more detailed analysis of the entire process the emissions will, however, increase due to high energy use in the processing step of the thermal pressure hydrolysis.

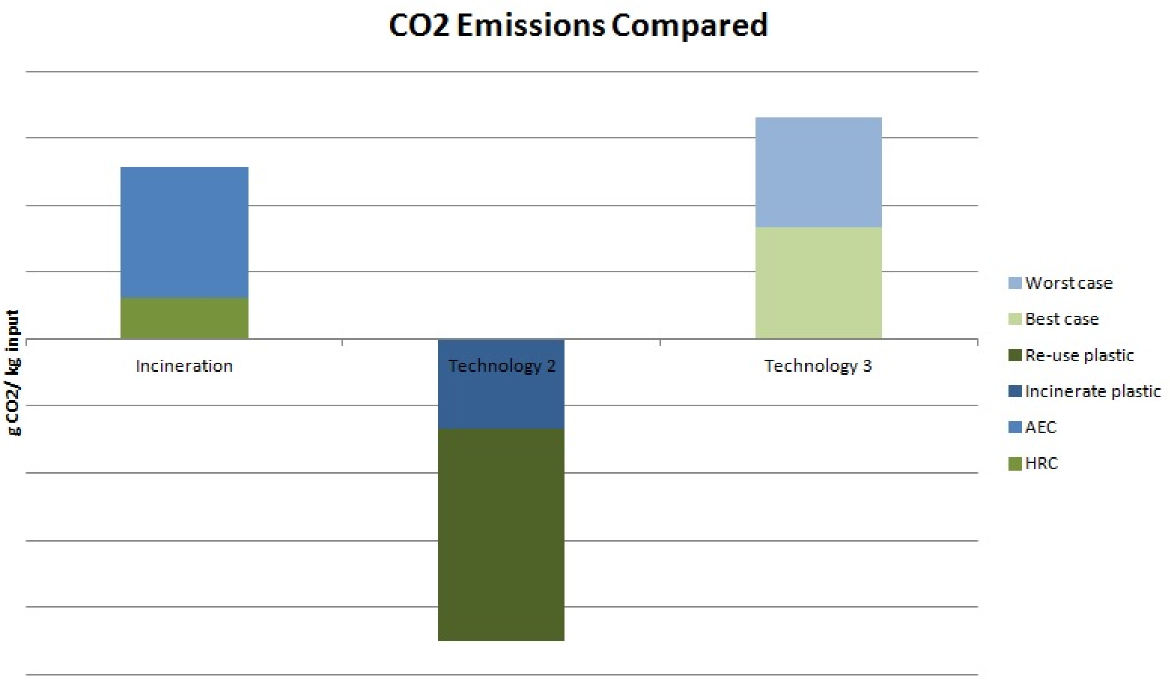

Figure 7.5.: The carbon dioxide emissions compared for the different technologies

7.4. Advantages and disadvantages

To sum up the analysis of the three technologies the advantages and disadvantages are considered. These include technological advantages as well as those related to the business case and the environmental aspects. The most important factors are summed up in Table 7.4, where for each technology it is indicated whether the factor is not satisfied (red), sort of satisfied (orange) or satisfied (green).

Factor	Technology 1	Technology 2	Technology 3
Recovering Resources	green	red	orange
CO_2 Emissions		green	red
Technology readiness	orange	orange	green
Capacity-market match	red	green	orange
Health risks products	orange	green	orange
CAPEX	orange	green	orange
Uncertainty income from products	red	orange	orange
Match with Waste 2 Aromatics	green	orange	green

Table 7.4.: Main advantages and disadvantages of the three future technologies compared

Due to the scope of the project, which was looking at new ways to recover more resources for AEB Amsterdam, a suiting factor to consider is 'Recovering Resources'. In Technology 1 all of material streams that are present in a diaper: plastic, cellulose and superabsorbent polymers are recovered, while in Technology 2 only the plastic is recovered, and in Technology 3 the plastic and the cellulose. The carbon dioxide emissions were also looked at in Section 7.3.3 and compared with waste incineration. Too much information was missing on the process to make a suitable estimation for Technology 1. Due to the retrieval of the biogas to produce electricity

Technology 2 has the lowest emissions.

An important factor to consider is how far along the technology has been developed. Technology 1 and 2 have both been tested on lab scale and are looking to scale the process up to pilot scale. Technology 3 has been tested at pilot scale and is now looking to scale up to full scale. This means that Technology 3 could be implemented sooner. The market of diaper waste was studied and can be compared with the final capacity of the three installations. With a capacity of 48.000 ton/year Technology 1 has the largest installation and requires approximately 5 million citizens to deliver 10 kg/year, while Technology 2 required 1 million and Technology 3 approximately 4 million. Due to the fact that it is an entirely new market for AEB and there is no seperate collection in the area it is a high risk to start with such a high capacity.

There remains uncertainty in the quality of the products especially concerning pathogens and medicine rests. For Technology 2 there is the lowest risk because a high temperature and pressure are used for sterilization and only the plastic stream will be reused in the production chain. For both Technology 1 and 3 the risk is slightly higher due to the reuse of the cellulose fibres.

Regarding the business case the capital expenditure and the operational expenditure was looked at. The CAPEX is dependant on the capacity of the full scale installation, giving Technology 2 the lowest CAPEX. Regarding the income the gate fee is important but also the income from selling the recovered resources. For Technology 1 there is uncertainty in this income because recovered superabsorbent polymers do not have a set market. For Technology 2 there is an uncertainty for the plastic, but also for the acceptation of the organic stream for digestion as it is technically considered a waste stream. Technology 3 also has uncertainty concerning the plastic and the cellulose.

In Section 6.3.1 the process of producing aromatics from cellulose was explained. AEB Amsterdam is investing in research into this subject and for them it is interesting if the output stream from the diaper recycling technique could be used in this process. In Technology 1 and 3 the cellulose leaves the process in a relatively pure form which is advantageous for the process. In Technology 2 the cellulose is mixed with the human excretions making it uncertain whether this would be suitable.

Clearly there are advantages and disadvantages for all the three technologies studied. Technology 1 fits the requirements for recovering resources the best, however, Technology 2 seems to have the least risks associated with it. The smaller scale makes it an investment that could be made easier without taking too many risks. The uncertainties for Technology 1 make it a risky business choice to invest in. Technology 3 has the advantage of being further in the technology development, however, the large market needed to satisfy the business case is a challenge in a setting where there is almost no capacity readily available.

8. Discussion and recommendations

One of the major drawbacks of this study was that not the same amount of information was available for all three of the technologies that were looked at. There was for example not enough data available about Technology 1, especially concerning the specifics of the technology. This was because the company that has been working on this technology has only just gone public with their existence and obviously do not want to make their technology public to everyone. This made it difficult to perform an in depth environmental analysis concerning carbon dioxide emissions as well as getting an indication of the costs of the process.

Something that is a clear difference between the technologies is the capacity of the full scale installation that will be built. For all three cases this capacity was probably determined so as to ensure that the business case is successful. The success of the business case is largely dependent on the income from the gate fee which is directly related to the amount of incoming waste. It is thus important to get a good indication of how much waste will be incoming. Although I was able to find an indication of the amount of waste that was collected per citizen when Knowaste was operating in Arnhem there was no further information on the breadth of the collection. It is thus necessary to determine how much diaper waste can actually be collected separately and up to what distances it is realistic to be transporting it.

A large uncertainty that the companies indicated also to have problems with was the health risks associated with the recovered materials. The RIVM is currently performing an in depth study into the potential risks of pathogens and medicine rests in the recovered materials. It is important to follow this study and to determine what the norms are for the presence of these risks in recovered material. Only once there are norms defined will it be easier to be able to sell the final recovered resources on the market.

The environmental analysis should also be extended and executed more carefully. In the determination of the carbon dioxide emissions some assumptions were made concerning the amount of energy used in the process because that specific data was not available. It is also important to consider other environmental effects such as the amount of water used; the human toxicity; the amount of final waste; and acidification. By performing an entire life cycle assessment these environmental aspects would be brought to light.

The business case is of course an aspect that is of utmost importance to a company like AEB that is looking at the opportunities in this sector. The business case, including the various operational and capital expenditures as well as the income streams, was received from one of the companies. The business case was adjusted to suit the situation in Amsterdam and specifically using the electricity and heat prices of AEB. This revealed the sensitivity of the business case to the amount of incoming waste and the gate fee. It would be interesting to receive the same information from the other companies to make a comparison. Clearly, however, it can be concluded that it is very important that the capacity of the installation is met.

The only way to make a well educated decision on which technology to pursue would be to receive the same data from all the initiatives. There are too many facts that are important for the comparison which are not available. My advice would be to look first further into Technology 2 and 3, because the risks associated with these two technologies is much lower than Technology 1. The process in Technology 2 is much simpler and does not have the risks associated with recovering all material streams. Technology 3 has been developed further and has less risks concerning the marketing of the recovered materials.

9. Conclusion

During this research project the potential of three upcoming technologies to recycle diapers has been evaluated. The three processes differ in the capacity of the planned full scale installation; in the material streams they look to recover and in the process that is used for this recovery. An analysis of the data of each technology highlighted the importance of having the same amount of data available for each technique. Information was missing on the specific technologies used, making it difficult to evaluate the processes.

The important factors that were used to evaluate the technologies were: environmental in the form of carbon dioxide emissions and amount of recovered resources; the technology readiness; the match between the capacity and the market; the health risks; the business case in the form of the capital expenditures and the uncertainty associated with incomes; as well as the match with the Waste 2 Aromatics program. Technology 1 is the furthest in recovering resources as all the material streams are recovered, while Technology 2 only looks to recover the plastic and uses the organic stream as an input for anaerobic digestion. As a result the saved CO_2 emissions of Technology 2 are the highest while the risks are minimized. The main advantage of Technology 2 is also the scale of the installation. Considering that AEB would be entering an entirely new market it is more realistic to start with a smaller capacity and increase it over time instead of requiring 48.000 ton of diaper waste per year.

An accurate assessment of the existing market and the potential on the diaper waste market has been made. For AEB Amsterdam, where there was no prior knowledge on the market of diaper waste, this report provides insight into a waste stream with significant potential. It is essential that the business cases of the three technologies are studied in more depth and evaluated according to the situation in Amsterdam.

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Appendices

A. Extra information manufacturers and brands of diapers

Brand	Retailer	Manufacturer	Sustainability score according to EOS
Pampers	Drogisterijen en supermarkten	Procter&Gamble	Nog lang niet
Kruidvat (huis)	Kruidvat	SCA	Goed bezig
Libero	Drogisterijen en supermarkten	SCA	Goed bezig
Europrofit (huis)	Kruidvat	SCA	Tandje erbij
Drynites	Drogisterijen en supermarkten	Kimberly-Clark	Tandje erbij
Huggies	Drogisterijen en supermarkten	Kimberly-Clark	Tandje erbij
Jumbo (huis)	Jumbo	Ontex	Goed bezig
Babycharm	Jumbo	Ontex	Actieve Runner-up
Bumblies (huis)	Superunie	Ontex	Tandje erbij
Moltex/moltex OKO	Plus supermarkt, online	Ontex	Tandje erbij
DA (huis)	DA	Ontex	Nog lang niet
Bambo Nature	Online	Abena	Actieve Runner-up
Albert Heijn (huis)	Ahold	Abena	Actieve Runner-up
Etos (huis)	Ahold	Abena	Actieve Runner-up
Toujours (huis)	Lidl	Drylock	Tandje erbij
Sweetcare	Online	Drylock	Tandje erbij
Magics	Online	Drylock	Actieve Runner-up
Naty	Etos, EcoPlaza, Online	Naty AB (Zweeds)	Actieve Runner-up
Pingo	Online	Hyga AG (Zwitserland)	Goed bezig
Bebino (huis)	Aldi	Intigena	Nog lang niet
Attitude	Online	Bio-Spectra	De Bezemwagen
Beaming Baby	Online	Beaming Baby	De Bezemwagen
Bellababy Happy	Online en L. Delhaize	TZMO	De Bezemwagen

Figure A.1.: Brands and manufacturers of baby diapers with sustainability scores according to EOS [31]

B. Results HHV and LHV

Material in used diapers	Chemical formula	Weight per diaper (g/diaper)	Weight percentage of diaper (%)	C (g)	C wt%	H (g)	H wt%	O (g)	O wt%	Total mass compound (g)	HHV_dry	LHV_dry	HHV_ar	LHV_ar
Fluff pulp	$(C_6H_{10}O_5)_n$	0,009	5,465	0,721	44,457	0,101	6,219	0,800	49,324	1,621	17,462	16,105	3,684	1,471
Superabsorbent polyacrylate (SAP)	C_2H_3COOH	0,013	7,568	0,360	50,012	0,040	5,597	0,320	88,759	0,720	13,802	12,581	2,912	0,728
LDPE	$(C_2H_4)_n$	0,002	1,081	0,240	85,627	0,040	14,373	0,000	0,000	0,281	48,200	45,064	10,170	7,582
PP	$(C_3H_6)_n$	0,008	4,745	0,360	85,627	0,060	14,373	0,000	0,000	0,421	48,200	45,064	10,170	7,582
Adhesive, tapes, elastic		0,002	1,141	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Faeces		0,008	5,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Urine		0,125	75,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Total		0,167	100,000								31,916	29,703	6,734	4,341

Figure B.1.: Results of the calculated higher heating and lower heating values of waste incineration